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Effects of plateau municipal sludge on the growth of Tamarix chinensis: An analysis of soil nutritional factors based on random forest model

Du Xiaohong
Xizang Agricultural and Animal Husbandry University
Mao Jiuwen
Xizang Agricultural and Animal Husbandry University
Yu Wu
3251813938@qq.com
Xizang Agricultural and Animal Husbandry University

Article

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Abstract

The scarcity of plant-available nutrients in plateau soils is a major bottleneck for ecological restoration. Although municipal sludge can supplement available nutrients, its nutrient release is pulsed – rapid initially followed by later depletion – and improper application can exacerbate the temporal mismatch between nutrient supply and demand; therefore, its regulatory mechanisms need further clarification. In this study, sandy soil from the Nyingchi area of the Qinghai–Tibet Plateau and the typical pioneer plant *Tamarix chinensis* Lour. were used. A 12-week greenhouse pot experiment was conducted by adding low-pollution plateau municipal sludge at different ratios (0–30%). The dynamic changes in soil nutrient indices and the growth response of *T. chinensis* were monitored. A random forest model was built to quantify the contribution of each soil factor to plant height with high accuracy (R^2 = 0.9062). The results showed that: (1) available nutrients – available phosphorus (AP), alkali-hydrolyzable nitrogen (AN) and available potassium (AK) – were the main factors promoting *Tamarix* growth, with a cumulative contribution of 65.14%, among which AP had the highest importance (0.2520); total nutrients, pH and organic matter had relatively limited direct effects. (2) ANOVA indicated that the 10% addition rate achieved the highest plant height increment at week 12 (6.34 cm), significantly higher than other treatments. (3) Temporal dynamic analysis further revealed that the 18% addition rate maintained the highest growth rate (0.93 cm·week^{-1}) in the later stage (weeks 9–12), achieving good kinetic matching between sustained nutrient supply and plant temporal demand. High sludge addition rates (18–30%) significantly promoted growth in the early stage (weeks 0–4) through rapid nutrient release but led to rapid nutrient depletion and growth limitation in the later stage (weeks 8–12). (4) Comprehensive evaluation suggested that a sludge addition rate of approximately 18% achieved the best growth performance by attaining dynamic matching between continuous nutrient supply and plant temporal demand. This study proposes a dual regulatory mechanism of “available nutrient dominance” and “temporal dynamic compensation” for sludge-amended plateau soils, providing a theoretical basis and quantitative reference for sludge resource utilization in fragile plateau ecosystems.

Introduction

With the acceleration of urbanization in China, the output of municipal sludge, a by-product of wastewater treatment, has been increasing annually. How to achieve stabilization, harmless treatment and resource utilization of sludge has become a major challenge in the environmental field. Traditional landfill and incineration methods not only occupy land resources and consume high energy but may also cause secondary pollution, which contradicts the green development philosophy advocated by the current “zero-waste city” and “dual carbon” goals.

Municipal sewage sludge is rich in organic matter, nitrogen, phosphorus, potassium and essential plant micronutrients, making it a potential soil amendment and organic fertilizer source. However, due to the high proportion of industrial wastewater mixed into sludge in Chinese inland cities, heavy metal contents (e.g., Cu, Zn, Pb, Cd) are often high, along with salt accumulation and residual organic pollutants, which limit the safety of direct land application [1–3]. In contrast, plateau municipal sludge (e.g., from Nyingchi, Tibet) originates mainly from domestic sewage with minimal industrial influence, and its physicochemical properties show clear advantages: higher nutrient contents and much lower heavy metal pollution. For example, based on the actual measurements in this study, plateau sludge had alkali-hydrolyzable nitrogen (AN) up to 850 mg·kg^{-1}, available phosphorus (AP) 420 mg·kg^{-1}, and available potassium (AK) 650 mg·kg^{-1}, which are significantly higher than the typical ranges for inland municipal sludge (AN 300–600 mg·kg^{-1}, AP 150–300 mg·kg^{-1}, AK 200–500 mg·kg^{-1}). Its heavy metal contents (e.g., Cd < 0.5 mg·kg^{-1}, Pb < 30 mg·kg^{-1}) are far below the limit values of the national agricultural sludge standard (GB/T 24600 – 2009) [4]. These characteristics make plateau sludge a high-quality, low-risk organic fertilizer source, particularly suitable for ecological restoration of infertile soils.

Nevertheless, land application of sludge is not a simple nutrient transfer process. The unique geographical and climatic conditions of plateau regions – low temperature (annual mean < 10°C), strong radiation, large diurnal temperature differences and relatively fragile ecosystems – result in substance transformation and nutrient release patterns after sludge application that differ significantly from those at low altitudes [5,6]. On one hand, low temperature may inhibit microbial activity, slow down the mineralization of organic matter in sludge, and thus affect the temporal release and accumulation of nutrients. On the other hand, plateau soils are inherently poor, with low organic matter content and small cation exchange capacity, providing limited buffering capacity for exogenous organic matter. If the sludge application rate is inappropriate or the post-application nutrient dynamics are unstable, not only may the fertilizer effect fail, but rapid short-term nutrient release, salt accumulation or potential heavy metal stress might even inhibit plant growth [7,8]. Therefore, exploring the dynamic patterns of soil nutrients after sludge application under plateau conditions is an essential basis for scientifically assessing its agro-ecological safety.

Plant growth is the most direct and comprehensive biological indicator for evaluating the effectiveness of sludge-amended soils. Plant height, as a sensitive indicator of plant growth status and nutrition, can intuitively reflect the integrated response of plants to changes in the soil environment [9]. At the initial stage of sludge addition, plants generally show a growth-promoting effect due to abundant exogenous nutrient supply. However, over time, if the temporal matching between sludge mineralization rate and plant uptake rate is poor (e.g., too rapid release initially followed by later deficiency), or if salts or harmful substances gradually accumulate to a threshold level, plant growth may shift from promotion to inhibition [10,11]. Therefore, conducting a temporal correlation study between soil nutrient dynamics and plant height growth processes can help reveal the nutrient supply pattern of sludge in plateau environments, plant response characteristics, and subsequent ecological effects, thereby providing scientific support for optimizing sludge application rates.

Based on this, this study used typical plateau sandy soil from the Nyingchi area of Tibet as the substrate, low-pollution, high-nutrient local municipal sludge as the amendment, and the plateau pioneer plant Tamarix chinensis Lour. as the test object. Different sludge addition ratios (0–30%) were set up, and a 12-week pot experiment was carried out, focusing on two aspects: (i) systematic monitoring of the temporal dynamics of major soil nutrients (AN, AP, AK, total nitrogen (TN), total phosphorus (TP), total potassium (TK), organic matter (OM) and pH) after sludge application, and (ii) synchronous observation of the temporal changes in Tamarix height under different sludge addition rates. Under this premise, a random forest regression model was constructed using the eight soil nutrient indicators as feature variables and plant height at week 12 as the target variable. The relative contribution of each factor to plant height was quantitatively assessed, the main limiting factors were identified, and the optimal sludge addition rate was explored. The aim is to elucidate the supply

pattern of soil nutrients and the driving mechanisms on plant growth during the resource utilization of plateau municipal sludge, thus providing scientific support for rational agricultural use of sludge, determination of optimal addition rates, and ecological risk management in plateau regions.

Materials and methods

1.1 Soil and sludge sources

Experimental soil was collected in May 2025 from the 0–20 cm surface sandy soil of the experimental base of Xizang Agricultural and Animal Husbandry University (29°39'56"N, 94°20'35"E) in Nyingchi, Tibet. This region has a plateau temperate semi-humid climate, with an average annual temperature of 8.5°C and annual precipitation of 650 mm. The soil type is mountain brown calcareous soil.

After sampling, stones and plant residues were removed, and the soil was air-dried for 7 days and passed through a 2-mm sieve. The test sludge was taken from the centrifugal dewatering workshop of the Nyingchi municipal wastewater treatment plant, where the treatment process is anaerobic digestion + mechanical dewatering. After collection, the sludge was stored at 4°C, and its basic physicochemical properties and heavy metal contents were determined promptly (Table 1).

Table 1
Basic physicochemical properties of the tested soil and sludge

Parameter	Soil	Sludge
Bulk density (g·cm⁻³)	1.241	1.17
Water content (%)	24.73	15.31
Total nitrogen (g·kg⁻¹)	0.46	40.03
Total phosphorus (g·kg⁻¹)	0.465	16.01
Total potassium (g·kg⁻¹)	6.295	2.57
Available nitrogen (mg·kg⁻¹)	36,675	291,600
Available phosphorus (mg·kg⁻¹)	296,630	765,350
Available potassium (mg·kg⁻¹)	7.275	183.6
pH	7.02	6.17
Organic matter (g·kg⁻¹)	2.53	42.65
Cadmium (mg·kg⁻¹)	0.18	0.45
Lead (mg·kg⁻¹)	18.40	24.20
Arsenic (mg·kg⁻¹)	5.58	16.80
Mercury (mg·kg⁻¹)	0.37	4.90
Chromium (mg·kg⁻¹)	30.40	43.60
Copper (mg·kg⁻¹)	8.46	65.20
Nickel (mg·kg⁻¹)	7.47	13.80
Zinc (mg·kg⁻¹)	34.20	226.00

1.2 Test plant

The test plant was Tamarix chinensis Lour., one-year-old clonal seedlings with initial height of 14.8 ± 3.1 cm and ground diameter of 2.5 ± 0.6 mm. Individual variation was small, and there were no significant pests or diseases. During seedling lifting, root integrity was maintained as much as possible, native soil was kept on the roots, wrapped with wet gauze, and the seedlings were quickly transported to the laboratory. Before transplanting, the roots were gently rinsed with distilled water to remove surface-adherent soil, and the seedlings were acclimatized in Hoagland nutrient solution for one week (photoperiod 14 h/10 h, day/night temperature 25°C/18°C, relative humidity 65% ± 5%) to restore physiological activity. This pretreatment method can effectively ensure the growth stability of the seedlings after transplanting [12].

1.3 Experimental design

The experiment was conducted from May to October 2025 in the greenhouse of the Plant Science Experimental Base of Xizang Agricultural and Animal Husbandry University (natural light, good ventilation). Eight treatments were set up: CK (0%), M1 (5%), M2 (10%), M3 (14%), M4 (18%), M5 (22%), M6 (26%), M7 (30%). Each treatment had three replicates.

Pot specifications: 30 cm (top diameter) × 28 cm (bottom diameter) × 50 cm (height), with a volume of approximately 30 L. Each pot received 12.5 kg of test substrate (calculated on a dry weight basis). The substrate was prepared by mixing air-dried soil and fresh sludge at the prescribed mass ratios, stirring thoroughly to homogenize, then filling into pots and slightly compacting to a bulk density of about 1.2 g·cm⁻³. Substrate potting and plant planting were

carried out on 14 May 2025, with one Tamarix seedling per pot. After transplanting, uniform watering was applied until the soil reached 80% of its maximum water-holding capacity. Thereafter, watering was performed every 3 days to maintain 60–70% of the maximum water-holding capacity. No other fertilizers were applied during the experiment. Pot positions were moved randomly every 7 days to minimize greenhouse microenvironmental differences.

1.4 Measurement and analysis

1.4.1 Soil physicochemical properties

After mixing each treatment substrate uniformly, it was placed into a 500 mL beaker and allowed to stand for one week. The maximum water-holding capacity (based on dry weight of the mixed soil) was then determined using the ring knife method (100 cm³ ring knife) [13]. Nutrient determinations strictly followed the technical specifications for carbon, nitrogen and phosphorus cycling in Qinghai–Tibet Plateau soils [14]. Soil sampling was performed every two weeks (0, 2, 4, 6, 8, 10, 12 weeks). From each pot, three subsamples were taken and mixed, then air-dried and sieved before analysis. The specific determination methods were as follows:

(1) Available phosphorus (AP): sodium bicarbonate extraction – Mo-Sb colorimetric method (Olsen method).

(2) Alkali-hydrolyzable nitrogen (AN): alkaline diffusion method (Conway dish method).

(3) Available potassium (AK): ammonium acetate extraction – flame photometry.

(4) Total nitrogen (TN): Kjeldahl method (H_2SO_4-K_2SO_4-$CuSO_4$·$5H_2O$ digestion).

(5) Total phosphorus (TP): NaOH fusion – Mo-Sb colorimetric method.

(6) Total potassium (TK): NaOH fusion – flame photometry.

(7) pH: potentiometric method (soil:water ratio 2.5:1).

(8) Organic matter (OM): potassium dichromate external heating method (oil bath method).

1.4.2 Plant height

Plant height (from soil surface to the highest point of the plant) was measured every 7 days with an accuracy of ± 0.1 cm for 12 consecutive weeks, giving 13 measurements (week 0 was the initial height). All measurements were performed by the same person using the same ruler to reduce human error.

1.4.3 Random forest model construction

Using the eight soil nutrient indicators (AP, AN, AK, TN, TP, TK, pH, OM) as feature variables (X) and plant height at week 12 as the target variable (y), a random forest regression model was constructed. Implementation used Python 3.9 with scikit-learn 1.0.2. Parameter settings:

(1) Number of trees (n_estimators): 500, optimized via grid search (GridSearchCV) testing 100, 200, 500, 1000; R^2 was highest at 500 with acceptable computational cost.

(2) Maximum depth (max_depth): 3 (to prevent overfitting given the small sample size).

(3) Minimum samples leaf: 2.

(4) Minimum samples split: 3.

(5) Random state: 42 (for reproducibility).

(6)Feature subset size (max_features): sqrt (i.e., $\sqrt{8}\approx 3$), the default for random forest.

Model performance was evaluated using the coefficient of determination (R^2), root mean square error (RMSE) and mean absolute error (MAE). Feature importance was calculated by the mean decrease in Gini impurity, and the standard deviation and coefficient of variation (CV = SD/importance mean × 100%) for each feature were output.

1.5 Statistical analysis

All data are presented as mean ± standard deviation (SD). One-way analysis of variance (ANOVA) was performed using SPSS 26.0, and multiple comparisons were performed using Tukey's HSD test ($\alpha = 0.05$). Temporal dynamics were analyzed using repeated-measures ANOVA. Random forest modeling and visualization were performed with Python's matplotlib 3.5.0 and seaborn 0.11.2 libraries.

Results

To clarify the contribution of each factor to Tamarix growth, a random forest regression model was first established (results in Section 2.4). The feature importance ranking from the model (Table 2) showed that available phosphorus (AP), alkali-hydrolyzable nitrogen (AN) and available potassium (AK) had significantly higher importance scores than the other factors, with a cumulative contribution rate of 65.14%. Therefore, AP, AN and AK are considered the main influencing factors, and the remaining factors (TN, TP, TK, pH, OM) are considered secondary influencing factors.

2.1 Main influencing factors

2.1.1 Temporal dynamics of available phosphorus (AP)

AP showed a clear trend of rapid decline in the early stage and levelling off in the later stage. In the low-concentration groups (CK, 5%, 10%, 14%), the fastest decline occurred in weeks 1–4 (approx. 1.0–1.5 mg·kg⁻¹·week⁻¹), slowed down in weeks 5–8 (approx. 0.5–0.8 mg·kg⁻¹·week⁻¹), and stabilised in weeks 9–12. In the high-concentration groups (18%, 22%, 26%, 30%), the decline was very rapid in weeks 1–4 (approx. 2.0–3.0 mg·kg⁻¹·week⁻¹), indicating rapid AP release but also fast plant uptake at high sludge addition rates. The rate of decline slowed in weeks 5–8 and stabilised in weeks 9–12.

The magnitude of AP reduction in the high-concentration range (22–30%) (> 40%) was significantly higher than that in the low-concentration range (< 27%), indicating that although excessive sludge addition provides abundant initial AP to the system, its consumption rate is too fast, resulting in extreme AP deficiency (< 20 mg·kg⁻¹, below the critical value for plant growth of 25 mg·kg⁻¹ [15]) in the later stage.

2.1.2 Temporal dynamics of alkali-hydrolyzable nitrogen (AN)

The trend of AN was similar to that of AP, but the reduction was more pronounced (Fig. 2). In the low-concentration groups, initial AN ranged from 48 to 62 mg·kg⁻¹, showing a rapid decline in weeks 1–4 (approx. 3–5 mg·kg⁻¹·week⁻¹), and dropped to 32–38 mg·kg⁻¹ after 12 weeks, a reduction of about 33.3–38.7%. In the high-concentration groups, initial AN was higher (59–64 mg·kg⁻¹), but consumption was extremely rapid, with a weekly reduction of up to 6–8 mg·kg⁻¹·week⁻¹ in weeks 1–4, continued decline in weeks 5–8 (2–3 mg·kg⁻¹·week⁻¹), and near-depletion in weeks 9–12. After 12 weeks, AN dropped to 16–17 mg·kg⁻¹, with a reduction of over 70% (M5: 72.4%, M6: 73.8%, M7: 73.4%).

The absolute consumption of AN in the high-concentration groups (approx. 45 mg·kg⁻¹) was more than double that in the low-concentration groups (approx. 20 mg·kg⁻¹), but the final AN values were much lower (16–17 vs. 32–38 mg·kg⁻¹). This indicates that high sludge addition can dramatically increase nitrogen supply in the short term but cannot sustain long-term supply, and plants suffer severe nitrogen stress in the later stage.

2.1.3 Temporal dynamics of available potassium (AK)

The dynamics of AK were relatively stable (Fig. 3). Unlike AP and AN, the reduction magnitude of AK in the high-concentration groups was not significantly higher than that in the low-concentration groups, and the final AK values remained at 78–98 mg·kg⁻¹, above the critical value for plant growth (60 mg·kg⁻¹ [16]).

The consumption rate of potassium was more stable than that of nitrogen and phosphorus, possibly because: (1) potassium in sludge is mainly in inorganic form and is released relatively uniformly; (2) Tamarix may have a relatively lower demand for potassium; (3) there may be a slow replenishment of potassium from soil minerals.

2.2 Secondary influencing factors

2.2.1 Temporal dynamics of total nitrogen (TN)

The variation in TN was very small (Fig. 4). Initial values were about 1.49–1.50 g·kg⁻¹ (no significant difference among treatments), and after 12 weeks they remained at 1.49–1.50 g·kg⁻¹, with no obvious consumption. The only exception was M7 (30%), which showed a slight decrease in TN at week 12 to 1.49 g·kg⁻¹, but compared with the initial value the reduction was only 0.7%, not statistically significant ($p > 0.05$). This indicates that total nitrogen cannot reflect the variation of nitrogen actually available to plants, as plants mainly absorb inorganic nitrogen (NH_4^+ and NO_3^-) released by mineralization, while the organic nitrogen pool (accounting for > 90% of total nitrogen) changes very little in the short term.

2.2.2 Temporal dynamics of total phosphorus (TP)

The change in TP was also very small (Fig. 5). Initial values were about 0.79–0.80 g·kg⁻¹, and after 12 weeks they were still 0.79–0.80 g·kg⁻¹, with no significant decrease ($p > 0.05$). This contrasts sharply with the dynamic changes in AP (20–40% reduction), further confirming the view that available forms, rather than total amounts, better reflect actual supply capacity.

2.2.3 Temporal dynamics of total potassium (TK)

In the low-concentration groups, TK in the CK treatment decreased from 5.00 g·kg⁻¹ to 4.89 g·kg⁻¹ (a reduction of 2.2%, $p < 0.05$), but in the sludge-amended treatments, TK remained at about 5.00 g·kg⁻¹ with no significant change (Fig. 6). This is because the sludge itself has a low TK content (8.5 g·kg⁻¹), so the dilution effect is not obvious. The importance of TK was the lowest in the random forest (0.0427), further indicating that total potassium has a limited direct effect on plant growth.

2.2.4 Temporal dynamics of organic matter (OM)

From week 1 to week 12, OM in the low-concentration groups decreased from 9.8 g·kg⁻¹ to 7.6 g·kg⁻¹, a reduction of 22.4%; in the high-concentration groups, it decreased from 9.7 g·kg⁻¹ to 7.5 g·kg⁻¹, a reduction of 22.7%. Both groups showed nearly parallel linear decreasing trends, with an average weekly decrease of about 0.18–0.20 g·kg⁻¹.

2.2.5 Temporal dynamics of pH

For low-concentration groups: soil pH ranged from 6.0 to 7.5, indicating weakly acidic to neutral. The CK treatment (0% sludge) had the highest pH (about 7.5). As sludge addition increased to 14%, pH gradually decreased to about 6.0. This suggests that moderate sludge addition can neutralise and buffer the alkaline tendency of plateau sandy soil, helping to improve soil acid-base conditions. For high-concentration groups: soil pH ranged from 5.2 to 6.4, generally weakly acidic. The 18% treatment had a pH of about 6.4, and the 30% treatment decreased to about 5.2. With further increase in sludge addition, pH showed a dose-dependent continuous decreasing trend.

2.3 Temporal dynamics of plant height

Figure 9 shows that in the low-concentration groups, CK and 5% treatment had generally low values from weeks 1 to 12, fluctuating in the range of 0–2 cm (relative increase), with similar trends. For the 10% treatment, plant height increased continuously from week 3, reaching a peak around weeks 8–9 (approx. 6–7 cm increase), and then decreased slightly during weeks 10–12. For the 14% treatment, the values remained at the highest level among low-concentration groups throughout the observation period, especially significantly higher than the 10% treatment during weeks 5–9, showing a concentration-promotion effect. Among the high-concentration groups, the 18% and 22% treatments showed a continuous upward trend from weeks 1 to 6, but the peak occurred slightly earlier than for the 10% treatment (around weeks 6–7), and the peak magnitude was also larger. However, when the concentration continued to increase, the dynamic curves for the 26% and 30% treatments showed an obvious downward characteristic: from week 4, the values were significantly lower than the 22% treatment, and further decreased after week 7, approaching or even falling below the CK level by week 12. Overall, the observed plant height increment showed a unimodal dose-response pattern, increasing first and then decreasing with increasing treatment concentration, with a critical concentration around 22%. Beyond this critical value, high-concentration treatments exhibited a sustained inhibitory effect.

2.4 Random forest model performance

Figure 10 shows the feature importance ranking of the eight soil nutrient indicators on Tamarix height from the random forest model, while Table 3 summarizes the ANOVA results. Random forest analysis showed that AP (0.2520), AN (0.2275) and AK (0.1719) were the three main factors promoting Tamarix growth, with a cumulative contribution of 65.14%, while the importance of total nutrients (TN, TP, TK), pH and OM was significantly lower – this available-dominance pattern strongly supports the view that plant growth is controlled by the flux rather than the stock of soil nutrients. ANOVA further indicated that sludge addition rate significantly affected plant height increment ($F = 131.878$, $p < 0.001$). The increase in plant height did not increase monotonically with sludge addition rate, but showed a unimodal response: the 10% treatment achieved the maximum increment (6.34 ± 0.11 cm), followed by decreasing increments for 14%, 18% and 22% treatments, with the 30% treatment reaching the lowest (4.56 ± 0.11 cm). This parabolic dose-response relationship, juxtaposed with the random forest feature importance ranking, shows apparent tension – univariate ANOVA indicated that 10% is the statistical optimum, while the random forest identified the advantage of the 18% treatment in actual growth performance. This discrepancy precisely reveals the crux of the issue: plant height increment is only limitedly directly affected by sludge addition rate (univariate model $R^2 = 0.0224$), and the truly dominant factors are the temporal dynamics of available nutrients and their kinetic matching with plant uptake rate. Therefore, the statistical optimum of the 10% treatment should be understood as an apparent condition within a specific time window, while the sustained advantage of the 18% treatment throughout the growth cycle demonstrates the biological superiority of long-term matching of release and uptake. Overall, the combined interpretation of random forest and ANOVA points to the same core conclusion: the key to resource utilization of plateau sludge is not simply the quantity added, but achieving precise matching between the dynamics of available nitrogen, phosphorus and potassium supply and plant demand dynamics through optimized application rates.

Table 3
Random forest feature importance scores, standard deviations and coefficients of variation

Nutrient	Importance score	Standard deviation	CV (%)
AP (available P)	0.2520	0.3329	132.14
AN (alkali-hydrolyzable N)	0.2275	0.3345	147.05
AK (available K)	0.1719	0.2918	169.76
TN (total N)	0.0993	0.22	221.53
TP (total P)	0.0900	0.20	222.25
pH	0.0661	0.1909	288.97
OM (organic matter)	0.0506	0.1435	283.54
TK (total K)	0.0427	0.1494	349.66

2.5 Temporal dynamics and nutrient consumption rate analysis

(1) Early stage (0–4 weeks): AP and AN consumption rates in the high-concentration groups (M5–M7) were significantly higher than those in the low-concentration groups (CK–M3). For example, M7 (30%) had AP and AN consumption rates of 2.50 and 4.75 $mg \cdot kg^{-1} \cdot week^{-1}$, respectively, while CK was only 0.88 and 2.25 $mg \cdot kg^{-1} \cdot week^{-1}$. Correspondingly, plant height growth rates in the high-concentration groups were also high (0.75–0.88 $cm \cdot week^{-1}$), with both M4 (18%) and M5 (22%) reaching 0.88 $cm \cdot week^{-1}$, significantly higher than the low-concentration groups (0.25–0.63 $cm \cdot week^{-1}$). This indicates that high sludge addition ratios release nutrients rapidly in the early stage, indeed promoting early plant growth.

(2) Middle stage (5–8 weeks): Nutrient consumption rates remained high in the high-concentration groups. AP consumption rates for M5–M7 reached 1.50–1.75 $mg \cdot kg^{-1} \cdot week^{-1}$, and AN consumption rates reached 2.50–3.00 $mg \cdot kg^{-1} \cdot week^{-1}$, both significantly higher than CK (AP 0.50 $mg \cdot kg^{-1} \cdot week^{-1}$, AN 1.50

mg·kg⁻¹·week⁻¹). However, the trend in plant height growth rate showed divergence: M4 and M7 saw an increase in growth rate compared to the early stage (M4 from 0.88 to 1.25 cm·week⁻¹, M7 from 0.75 to 0.88 cm·week⁻¹), while M5 and M6 maintained the previous level (0.88 and 0.75 cm·week⁻¹, respectively). Notably, although nutrient consumption remained vigorous in M5–M7, the growth rate did not increase synchronously except for M7, indicating signs of mismatch between nutrient supply and absorption efficiency in some treatments.

(3) Late stage (9–12 weeks): Nutrient consumption rates generally decreased compared to the middle stage, but AP and AN consumption in the high-concentration groups remained higher than in the low-concentration groups. In terms of height growth rate, M5 and M6 showed significant declines, from 0.88 and 0.75 cm·week⁻¹ in the middle stage to 0.50 and 0.38 cm·week⁻¹, respectively; M7 also declined from 0.88 to 0.68 cm·week⁻¹. In contrast, M4 (18%) maintained the highest growth rate of 0.93 cm·week⁻¹ in the late stage, while its AP and AN consumption rates (0.50 and 1.50 mg·kg⁻¹·week⁻¹) had decreased to levels similar to CK. This suggests that the M4 treatment achieved a good dynamic balance of sustained nutrient supply and efficient plant uptake throughout the growth period, whereas higher sludge addition rates (M5–M7) showed an unbalanced pattern of excessive early nutrient release and later supply deficiency, resulting in weakened growth momentum later.

2.6 Dual regulatory mechanism of plateau sludge addition on plants

Synthesizing the above temporal dynamic characteristics and the feature importance ranking from the random forest model (Section 2.4, Table 2), the dual regulatory mechanism of plateau sludge addition on plants can be clearly identified:

(1) Available nutrient dominance mechanism: The random forest model showed that AP, AN and AK ranked top three in importance, with a cumulative contribution rate of 65.14%, while total nutrients (TN, TP, TK), pH and OM had extremely low importance. This indicates that in plateau infertile sandy soils, plant growth is limited by the instantaneous flux of nutrients, not the total stock of soil nutrients.

(2) Temporal dynamic compensation mechanism: From the stage-specific data in Table 4, it can be seen that high addition treatments (22–30%) showed extremely high nutrient consumption and height growth in the early stage (0–4 weeks), but growth rates declined sharply in the late stage (9–12 weeks). In contrast, the 18% treatment (M4) maintained a high growth rate of 0.93 cm·week⁻¹ even in the late stage. This indicates that the degree of matching between the temporal supply of nutrients and plant demand determines the cumulative growth over the entire growth cycle.

Table 4
Multiple comparisons of plant height increment among different sludge treatments (Tukey HSD test)

Treatment	Plant height increment (cm)	F	p
CK	4.98 ± 0.06 < sup > f</sup>	131.878	< 0.001
5%	5.63 ± 0.11 < sup > d</sup>		
10%	6.34 ± 0.11 < sup > a</sup>		
14%	6.17 ± 0.07 < sup > b</sup>		
18%	5.96 ± 0.11 < sup > c</sup>		
22%	5.65 ± 0.09 < sup > d</sup>		
26%	5.28 ± 0.03 < sup > e</sup>		
30%	4.56 ± 0.11 < sup > g</sup>		

Table 5
Stage-specific nutrient consumption rates and plant height growth rates under different sludge treatments

Treatment	0–4 weeks AP consumption (mg·kg⁻¹·week⁻¹)	0–4 weeks AN consumption (mg·kg⁻¹·week⁻¹)	0–4 weeks height growth (cm·week⁻¹)	5–8 weeks AP consumption	5–8 weeks AN consumption	5–8 weeks height growth	9–12 weeks AP consumption	9–12 weeks AN consumption	9–12 weeks height growth
CK (0%)	0.88	2.25	0.38	0.50	1.50	0.50	0.25	1.00	0.68
M1 (5%)	0.88	2.50	0.25	0.50	1.50	0.30	0.25	0.75	0.20
M2 (10%)	0.75	2.75	0.45	0.50	1.75	0.45	0.25	1.00	0.28
M3 (14%)	1.00	3.25	0.63	0.75	2.00	0.75	0.50	1.25	0.68
M4 (18%)	1.38	3.50	0.88	1.00	2.25	1.25	0.50	1.50	0.93
M5 (22%)	2.00	4.25	0.88	1.50	2.50	0.88	0.75	1.75	0.50
M6 (26%)	2.25	4.50	0.75	1.75	2.75	0.75	0.75	1.50	0.38
M7 (30%)	2.50	4.75	0.75	1.75	3.00	0.88	0.50	1.50	0.68

Together, these two mechanisms constitute the core mechanism of resource utilization of plateau sludge: available nutrients (especially AP and AN) as the driving force, and temporal matching of nutrient release and uptake as the regulatory lever. Ignoring either aspect makes it difficult to accurately explain the impact of sludge addition rate on plant growth.

Discussion

This study, integrating a high-precision random forest model and temporal dynamic analysis, identified the main limiting factors and regulatory mechanisms for plant growth in municipal sludge-amended soils under the special plateau environment. Our findings challenge the traditional approach of evaluating sludge fertilizer efficiency based only on total nutrient content or fixed addition ratios, emphasizing instead the dominant role of available nutrients and their dynamic supply process.

The random forest model identified AP as the primary factor promoting Tamarix growth, which is highly consistent with the widespread phosphorus deficiency in Qinghai–Tibet Plateau soils [7,22]. Low temperatures on the plateau constrain the activation of native soil mineral phosphorus and the microbial mineralization of organic phosphorus [6,35], making the high-activity available phosphorus from external sludge input a key limiting resource for plant growth. AN followed, reflecting the importance of nitrogen as another major limiting element [32]. Although Tamarix has inherent nitrogen-fixing potential [21], timely supply of exogenous available nitrogen is crucial for breaking growth constraints during the rapid growth phase. AK ranked third, and its consumption pattern was much more moderate than that of nitrogen and phosphorus, indicating that it is not a primary limiting factor in plateau sandy soil environments.

Notably, total nutrients and organic matter had very low importance. This does not deny their long-term ecological role, but shows that over the short period of rapid plant growth (12 weeks), the mineralization and release rates of these stable nutrient pools cannot match the immediate plant demand [18]. Therefore, when assessing the short-term ecological benefits of sludge amendment, available nutrients are more accurate and sensitive indicators than total nutrients. This finding provides a theoretical basis for optimizing fertilization schemes in plateau ecological restoration, namely aiming to increase and maintain the flux of soil available nutrients.

The growth inhibition observed in the later stage of high sludge treatments is a typical manifestation of the temporal dynamic compensation mechanism. Excessively high nutrient release rates (especially nitrogen and phosphorus) in the early stage exceed plant uptake capacity, leading to nutrient loss through water leaching or fixation by soil, causing resource waste [10]. In the later stage, when plants enter a vigorous growth period with increased demand, the rapidly mineralized nutrient pool from the early stage is nearly exhausted, causing soil available nutrient concentrations to drop sharply below critical values, thereby imposing stress and limiting growth potential [11]. This mechanism explains why the highest sludge addition rate (e.g., 30%) ultimately resulted in the lowest net plant height increment (4.56 cm), even lower than the control (4.98 cm). Therefore, the optimal sludge addition rate is not a simple statistical optimum, but a dynamic equilibrium point that maximizes the temporal matching between nutrient supply and plant demand. In this study, the 18% addition ratio was such an equilibrium point: it provided sufficient nutrients in the early stage to support rapid growth initiation, while maintaining relatively stable and sustained supply capacity throughout the 12-week period, thereby maximizing cumulative growth over the entire growth cycle. This finding has important practical value, indicating that in plateau ecological restoration projects, sludge application schemes should shift from focusing on total quantity to optimizing temporal patterns, such as split applications or combination with slow-release materials, to precisely match plant growth patterns.

Although this study has made important findings, there are still some limitations. First, the experimental period was 12 weeks, not covering the full life cycle of Tamarix; long-term effects (such as organic matter accumulation, soil structure improvement, heavy metal accumulation risk) still need further evaluation [24,36]. Second, this study was a greenhouse pot experiment; although the environmental conditions were controllable, they differ from complex field conditions. Future field-based experiments are needed to verify the generalizability of the conclusions. Finally, this study did not delve into the regulatory roles of belowground ecological processes such as microbial community structure and enzyme activity on nutrient transformation. These micro-mechanisms are central to understanding the deeper principles of available nutrient dominance and temporal dynamic compensation [29]. Future research could use metagenomics, metabolomics and other methods to comprehensively analyze the response and feedback of the plant–soil–microbe interaction network during plateau sludge resource utilization, providing a more comprehensive scientific basis for efficient and safe restoration of degraded plateau ecosystems.

Conclusions

4.1 Available nutrients dominate the core regulation of plant growth

The random forest regression model showed excellent performance (R^2 = 0.9062, Fig. 10) in predicting Tamarix height at 12 weeks, verifying that the measured soil nutrient indicators have strong explanatory power for plant growth. The model revealed a clear available-dominant pattern: among all eight feature variables, AP (importance score 0.2520), AN (0.2275) and AK (0.1719) ranked top three, with a cumulative contribution rate of 65.14% (Table 2). In stark contrast, total nutrient indicators representing the soil nutrient stock – TN (0.0993), TP (0.0900) and TK (0.0427), along with pH (0.0661) and OM (0.0506) – had relatively low importance. This result quantitatively confirms that, over the short term of plateau sludge amendment, Tamarix growth is not limited by the total nutrient storage in the soil but is driven by the current available nutrient flux.

4.2 Temporal dynamics of nutrient supply and optimal addition rate threshold

ANOVA showed that sludge addition rate significantly affected the net increase in Tamarix height ($F = 131.878$, $p < 0.001$), and the response pattern was parabolic (Fig. 9). Although the explanatory power of the univariate quadratic model was limited (R^2 = 0.0224), combined with temporal dynamic analysis the underlying mechanism was revealed. During the rapid growth phase of 0–4 weeks, high-concentration treatments (e.g., M7, 30%) had AP and AN consumption rates of 2.50 and 4.75 $mg \cdot kg^{-1} \cdot week^{-1}$, respectively, which were 2.8 and 1.9 times those of low-concentration treatments (e.g., M1, 5%), corresponding to faster early height increases (Table 2). However, this pattern of early surge was unsustainable. In the late growth phase of 9–12 weeks, the plant height growth rates of high-concentration treatments (M5–M7) significantly declined (e.g., M5 from 0.88 to 0.50 $cm \cdot week^{-1}$), while the 18% treatment (M4) maintained the highest and most stable growth rate (0.93 $cm \cdot week^{-1}$). This indicates that although the net height increment of the 18% treatment was

not statistically the highest (6.34 cm, lower than the 10% treatment), it exhibited the best sustained nutrient supply capacity throughout the growth cycle, effectively avoiding the nutrient depletion stress faced by high-rate treatments in the later stage. Therefore, the essence of the optimal sludge addition rate is to achieve temporal matching between nutrient release kinetics and plant uptake kinetics.

4.3 Dynamics of total nutrients and pH

In contrast to the large fluctuations in available nutrients, TN, TP and TK changed very little over the 12-week experimental period (Figs. 4–6), showing no statistical differences ($p > 0.05$), which corroborates the stability of the total nutrient pool in the short term and its limitation in indicating immediate fertility changes. Soil pH showed a dose-dependent decreasing trend; as the sludge addition rate increased from 0% to 30%, pH decreased from about 7.5 to about 5.2 (Fig. 8), due to the decomposition of organic matter in sludge and nitrification.

Declarations

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Competing Interests

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

Author Contributions

Du Xiaohong: Methodology, Investigation, Writing – original draft, Data curation. Mao Jiuwen: Formal analysis, Validation, Visualization. Yu Wu: Conceptualization, Supervision, Writing – review & editing, Project administration. All authors read and approved the final manuscript.

Availability

All analytical data supporting the findings of this study are fully included within the manuscript and its supplementary information files. The raw datasets generated during the current study (e.g., original growth measurements, soil nutrient values) are available from the corresponding author upon reasonable request.

Soil collected

Experimental soil was collected in May 2025 from the 0–20 cm surface sandy soil layer at the experimental base of Xizang Agricultural and Animal Husbandry University (29°39'56"N, 94°20'35"E) in Nyingchi. The soil sampling was officially permitted by the management office of the university experimental base, and all sampling activities complied with institutional regulations as well as local ecological and environmental protection management requirements.

About the test plant

The test material used in this study was one-year-old clonal seedlings of *Tamarix chinensis Lour.*, which were purchased from a formal licensed nursery in Nyingchi, Xizang, rather than collected from wild populations.The plant material was formally identified by a professional botanist from the College of Forestry, Xizang Agricultural and Animal Husbandry University. The voucher specimen of *Tamarix* chinensis has been deposited in the Herbarium of Xizang Agricultural and Animal Husbandry University.No wild plant individuals were collected in this study. The introduction and utilization of seedlings complied with institutional rules, national wild plant protection laws and relevant international research guidelines, and fully conformed to the IUCN policy and related regulatory requirements.

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Tables

Table 2 is not available with this version.

Figures

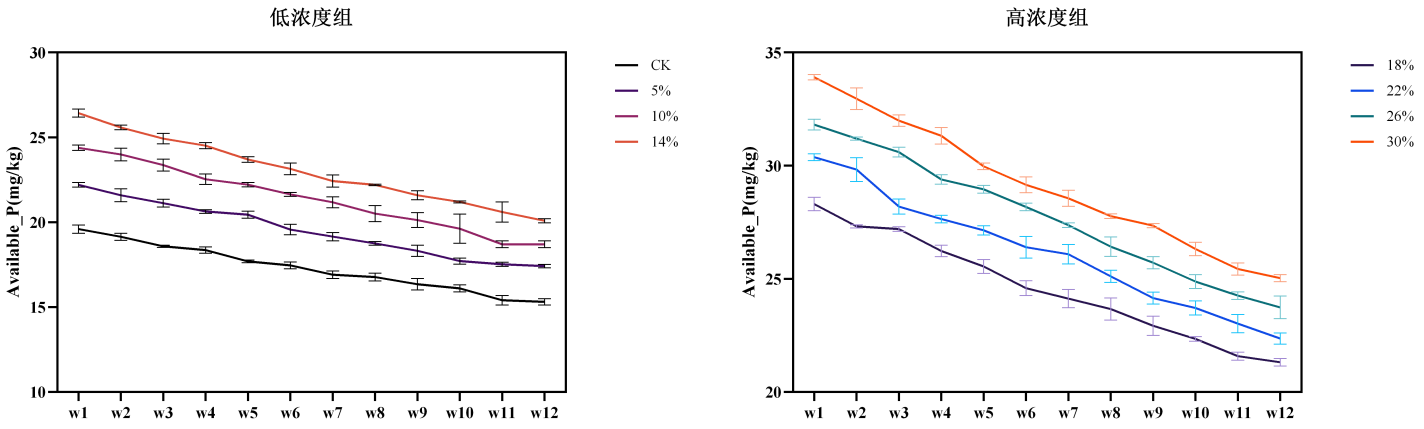


Figure 1

Temporal dynamics of available phosphorus (AP)

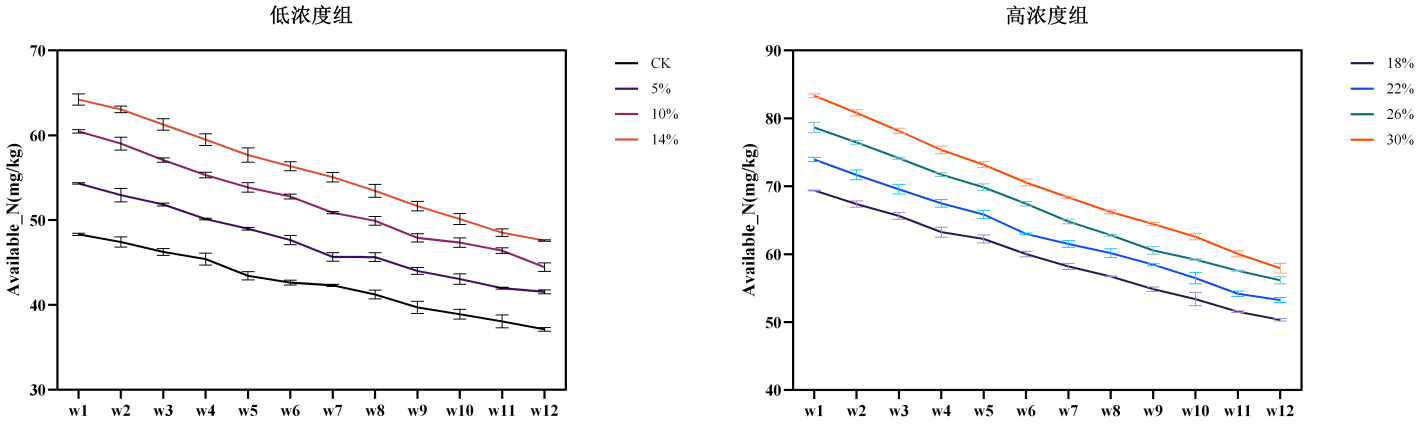


Figure 2

Temporal dynamics of alkali-hydrolyzable nitrogen (AN)

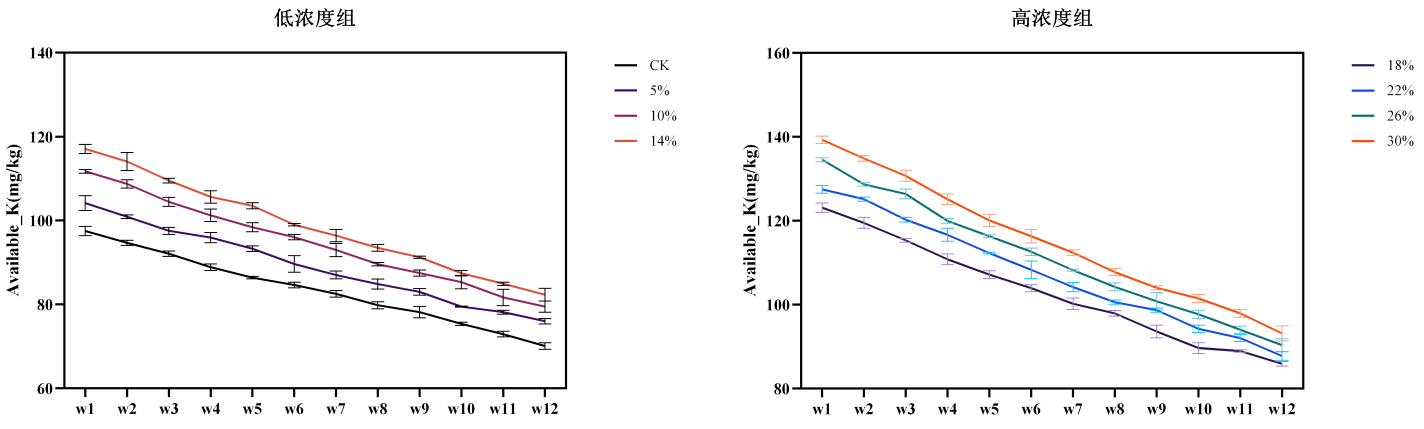


Figure 3

Temporal dynamics of available potassium (AK)

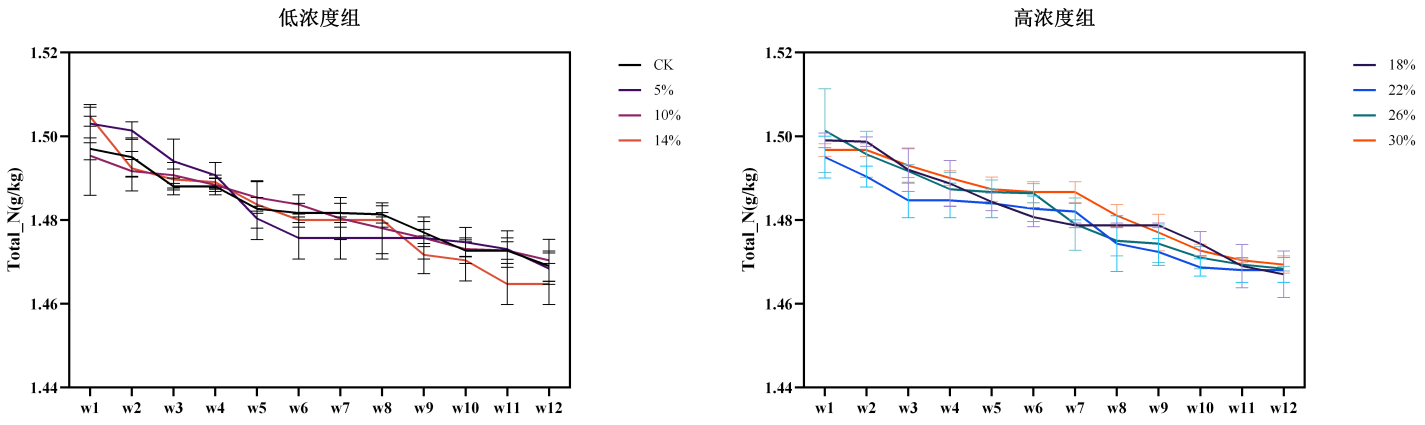


Figure 4

Temporal dynamics of total nitrogen (TN)

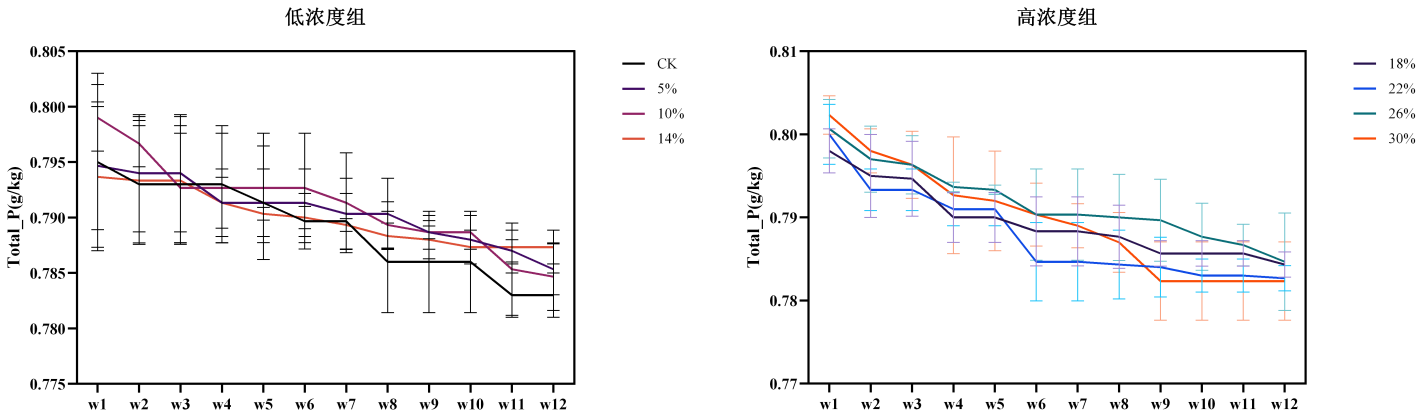


Figure 5

Temporal dynamics of total phosphorus (TP)

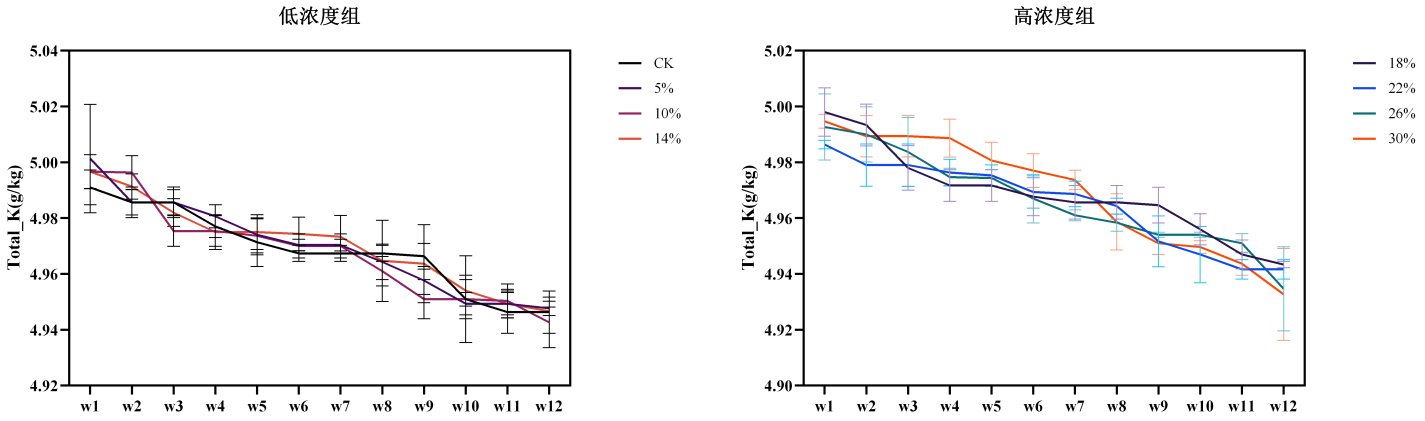


Figure 6

Temporal dynamics of total potassium (TK)

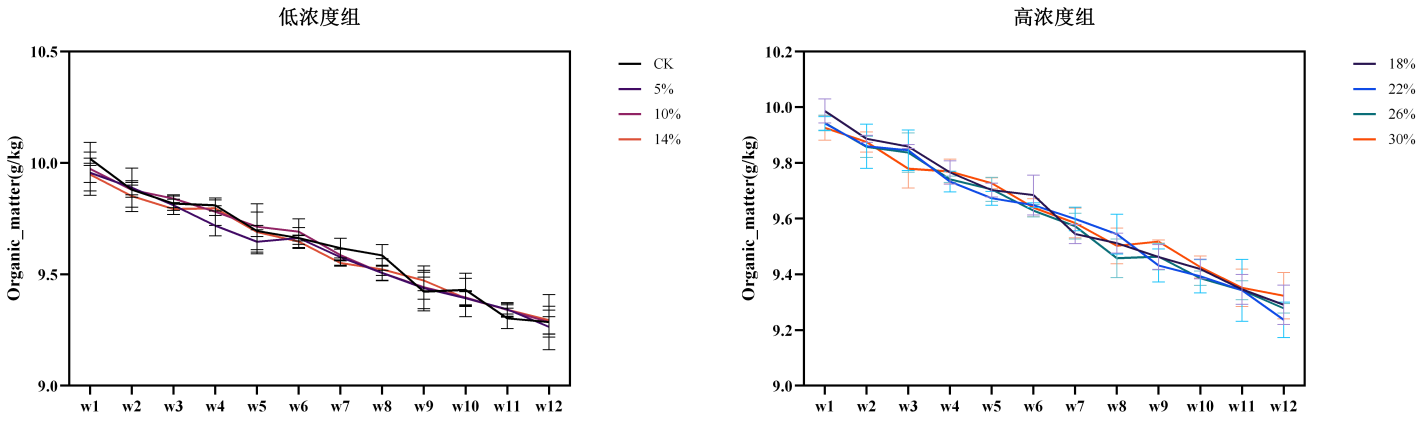


Figure 7

Temporal dynamics of organic matter (OM)

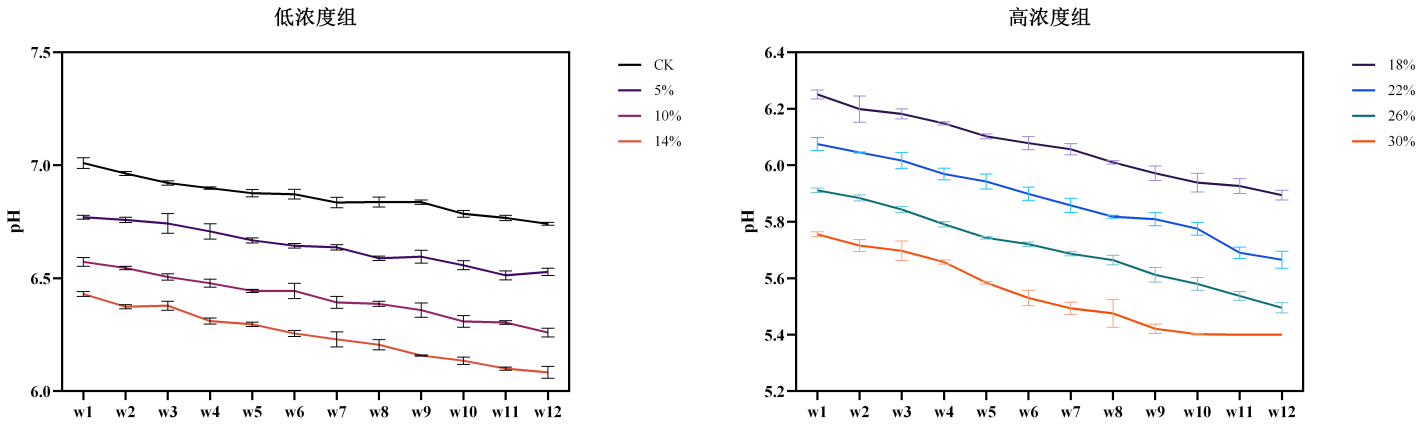


Figure 8

Temporal dynamics of soil pH

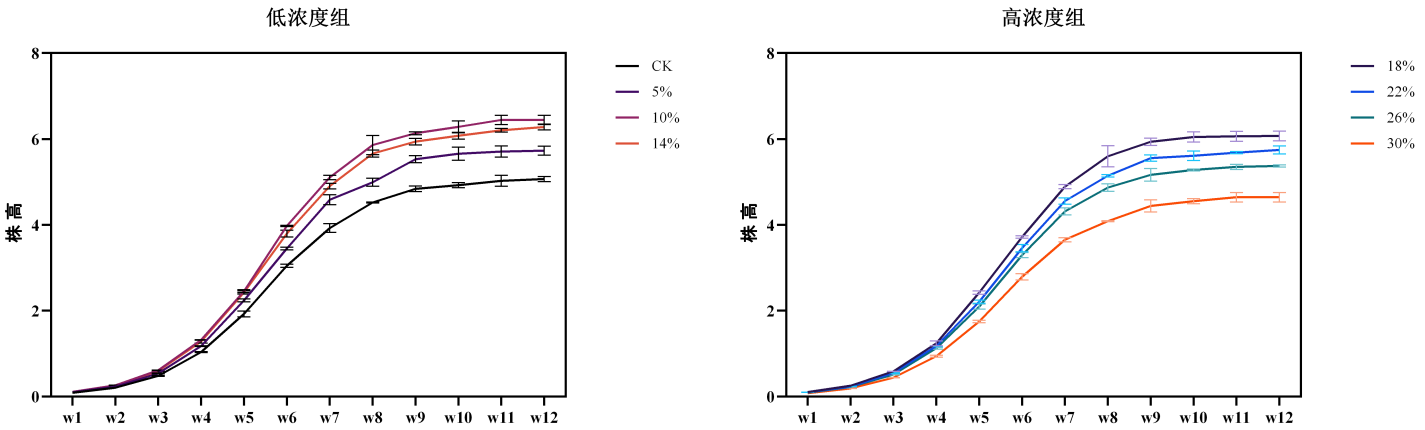


Figure 9

Plant height over time under different sludge concentrations

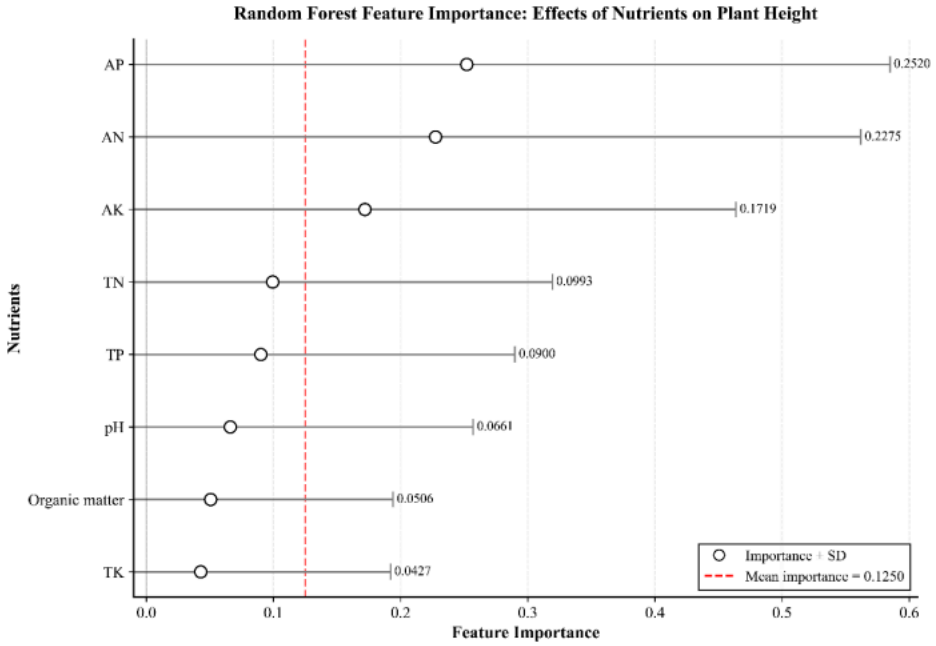


Figure 10

Performance evaluation of the random forest regression model