Effects of Fertilization on Growth and Leaf Physiological Characteristics of Young Toona ciliata var. pubescens Plantations: Postprint

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Abstract

This study aimed to investigate the response of the valuable tree species *Toona ciliata* var. *pubescens* to different fertilizer types and application rates. Young *T. ciliata* var. *pubescens* plantations were used as the research object, with four fertilizer types—nitrogen fertilizer (N), phosphorus fertilizer (P), compound fertilizer (CF), and slow-release fertilizer (SRF)—applied at three levels (high, medium, low) to examine the effects of fertilization on growth, leaf nutrient content, and leaf physiology. The results showed that: (1) Fertilization promoted tree height and DBH growth in *T. ciliata* var. *pubescens*, with nitrogen and compound fertilizers showing more pronounced effects. Compared with the control (CK), nitrogen fertilizer treatment increased the average tree height, average DBH, and average volume of 4-year-old *T. ciliata* var. *pubescens* by 15.0%, 21.9%, and 67.5%, respectively, with low nitrogen (N1) treatment producing the maximum annual DBH increment (2.99 cm). Compound fertilizer treatment increased average tree height, average DBH, and average volume by 16.7%, 19.2%, and 54.3% compared with CK, respectively. High slow-release fertilizer (SRF3) and low phosphorus (P1) achieved maximum annual increments in tree height and DBH (1.96 m and 2.33 cm, respectively) in the fourth year. (2) Fertilization significantly increased leaf chlorophyll content and non-structural carbohydrate content in *T. ciliata* var. *pubescens*; nitrogen fertilizer significantly promoted soluble sugar synthesis, whereas phosphorus fertilizer significantly promoted starch synthesis. (3) Low nitrogen (N1) and phosphorus fertilizer significantly promoted increases in leaf nitrogen and phosphorus contents, respectively; phosphorus fertilizer, compound fertilizer, and nitrogen fertilizer all significantly increased leaf potassium content. (4) Principal component analysis results indicated that the growth-promoting effects of fertilizers ranked as nitrogen fertilizer > compound fertilizer > phosphorus fertilizer > slow-release fertilizer > control, with low nitrogen (N1), i.e., 100 g $\cdot$ plant^{-1} $\cdot$ year^{-1}, yielding

the highest comprehensive evaluation value. Considering both fertilization costs and benefits, applying nitrogen or compound fertilizer can effectively promote the growth and development of young *T. ciliata* var. *pubescens* plantations, with an annual application of 100 g nitrogen fertilizer per plant recommended during the young plantation stage. These research findings can provide references for nutrient management of *T. ciliata* var. *pubescens* during the initial afforestation period.

Full Text

Preamble

Effects of Fertilization on Growth and Leaf Physiological Characteristics of Young *Toona ciliata* var. *pubescens* Forests

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Abstract

To investigate the response of the precious tree species *Toona ciliata* var. *pubescens* to different fertilizer types and application rates, we examined the effects of fertilization on the growth, leaf nutrients, and physiology of young *T. ciliata* var. *pubescens* plantations. Four fertilizer types—nitrogen fertilizer (N), phosphorus fertilizer (P), compound fertilizer (CF), and slow-release fertilizer (SRF)—were applied at three levels (high, medium, and low). The results showed that: (1) All fertilization treatments promoted tree height and diameter at breast height (DBH) growth, with nitrogen and compound fertilizers showing the most pronounced effects. Compared with the control (CK), four-year-old trees under nitrogen fertilization exhibited average increases of 15.0% in height, 21.9% in DBH, and 67.5% in volume. The low nitrogen treatment (N1) produced the maximum annual DBH increment (2.99 cm). Compound fertilizer increased average tree height, DBH, and volume by 16.7%, 19.2%, and 54.3% compared to CK, respectively. High slow-release fertilizer (SRF3) and low phosphorus (P1) achieved the maximum annual growth increments in height and DBH (1.96 m and 2.33 cm, respectively) during the fourth year. (2) Fertilization significantly increased leaf chlorophyll and non-structural carbohydrate contents. Nitrogen fertilizer significantly promoted soluble sugar synthesis, while phosphorus fertilizer significantly enhanced starch synthesis. (3) Low nitrogen (N1) and phosphorus fertilizer significantly increased leaf nitrogen and phosphorus contents, respectively. Phosphorus, compound, and nitrogen fertilizers all significantly elevated leaf potassium content. (4)

Principal component analysis revealed that the growth-promoting effects of fertilizers ranked as follows: nitrogen fertilizer > compound fertilizer > phosphorus fertilizer > slow-release fertilizer > control. The low nitrogen treatment (N1), at 100 g $\cdot$ plant^{-1} $\cdot$ year^{-1}, yielded the highest comprehensive evaluation value. Considering both cost and benefit, applying nitrogen or compound fertilizer effectively promoted the growth and development of young *T. ciliata* var. *pubescens* forests, with an annual application of 100 g nitrogen per plant recommended. These findings provide a reference for nutrient management in young *T. ciliata* var. *pubescens* plantations.

Keywords: *Toona ciliata* var. *pubescens*, young forest, fertilization, growth, physiology

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Toona ciliata var. *pubescens* is a deciduous tree belonging to the Meliaceae family and *Toona* genus. Currently classified as *T. ciliata*, it is a nationally protected second-class species in China. Valued for its attractive red wood color, beautiful grain, and fast growth, it represents an excellent species for cultivating high-quality timber and large-diameter logs (Zhang et al., 2006). The species is now primarily distributed in remote mountainous areas of Jiangxi, Sichuan, Yunnan, Anhui, Hunan, and Guangxi provinces, where it faces endangered status. Establishing artificial plantations of this precious species and implementing silvicultural measures such as fertilization to shorten rotation periods (Achat et al., 2018; Sullivan et al., 2018) and increase resource reserves is therefore of significant importance. While numerous studies have investigated fertilization during the seedling stage—demonstrating that nitrogen fertilizer or combined N-P-K and magnesium fertilizers, as well as calcium and magnesium applications, can promote seedling growth (Huang et al., 2012; Dao et al., 2018; Wen, 2019), and that low nitrogen with high phosphorus optimizes biomass accumulation while high nitrogen with high phosphorus maximizes leaf nutrient content (Liu et al., 2021)—research on nutrient requirements, physiological mechanisms, and fertilization effects in young *T. ciliata* var. *pubescens* forests remains limited.

Forest fertilization represents a crucial technical measure for stand nutrient management and an important approach for cultivating large-diameter precious timber species to enhance economic benefits. Rational fertilization is essential for reducing forestry inputs and protecting ecological environments. Current forest fertilization research predominantly focuses on N-P-K ratio studies for specific tree species (Wei et al., 2020; Tang et al., 2022), yielding results with limited generalizability. Consequently, commercial forest fertilization primarily relies on low-cost, fast-acting chemical fertilizers such as urea, compound fertilizer, and calcium magnesium phosphate. Studies have shown that nitrogen fertilizer most effectively promotes growth in young *Moringa oleifera* plantations, while phosphorus fertilizer has the least impact (Zhang et al., 2019), and compound fertilizer enhances height and DBH growth in young *Eucalyptus grandis* forests (He et al., 2019). Conversely, increasing nitrogen application rates has been found to decrease growth indicators in young *Zelkova schneideriana* and *Phoebe* *bournei* plantations (Lu et al., 2022). Slow-release fertilizer, a novel fertilizer type characterized by reduced volatilization, minimal leaching, and extended nutrient release, has been widely applied in container seedling cultivation. Applications of slow-release fertilizer have promoted growth and root development in *Carya illinoensis* container seedlings (Pan et al., 2019), with low rates benefiting root growth in *Pistacia chinensis* container seedlings (Song et al., 2018) and 2.5 $kg \cdot m^{-3}$ proving optimal for *Aquilaria sinensis* container seedlings (Pang et al., 2018). These studies collectively demonstrate that different fertilizer types and application rates significantly influence forest tree growth.

As essential macronutrients for plant growth and development, nitrogen, phosphorus, and potassium play vital roles in synthesizing non-structural carbohydrates (such as soluble sugars and starch), photosynthetic pigments (especially chlorophyll), and enzyme activities, thereby influencing plant metabolism and stress resistance (Jiang et al., 2015). Research on young *Castanopsis hystrix* forests revealed significant differences in chlorophyll content, soluble sugars, and leaf N-P-K nutrients under various N-P-K ratios, with excessive fertilization reducing soluble sugar content and phosphorus application inhibiting leaf potassium content (Wei et al., 2020). Phosphorus fertilizer showed no significant effect on chlorophyll content in *Brucea javanica*, while chlorophyll content increased with nitrogen application rate (Li, 2010). Slow-release fertilizer significantly increased chlorophyll and carotenoid contents, phosphorus and potassium nutrient levels, and enhanced maximum fluorescence (Fm) and variable fluorescence (Fv) in *Cunninghamia lanceolata* leaves (Li et al., 2022). Zhang (2020) found that short-term nitrogen addition promoted non-structural carbohydrate accumulation in *Reaumuria songarica* leaves, while long-term excessive nitrogen addition inhibited soluble sugar and starch accumulation. These findings illustrate that varying application rates of nitrogen, phosphorus, compound, and slow-release fertilizers differentially affect forest tree physiology and nutrient uptake.

This study investigated the effects of four fertilizer types—nitrogen, phosphorus, compound, and slow-release fertilizers—at different application rates on the growth and physiological characteristics of young *T. ciliata* var. *pubescens* forests. Our objectives were to explore the response patterns of growth and physiological traits to fertilizer type and dosage, identify optimal fertilizer types and application rates for young *T. ciliata* var. *pubescens* forests, and provide technical guidance for nutrient management and scientific cultivation.

1.1 Study Site Description

The experimental site was located at the Shanzhuang Branch of Mingyueshan Forestry Centre in Anfu County, Ji'an City, Jiangxi Province (114°43 E, 27°33 N). The region features a subtropical monsoon humid climate with mild temperatures, abundant rainfall, and ample sunshine. The average annual temperature is 17.7 °C, with monthly averages of 28.9 °C in July and 5.9 °C in January. Annual precipitation averages 1,553 mm across 166 rainy days, with 1,649 hours of annual sunshine and a frost-free period of 279 days. The soil is classified as red soil with the following properties: total nitrogen 1.20 $g \cdot kg^{-1}$, total phosphorus 0.25 $g \cdot kg^{-1}$, total potassium 15.80 $g \cdot kg^{-1}$, hydrolyzable nitrogen 55.17 $mg \cdot kg^{-1}$, available phosphorus 0.59 $mg \cdot kg^{-1}$, rapidly available potassium 67.40 $mg \cdot kg^{-1}$, pH 5.08, and organic matter 14.93 $g \cdot kg^{-1}$. The site was previously a *Cunninghamia lanceolata* clear-cut area with an 18° slope facing southeast. Full-site preparation was implemented, and planting occurred in 2018.

1.2 Experimental Design

A randomized block design was employed with four fertilizer types: nitrogen fertilizer (N), phosphorus fertilizer (P), compound fertilizer (CF), and slow-release fertilizer (SRF). Three application levels were established for each fertilizer type, with a no-fertilizer control (CK), totaling 13 treatments (Table 1). Fertilizer rates were determined based on proportions used for three-year-old container seedlings of *Phoebe chekiangensis* and *Taxus chinensis* var. *mairei* (slow-release to compound fertilizer ratio of 1:3), and considering the low available phosphorus content of the site soil (Qiu et al., 2016; Wang et al., 2016). Each treatment comprised eight trees planted in a single row along the slope, with 3 m spacing between treatments arranged randomly. Three replicates were positioned in the upper, middle, and lower slope positions, with 9 m intervals between replicates. Fertilizer was applied annually in June of 2019, 2020, and 2021 by digging semicircular trenches 20–30 cm deep on the upslope side of each plant, with backfilling after application. Understory shrubs and weeds were manually removed before fertilization.

1.3 Measurement Indicators

From 2018 to 2021, annual measurements of DBH and tree height (H) were conducted each December, with an additional measurement in August 2021. Individual tree volume (V) was calculated using formula (1) (Huang et al., 2020). Based on the August 2021 survey data, three representative trees per treatment were selected, and healthy functional leaves from the upper canopy were collected. One portion was sealed in plastic bags with dry ice, transported to the laboratory, and stored at -80 °C for chlorophyll, carotenoid, soluble sugar, and soluble starch analyses. Another portion was oven-dried for leaf nitrogen, phosphorus, and potassium content determination.

Soluble sugars and starch were measured using the anthrone colorimetric method, soluble protein via the Coomassie brilliant blue G-250 method, and chlorophyll via ethanol extraction. Oven-dried leaf samples were digested using the H_2SO_4-H_2O_2 method. Nitrogen content was determined by the Kjeldahl method, phosphorus by UV spectrophotometry, and potassium by flame photometry (Yu et al., 2018).

$$V = 0.00005276 \times D^{1.882161} \times H^{1.009317}$$

where V is individual tree volume (m^3), D is DBH (cm), and H is tree height (m).

1.4 Data Processing

Data were organized using Excel 2019. SPSS 25.0 software was used for variance analysis and Duncan's multiple comparison tests ($P < 0.05$). Figures were generated using Origin 2021. Principal component analysis was performed through dimensionality reduction.

Results

2.1 Effects of Fertilization on Growth

Variance analysis of DBH, height, and volume in four-year-old *T. ciliata* var. *pubescens* plantations revealed significant differences among fertilization treatments ($P < 0.05$) [Figure 1: see original paper]. All fertilization treatments promoted DBH and height growth, though responses varied among treatments. Nitrogen (N1, N2, N3) and compound fertilizer (CF1, CF2, CF3) treatments increased four-year average height (6.34 m and 6.44 m, respectively), DBH (8.81 cm and 8.61 cm), and individual volume (0.022 m^3 and 0.021 m^3) by 15.0%/16.7%, 21.9%/19.2%, and 67.5%/54.3% compared to CK, respectively. Low phosphorus (P1) and high slow-release fertilizer (SRF3) enhanced height growth, showing increases of 10.6% and 13.8% over CK, respectively.

As shown in Table 2, DBH growth rate generally followed a "fast-slow" pattern, while height growth rate exhibited a "fast-slow-fast" trend with increasing stand age. Variance analysis indicated significant differences in annual DBH and height growth increments among fertilization treatments at different stand ages ($P < 0.05$). Except for SRF1, all fertilization treatments produced higher annual DBH and height increments than CK (2.45 cm and 1.45 m, respectively). Nitrogen and compound fertilizers showed prominent growth-promoting effects during the first two years, whereas phosphorus and slow-release fertilizer effects became apparent in the fourth year, with efficacy increasing with slow-release fertilizer rate. Low phosphorus (P1) achieved the maximum fourth-year DBH increment (2.33 cm), while high slow-release fertilizer (SRF3) produced the maximum fourth-year height increment (1.96 m). These results demonstrate that fertilization during the initial afforestation stage effectively enhances stand productivity.

2.2 Leaf Physiological Characteristics and Nutrient Content Response

Variance analysis of leaf physiological indicators from August 2021 revealed significant differences in photosynthetic pigments and non-structural carbohydrates among treatments ($P < 0.05$) [Figure 2: see original paper]. Fertilization increased chlorophyll a, chlorophyll b, carotenoid, soluble sugar, and soluble starch contents while decreasing the chlorophyll a/b ratio. Nitrogen fertilization was most effective for chlorophyll synthesis and soluble sugar enhancement, with low nitrogen (N1) increasing chlorophyll a and b contents by 29.5% and 68.5% compared to CK, respectively. Both low (N1) and high (N3) nitrogen treatments increased soluble sugar content by 41.5% and 47.9% over CK, respectively. Phosphorus fertilization most significantly enhanced soluble starch content, with medium phosphorus (P2) achieving the highest starch content (84.6% increase over CK). Low compound fertilizer (CF1) increased carotenoid content by 20.9% compared to CK.

Analysis of leaf nutrient contents across fertilization treatments showed increased leaf nitrogen, phosphorus, and potassium contents. Low nitrogen (N1) produced the highest leaf nitrogen content (19.3% higher than CK), while phosphorus fertilizer (P1, P2, P3) increased leaf phosphorus content by 16.3%, 13.1%, and 17.5% compared to CK, respectively. Leaf nitrogen and phosphorus contents under slow-release fertilizer treatments increased with application rate. Overall, leaf nitrogen content ranged from 27.19–31.24 $mg \cdot g^{-1}$, phosphorus from 0.191–0.225 $mg \cdot g^{-1}$, and potassium from 5.83–8.19 $mg \cdot g^{-1}$ across treatments, with all three indicators showing significant differences among fertilization treatments ($P < 0.05$) . These results indicate that leaf N-P-K contents in *T. ciliata* var. *pubescens* are highly sensitive to fertilization.

2.3 Correlation Analysis and Principal Component Analysis

Correlation analysis revealed significant relationships among all 13 indicators [Figure 3: see original paper]. DBH showed highly significant positive correlations with tree height and soluble sugar content ($P < 0.01$) and significant positive correlations with chlorophyll a, chlorophyll b, total chlorophyll, non-structural carbohydrates, leaf nitrogen, and leaf potassium contents ($P < 0.05$). Tree height exhibited significant positive correlations with photosynthetic pigments, soluble sugar, and leaf potassium content ($P < 0.05$). Volume showed a correlation coefficient of 0.75 with soluble sugar content ($P < 0.01$) and significant positive correlations with photosynthetic pigments ($P < 0.05$). Chlorophyll a demonstrated a correlation coefficient of 0.57 with soluble sugar content ($P < 0.05$). Leaf nitrogen content was highly significantly correlated with chlorophyll content ($P < 0.01$), while leaf potassium content was highly significantly correlated with carotenoid content ($P < 0.01$). These relationships indicate that growth, physiological, and nutrient indicators interact extensively, predominantly through positive correlations.

Principal component analysis showed that the first three components accounted for 56.43%, 16.62%, and 12.12% of the variance, respectively, with a cumulative contribution of 85.16% . The first principal component exhibited correlation coefficients above 0.6 with all indicators except soluble starch and leaf phosphorus content, indicating positive correlations with these variables, with individual tree volume showing the highest correlation coefficient. The second principal component was positively correlated with soluble starch, leaf phosphorus, and carotenoid contents. The third principal component was positively correlated with chlorophyll content and leaf nitrogen content. Based on eigenvalues, standardized weighting of the three principal components yielded comprehensive evaluation values for each treatment . The top three treatments were low nitrogen (N1), high compound fertilizer (CF3), and medium nitrogen (N2), while CK ranked lowest. These results confirm that nitrogen or compound fertilizers effectively promote *T. ciliata* var. *pubescens* growth, with low nitrogen (N1) showing the optimal effect.

Discussion and Conclusion

Growth indicators such as DBH and height during the initial afforestation stage are critical measures of plantation establishment success (Zhou et al., 2022), with rational fertilization being key to maintaining fast growth and high yield in plantations. This study found that *T. ciliata* var. *pubescens* growth responded differently to various fertilization treatments during the rapid growth phase of early plantation establishment, with fertilizer type and application rate significantly affecting tree growth. Nitrogen and compound fertilizers demonstrated the most obvious effects, particularly the application of 100 g nitrogen per plant annually (N1), which most significantly increased stand growth. This aligns with findings that compound fertilizer applications (150 g and 225 g per plant) significantly increased DBH and volume growth in four-year-old *Cinnamomum camphora* timber plantations compared to unfertilized controls (Liu et al., 2020), and that nitrogen fertilization promotes *T. ciliata* var. *pubescens* seedling growth (Dao et al., 2018).

Fertilization effects on forest tree growth depend on multiple factors, including fertilizer type, application rate, timing, and stand age. The experimental site had extremely low available phosphorus content ($0.59\ mg \cdot kg^{-1}$). Research indicates that available phosphorus shows the greatest variation among fertilization treatments and that the element with lowest soil availability constrains plant yield (Tai et al., 2023), which may explain the suboptimal growth-promoting effect of phosphorus fertilizer in this study. Although leaf phosphorus content differed significantly among fertilization treatments and exceeded CK values, the range ($0.191–0.225\ mg \cdot g^{-1}$) was substantially lower than the average leaf phosphorus concentration of Chinese vegetation ($1.1\ mg \cdot g^{-1}$) (Tang et al., 2018). Conversely, leaf nitrogen content across treatments ($27.19–31.24\ mg \cdot g^{-1}$) far exceeded the average leaf nitrogen concentration of Chinese vegetation ($14.1\ mg \cdot g^{-1}$). These findings indicate that nitrogen and phosphorus are primary factors influencing *T. ciliata* var. *pubescens* growth, with nitrogen fertilization improving leaf nutrient status and thereby promoting tree growth. The overall limited effect of slow-release fertilizer may be attributed to application timing in June, prior to the growth peak (July–September), as slow-release fertilizers require approximately eight months for complete nutrient release. This delayed release may have reduced fertilizer efficiency and affected tree growth. Additionally, slow-release fertilizer costs approximately 30 $yuan \cdot kg^{-1}$, substantially higher than the other three fertilizers (3–4 $yuan \cdot kg^{-1}$), and the three application levels established based on previous research were relatively low, resulting in limited promotion effects. However, as stand age increased, high slow-release fertilizer (SRF3) produced the most pronounced height growth promotion in the fourth year (1.96 m), indicating that application rate significantly influences tree growth. Liu et al. (2021) suggested that for *T. ciliata* var. *pubescens* seedlings under adequate water conditions, early fertilization should emphasize low nitrogen and high phosphorus, a result inconsistent with our findings. This discrepancy reflects that water is a crucial factor affecting nutrient absorption and that nutrient requirements may differ between seedling and young forest stages.

Photosynthetic pigments absorb, transfer, and convert light energy, with their content and composition directly affecting leaf photosynthetic rates and products, thereby influencing plant growth. Previous studies found that fertilization significantly increased photosynthetic pigment contents and decreased chlorophyll a/b ratios in *Pinus massoniana* and *Gardenia sootepensis* seedlings (Luo et al., 2022; Yin et al., 2022). Our results showed that fertilization increased leaf chlorophyll and carotenoid contents while decreasing the chlorophyll a/b ratio compared to CK, with nitrogen fertilization producing the highest photosynthetic pigment content, consistent with Huang et al. (2012) regarding *T. ciliata* var. *pubescens*. This indicates that fertilization effectively promotes light energy conversion, capture, and transfer capacity, enhances photosynthetic pigment synthesis, and increases biomass accumulation and tree growth, with nitrogen playing a crucial role in plant photosynthetic pigment synthesis. Nitrogen is essential for binding magnesium ions to chlorophyll porphyrin rings, and nitrogen fertilization benefits chlorophyll synthesis while increasing leaf area and photosynthetic efficiency to synthesize more organic compounds. However, excessive nitrogen can inhibit root absorption and transport, potentially affecting chlorophyll synthesis, which may explain why low nitrogen (N1) produced the greatest chlorophyll content increase in this study.

Research has shown that fertilization promotes soluble sugar synthesis in *Tsoongiodendron odorum* leaves while increasing chlorophyll content (Tang et al., 2022). Our results align with these findings, as fertilization increased soluble sugar and starch contents in *T. ciliata* var. *pubescens* leaves, with nitrogen fertilizer (N1) producing the highest soluble sugar content and phosphorus fertilizer (P2) most significantly increasing soluble starch content. Soluble sugars are integral to plant life processes, and phosphorus is associated with photosynthesis and carbohydrate synthesis. These effects likely result from improved soil nutrient utilization, increased mineral element content in leaves, enhanced chlorophyll synthesis, strengthened photosynthesis, and promoted nutrient accumulation and physiological metabolic activity.

Strong correlations exist among *T. ciliata* var. *pubescens* growth, leaf physiological characteristics, and nutrient content. DBH, height, and volume were all significantly positively correlated with photosynthetic pigments and leaf nitrogen and potassium contents, indicating that young forest growth and photosynthetic capacity are mutually reinforcing. Larger individuals can capture and absorb more light resources to form photosynthetic pigments, while higher leaf nutrient content promotes photosynthetic pigment synthesis and photosynthesis, thereby enhancing tree growth. Additionally, the significant correlation between chlorophyll a and soluble sugar (correlation coefficient 0.57, $P < 0.05$) and between leaf potassium content and soluble sugar suggests that photosynthetic pigments and leaf potassium influence soluble sugar synthesis, likely because individuals with stronger photosynthesis exhibit more vigorous growth metabolism, thereby promoting soluble sugar synthesis.

Principal component analysis reorganizes correlated indicators into a new set of independent comprehensive indicators that retain original variable information while remaining mutually uncorrelated (Wei et al., 2020), with higher comprehensive evaluation values indicating better growth quality. The top three treatments (N1, CF3, and N2) demonstrate that low to medium nitrogen and high compound fertilizer significantly promote young forest growth, with application rate affecting fertilization efficacy. The decreasing growth-promoting effect with increasing nitrogen rate may result from excessive nitrogen inhibiting photosynthetic pigment formation and non-structural carbohydrate synthesis (Wen et al., 2021), causing comprehensive evaluation values to decline with increasing application rates.

This study investigated the effects of different fertilizer types and application rates on growth, physiology, and leaf nutrient content in young *T. ciliata* var. *pubescens* forests. The results demonstrate that fertilization promotes growth, photosynthetic pigment and non-structural carbohydrate synthesis, and improves leaf nutrient status. Different treatments produced varying effects on annual DBH and height growth increments, with early growth showing nitrogen demand and high slow-release fertilizer demonstrating prominent height-promoting effects in the fourth year. Based on fertilization labor costs of 1,350 yuan $\cdot$ hm^{-2}, urea at 4 yuan $\cdot$ kg^{-1}, and timber at 1,000 yuan $\cdot$ m^{-3}, the input-output ratio for four-year-old stands reached 79%. Considering both costs and benefits, nitrogen and compound fertilizers showed obvious promotion effects, with low nitrogen (N1) at 100 g per plant annually producing the best results. Future research should conduct extended monitoring of fertilization effects on young and post-closure stands to understand fertilizer efficacy impacts and response mechanisms across different growth stages.

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