

Article

Effects of NPK Fertilization on Growth, Fruit Yield, and Gross Output Value of *Sapindus mukorossi* ‘Yuanhua’

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Abstract

Balanced fertilization is essential for improving the growth and productivity of *Sapindus mukorossi* plantations. In this study, a three-year “3414” fertilization experiment was conducted in a six-year-old plantation of the new *S. mukorossi* cultivar ‘Yuanhua’ to evaluate the effects of nitrogen, phosphorus, and potassium fertilization on vegetative growth, fruit yield, yield stability, and gross output value. Fertilizer levels were set at 0, 300, 600, and 900 kg N ha⁻¹, 0, 250, 500, and 750 kg P₂O₅ ha⁻¹, and 0, 200, 400, and 600 kg K₂O ha⁻¹. NPK fertilization promoted tree height, ground diameter, crown width, and fruit yield compared with the unfertilized control. Among the 14 fertilization treatments, N₁P₁K₂ produced the greatest mean annual increment in tree height, N₁P₂K₁ produced the greatest ground-diameter increment, and N₂P₂K₁ produced the greatest crown-width increment. Fruit yield was highest under N₂P₂K₂ in 2021 and 2022 and under N₂P₂K₁ in 2023. The highest three-year mean yield was obtained under N₂P₂K₂, reaching 1278.93 kg ha⁻¹, and the highest yield stability index was observed under N₂P₂K₂ and N₂P₁K₂. Gross output value showed a pattern consistent with fruit yield, with N₂P₂K₂ producing the highest values in 2021 and 2022 and N₂P₂K₁ producing the highest value in 2023. Among the tested fertilization combinations, N₂P₂K₂, corresponding to 600 kg N ha⁻¹, 500 kg P₂O₅ ha⁻¹, and 400 kg K₂O ha⁻¹, showed the best overall performance for six-year-old *S. mukorossi* ‘Yuanhua’ plantations under the conditions of this study. These findings indicate that balanced NPK fertilization can improve vegetative growth, fruit yield, yield stability, and gross output value in *S. mukorossi* ‘Yuanhua’ plantations.

Keywords: formula fertilization; *Sapindus mukorossi*; fruit yield; yield stability; gross output value



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1. Introduction

Sapindus mukorossi Gaertn. is an economically important species of Sapindaceae and is distributed mainly in tropical and subtropical regions. The species is rich in triterpenoid saponins, which are closely associated with its potential value in biomedicine, cosmetics, and natural surfactant production [1]. Fujian Province is one of its major production areas in China, with a planted area of approximately 20,000 ha. However, many plantations have long been managed extensively, resulting in uneven tree growth and relatively low fruit yield. Improving nutrient supply is therefore essential for increasing plantation productivity and realizing the economic potential of this species.

Fertilization is a key silvicultural practice for regulating tree growth and stand productivity [2–4]. In addition to improved cultivars, planting density, training, and pruning, appropriate fertilization can enhance nutrient availability, photosynthetic capacity, and biomass accumulation, thereby improving stand quality and yield [5–7]. Nitrogen (N), phosphorus (P), and potassium (K) are the major macronutrients required for plant growth and are closely associated with photosynthesis, nutrient metabolism, and reproductive development [4]. Recent studies on *S. mukorossi* have shown that balanced N, P, and K fertilization can affect fine-root traits, soil properties, leaf functional traits, and fruit yield [8–10]. These findings indicate that not only fertilizer amount but also the N:P:K ratio may influence the growth and productivity of *S. mukorossi* plantations.

Tree height, ground diameter, and crown width are commonly used to evaluate vegetative growth and stand development. For fruit-bearing economic forests, canopy structure is also closely linked to fruit production; within a suitable height range, a well-developed crown can improve light interception and support higher yield [11–13]. Recent studies on forest fertilization have increasingly focused on fertilization regimes, fertilizer-use efficiency, and fertilizer formulations [14–17]. The “3414” soil-testing and formula-fertilization design is an optimal regression design with three factors, four levels, and 14 treatments, and is commonly used to estimate fertilizer-response functions with relatively few treatments [18]. Similar fertilizer-response or fertilizer-optimization approaches have been applied to woody and perennial crops, including *Phoebe bournei*, *Xanthoceras sorbifolium*, and *Olea europaea* [19–21]. The results of these studies suggest that fertilizer responses vary with plant species, stand age, site conditions, and the growth or yield traits considered [16,17,21].

At present, information remains limited on the response of clonal *S. mukorossi* plantations to different N, P, and K combinations. The new cultivar ‘Yuanhua’, selected by our research team, is being promoted as a major cultivar in Fujian, but a standardized fertilization regime for clonal orchards has not yet been established. In this study, we conducted a three-year ‘3414’ NPK fertilization experiment in a six-year-old *S. mukorossi* ‘Yuanhua’ plantation. The objectives were to evaluate the effects of combined N, P, and K application on vegetative growth, fruit yield, yield stability, and gross output value, and to identify the best-performing treatment among the tested fertilization combinations for high-quality management of *S. mukorossi* clonal orchards.

2. Materials and Methods

2.1. Study Site

The experiment was conducted in Jianning County, Fujian Province, China (116°47′20″ E, 26°40′3″ N). The mean annual temperature is 16.8 °C, and the mean annual precipitation is 1822 mm. The soil at the experimental site is sandy clay loam, with soil organic carbon of 7.75 g kg^{−1}, total N of 1.40 g kg^{−1}, total P of 0.36 g kg^{−1}, total K of 27.95 g kg^{−1}, available K of 48.16 mg kg^{−1}, available P of 1.32 mg kg^{−1}, and alkali-hydrolysable N of 36.01 mg kg^{−1}. The slope is 5–15°, the elevation is approximately 150 m, stand canopy closure is 0.4–0.5, and understory vegetation cover is 15–35%.

2.2. Plant Material

The tested material was the *S. mukorossi* clone ‘Yuanhua’. Scions were obtained from elite individual trees with high and stable yield as well as resistance to diseases and insect pests. The stand was 6 years old, with a planting spacing of 4 m × 4 m and a planting density of 600–650 plants ha^{−1}.

2.3. Experimental Design

A '3414' optimal regression design was adopted, and fertilization was applied continuously for three years (2021, 2022, and 2023). Different N, P, and K fertilizer levels were combined with an unfertilized control in the field experiment: level 0, 0 kg ha⁻¹ N, P₂O₅, and K₂O; level 1, 300 kg ha⁻¹ N, 250 kg ha⁻¹ P₂O₅, and 200 kg ha⁻¹ K₂O; level 2, 600 kg ha⁻¹ N, 500 kg ha⁻¹ P₂O₅, and 400 kg ha⁻¹ K₂O; and level 3, 900 kg ha⁻¹ N, 750 kg ha⁻¹ P₂O₅, and 600 kg ha⁻¹ K₂O. Fertilizer rates for phosphorus and potassium are expressed as P₂O₅ and K₂O equivalents, respectively, following conventional fertilizer-labeling practice. The design included three factors (N, P, and K), four fertilization levels, and 14 fertilization treatments with three replicates, giving 42 treatment plots in total. The experiment was conducted in a 3-ha experimental plantation with a planting spacing of 4 m × 4 m. The experiment was arranged as a randomized complete block design, and each block contained all 14 fertilization treatments. Treatments were randomly assigned within each block. The unfertilized level 0 was used as the control. Fertilizer application rates are shown in Table 1, and buffer rows were established between treatment plots. In each plot, four representative central trees with average growth status were selected for growth and yield measurements, and border trees were excluded from data collection to reduce edge effects. Fertilizer was applied three times each year: on 10 April (flowering fertilizer, 30% of the annual total), 20 July (fruit-strengthening fertilizer, 30%), and 1 November (post-harvest fertilizer, 40%). Fertilizer was applied by trenching; after the calculated fertilizer amount was mixed into the soil, the trench was immediately covered. Other management practices were the same as those used for the control. Urea (46.0% N) was the only N source, calcium superphosphate (12.0% P₂O₅) was the only P source, and potassium sulfate (60.0% K₂O) was the only K source. In early November of 2021, 2022, and 2023, tree height (from the ground to the plant growth point) and crown width (east–west and north–south directions) were measured using a telescopic tower ruler, and ground diameter (at the graft union) was measured with a Vernier caliper. Measurements were conducted continuously for three years.

Table 1. Experimental fertilization treatments.

Treatment	N (kg ha ⁻¹)	P ₂ O ₅ (kg ha ⁻¹)	K ₂ O (kg ha ⁻¹)
N ₀ P ₀ K ₀	0	0	0
N ₀ P ₂ K ₂	0	500	400
N ₁ P ₂ K ₂	300	500	400
N ₂ P ₀ K ₂	600	0	400
N ₂ P ₁ K ₂	600	250	400
N ₂ P ₂ K ₂	600	500	400
N ₂ P ₃ K ₂	600	750	400
N ₂ P ₂ K ₀	600	500	0
N ₂ P ₂ K ₁	600	500	200
N ₂ P ₂ K ₃	600	500	600
N ₃ P ₂ K ₂	900	500	400
N ₁ P ₁ K ₂	300	250	400
N ₁ P ₂ K ₁	300	500	200
N ₂ P ₁ K ₁	600	250	200

2.4. Yield Stability and Gross Output Value Analysis

Fruit yield was recorded annually from 2021 to 2023 and expressed as yield per unit area. Yield stability was evaluated using the sustainability yield index (SYI), which is

commonly used to assess the stability of crop or plantation productivity across years [22]. The SYI was calculated as follows:

$$SYI = (\bar{Y} - SD)/Y_{\max}$$

where $\bar{Y}$ is the mean annual yield per unit area, SD is the standard deviation of annual yield, and $Y_{\max}$ is the maximum yield observed among all treatments. The SYI ranges from 0 to 1; a higher SYI value indicates greater yield stability, whereas a lower value indicates greater interannual yield variation.

Gross output value was calculated by multiplying annual fruit yield by the corresponding market price. The fruit prices of *S. mukorossi* ‘Yuanhua’ were 20, 30, and 26 CNY kg^{−1} in 2021, 2022, and 2023, respectively. Gross output value was expressed as CNY ha^{−1} and represents gross return before deducting fertilizer, labor, and other production costs.

2.5. Statistical Analysis

All statistical analyses were performed using R version 4.3.2. Annual increments in tree height, ground diameter, and crown width were calculated from consecutive annual measurements. Linear mixed-effects models were used to analyze annual growth increments, with fertilization treatment, year, and their interaction as fixed effects and plot identity as a random effect. When significant effects were detected, estimated marginal means were compared using Tukey-adjusted pairwise comparisons at $p < 0.05$. Three-year mean annual increments were calculated to summarize the overall growth performance of each treatment.

Fruit yield was recorded annually from 2021 to 2023 and expressed on a per-hectare basis. Treatment effects on annual fruit yield were analyzed separately for each experimental year, and different lowercase letters indicate significant differences among treatments within the same year at $p < 0.05$. Gross output value was calculated by multiplying annual fruit yield by the corresponding annual fruit price. The fruit prices of *Sapindus mukorossi* ‘Yuanhua’ were 20, 30, and 26 CNY kg^{−1} in 2021, 2022, and 2023, respectively.

Yield stability across the three years was evaluated using the sustainability yield index (SYI). Descriptive quadratic response curves were fitted to illustrate the responses of three-year mean fruit yield to N, P₂O₅, and K₂O application rates based on the standard single-factor treatment sequences in the “3414” design. Figures were prepared using R version 4.3.2, and statistical significance was determined at $p < 0.05$.

3. Results

3.1. Effects of Fertilization Duration on Tree Height, Ground Diameter, and Crown Width

Tree height, ground diameter, and crown width of *Sapindus mukorossi* ‘Yuanhua’ increased continuously with fertilization duration (Figure 1). The mean tree height increased from 2.34 m before fertilization to 2.86, 3.29, and 4.03 m after one, two, and three years of fertilization, respectively. Ground diameter increased from 6.55 cm to 7.78, 8.47, and 10.37 cm, whereas crown width increased from 2.12 m to 2.63, 3.24, and 3.91 m, respectively. These results indicate that continuous NPK fertilization promoted vegetative growth of six-year-old *S. mukorossi* ‘Yuanhua’ trees. Among the three traits, crown width showed a relatively stable increase during the experimental period, suggesting that fertilization contributed to canopy expansion and stand development.

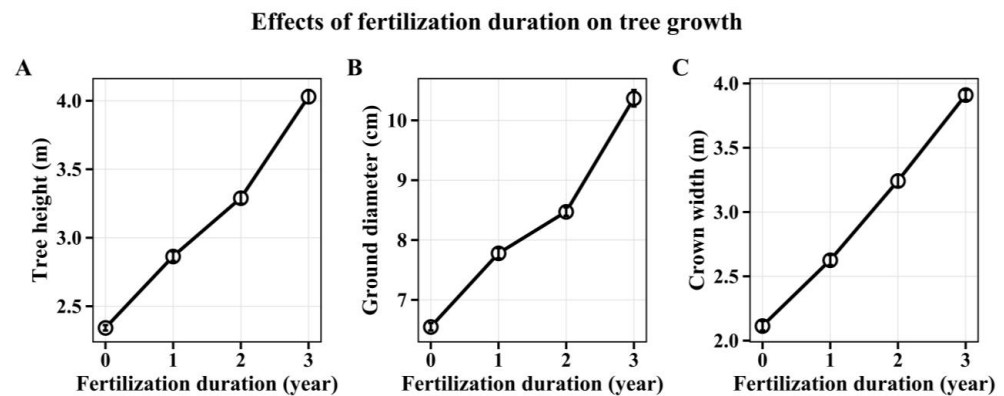


Figure 1. Effects of fertilization duration on the growth of *Sapindus mukorossi* 'Yuanhua'. (A–C) Panels show tree height, ground diameter, and crown width during 0–3 years of continuous fertilization. Points represent grand means across all 14 fertilization treatments, and error bars represent standard errors.

3.2. Effects of Different Fertilization Treatments on Growth

Different fertilization treatments significantly affected the mean annual increments in tree height, ground diameter, and crown width of *S. mukorossi* 'Yuanhua' (Figure 2). Compared with the unfertilized control, most NPK fertilization treatments promoted vegetative growth, but the magnitude of the response varied among growth traits and fertilizer combinations. For tree height, the numerically greatest mean annual increment was observed under $N_1P_1K_2$, followed by $N_3P_2K_2$ and $N_1P_2K_1$. The unfertilized control showed the lowest height increment, indicating that nutrient supply was an important limiting factor for height growth.

Three-year mean annual growth increments under different fertilization treatments

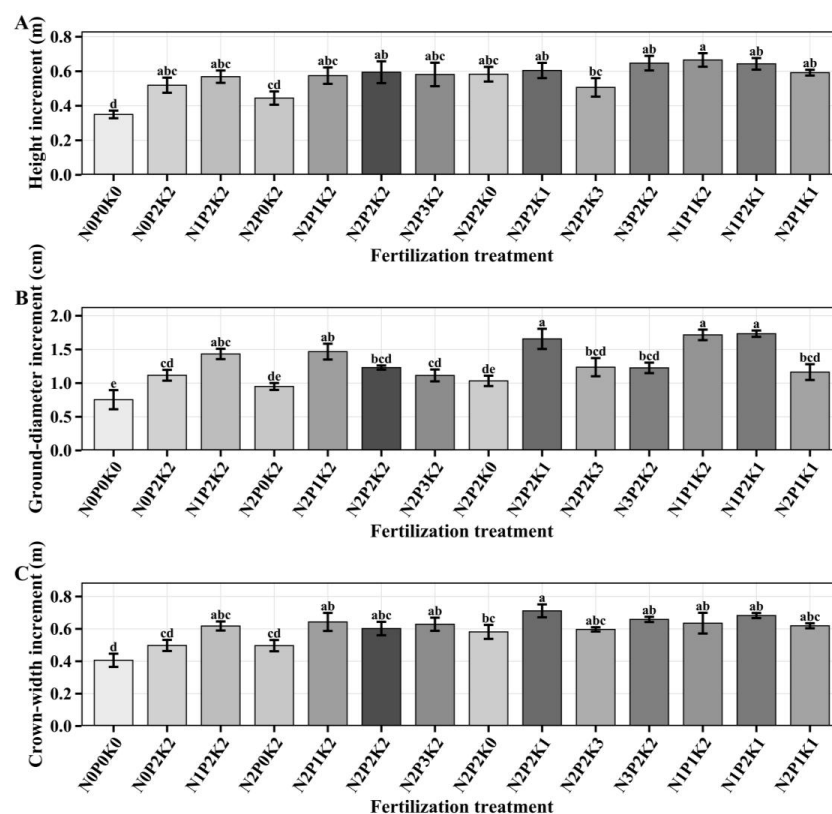


Figure 2. Effects of different NPK fertilization treatments on the three-year mean annual growth increments of *Sapindus mukorossi* 'Yuanhua'. (A) Mean annual increment in tree height; (B) mean annual

increment in ground diameter; and (C) mean annual increment in crown width. Bars represent means, and error bars represent standard errors. Different lowercase letters indicate significant differences among treatments based on estimated marginal means from the linear mixed-effects model at $p < 0.05$.

For ground diameter, $N_1P_2K_1$ produced the highest mean annual increment, followed by $N_1P_1K_2$ and $N_2P_2K_1$. These results suggest that appropriate NPK combinations were favorable for stem-base growth. In contrast, the unfertilized control and nutrient-deficient treatments, especially $N_2P_0K_2$ and $N_2P_2K_0$, generally showed lower ground-diameter increments.

For crown width, the highest mean annual increment was recorded under $N_2P_2K_1$, followed by $N_1P_2K_1$ and $N_3P_2K_2$. Crown-width increment was relatively low under the unfertilized control, $N_2P_0K_2$, and $N_0P_2K_2$, indicating that balanced fertilization promoted canopy expansion. Overall, the response patterns showed that moderate and balanced NPK fertilization improved vegetative growth, whereas excessive or unbalanced nutrient application did not consistently further increase growth.

3.3. Effects of NPK Fertilization on Fruit Yield, Yield Stability, and Gross Output Value

Fruit yield of *Sapindus mukorossi* ‘Yuanhua’ differed among fertilization treatments and years (Figure 3A). Across all fertilized treatments, the mean fruit yields in 2021, 2022, and 2023 were 1095, 944, and 1028 kg ha^{-1} , respectively. The corresponding yields of the unfertilized control were 408.33, 683.33, and 568.75 kg ha^{-1} , respectively. Compared with the unfertilized control, the mean yield of the fertilized treatments increased by 168%, 38%, and 81% in 2021, 2022, and 2023, respectively.

Annual fruit yield and gross output value under different fertilization treatments

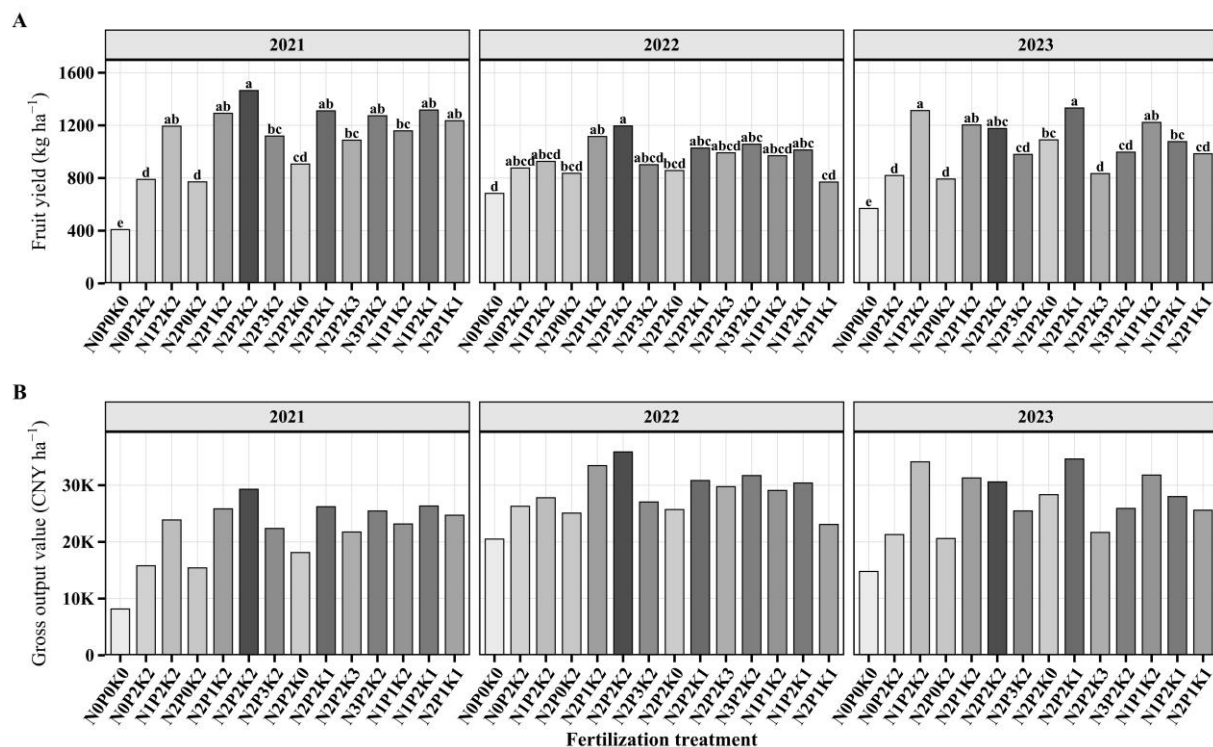


Figure 3. Effects of different NPK fertilization treatments on annual fruit yield and gross output value of *Sapindus mukorossi* ‘Yuanhua’ from 2021 to 2023. (A) Fruit yield in 2021, 2022, and 2023; (B) gross output value in 2021, 2022, and 2023. Bars represent treatment means. Different lowercase letters above the bars in panel (A) indicate significant differences among treatments within the same year at $p < 0.05$. Fruit prices were 20, 30, and 26 CNY kg^{-1} in 2021, 2022, and 2023, respectively.

In 2021, fruit yield ranged from 408.33 to 1464.58 kg ha⁻¹ among treatments, with the highest value observed under N₂P₂K₂. In 2022, fruit yield ranged from 683.33 to 1195.83 kg ha⁻¹, and N₂P₂K₂ again produced the highest yield. In 2023, fruit yield ranged from 568.75 to 1331.94 kg ha⁻¹, with the highest value recorded under N₂P₂K₁. Compared with the unfertilized control, N₂P₂K₂ increased yield by 259% in 2021 and 75% in 2022, whereas N₂P₂K₁ increased yield by 134% in 2023. Yield stability varied among treatments. The SYI values ranged from 0.28 to 0.76 (Figure 4B). The highest SYI values were observed under N₂P₂K₂ and N₂P₁K₂, both reaching 0.76, whereas the unfertilized control had the lowest SYI value. These results indicate that appropriate NPK fertilization not only increased annual fruit yield but also improved interannual yield stability.

Three-year mean fruit yield and yield stability

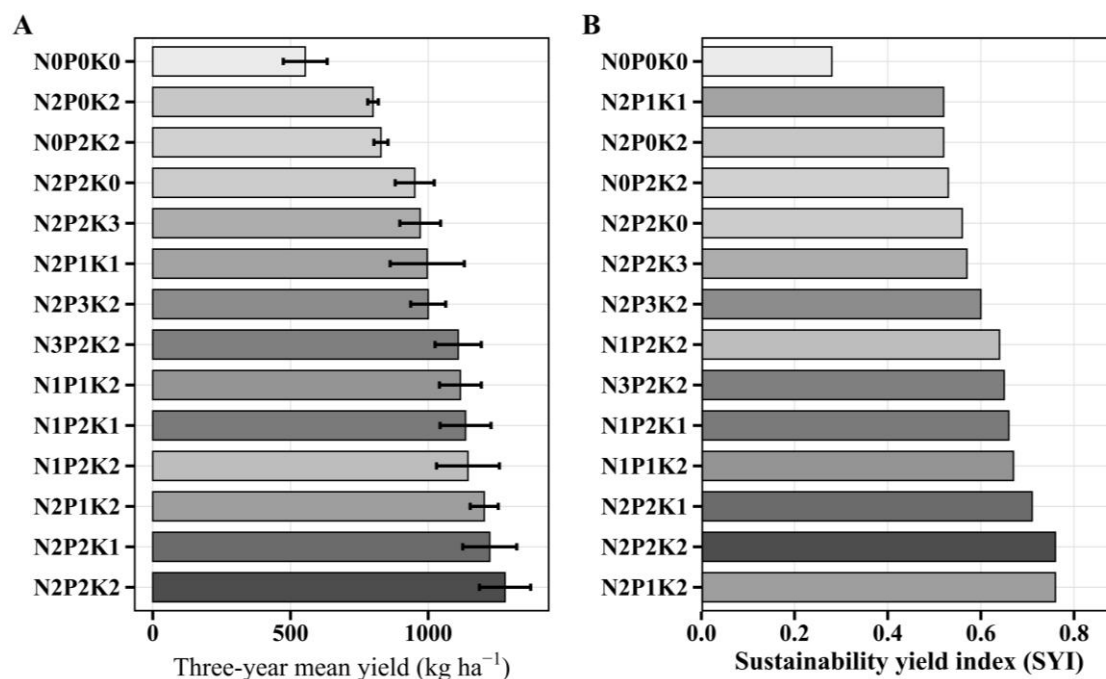


Figure 4. Three-year mean fruit yield and yield stability of *Sapindus mukorossi* 'Yuanhua' under different NPK fertilization treatments. Panel (A) shows treatment ranking by three-year mean fruit yield, and panel (B) shows treatment ranking by sustainability yield index. Bars in panel (A) represent means, and error bars represent standard errors. Gray shades are used only to distinguish fertilization treatments and have no quantitative meaning.

Gross output value showed a pattern generally consistent with fruit yield because it was calculated from annual fruit yield and the corresponding market price (Figure 3B). In 2021, gross output value ranged from 8166.66 to 29,291.66 CNY ha⁻¹, with the highest value under N₂P₂K₂. In 2022, gross output value ranged from 20,499.98 to 35,874.98 CNY ha⁻¹, and N₂P₂K₂ again produced the highest value. In 2023, gross output value ranged from 14,787.50 to 34,630.54 CNY ha⁻¹, with the highest value under N₂P₂K₁.

The three-year mean yield and SYI further confirmed the overall advantage of balanced NPK fertilization (Figure 4). Among the tested treatments, N₂P₂K₂ produced the highest three-year mean yield and gross output value, followed by N₂P₂K₁ and N₂P₁K₂. Overall, N₂P₂K₂ showed the best overall performance among the 14 fertilization treatments, combining high annual yield, high three-year mean yield, high yield stability, and high gross output value.

The descriptive yield-response curves further showed that fruit yield generally increased from nutrient-deficient or low-input treatments to moderate and balanced fertilizer

levels, but did not consistently increase under higher fertilizer inputs (Figure 5). This pattern supports the conclusion that balanced NPK fertilization was more favorable for fruit production than nutrient deficiency or excessive single-nutrient application.

Fruit-yield response to N, P₂O₅, and K₂O fertilization

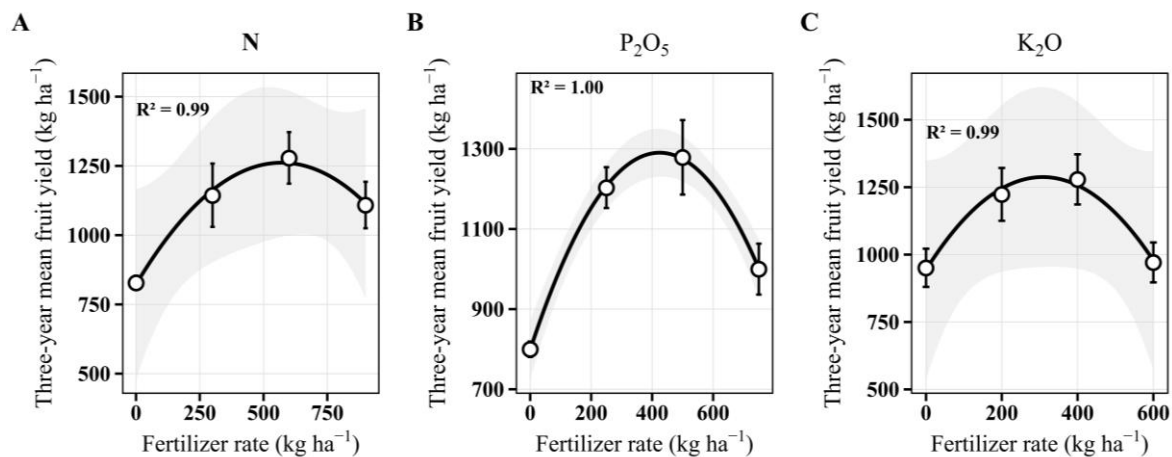


Figure 5. Descriptive response curves of three-year mean fruit yield to (A) N, (B) P₂O₅, and (C) K₂O application rates. Points represent treatment means, and error bars represent standard errors. Curves were fitted using quadratic models based on the standard single-factor treatment sequences in the “3414” design.

4. Discussion

4.1. Reasonable Formula Fertilization Promotes the Growth of ‘Yuanhua’

Fertilization is an important management practice for improving tree growth in raw-material plantations. Nitrogen, phosphorus, and potassium are essential macronutrients involved in plant growth, photosynthesis, and nutrient metabolism, and their appropriate application can improve soil nutrient availability and support stand development [4,23–27]. In the present study, tree height, ground diameter, and crown width of *Sapindus mukorossi* ‘Yuanhua’ increased with the duration of formula fertilization, indicating that continuous NPK supply promoted vegetative growth in this six-year-old clonal stand.

Similar positive effects of combined NPK fertilization have been reported in other tree species. Ma et al. [25] found that NPK application promoted growth, biomass accumulation, and nutrient allocation in 6-year-old grafted *Torreya grandis* saplings, and Ferreira et al. [3] reported positive fertilization effects on early stand development of *Pinus taeda*. These findings support the view that balanced nutrient supply is beneficial for the establishment and growth of young forest stands [28–34]. However, the growth response of ‘Yuanhua’ varied among fertilization treatments, suggesting that the effect of fertilization depends not only on nutrient supply but also on fertilizer ratio and application rate.

Both insufficient and excessive fertilization may limit tree growth. Insufficient fertilizer input cannot meet the nutrient demand of trees, whereas excessive application may disturb nutrient balance, reduce fertilizer-use efficiency, or even cause physiological stress [19,34–36]. Therefore, formula fertilization should aim to balance N, P₂O₅, and K₂O supply rather than simply increase total fertilizer input. The treatment comparisons in this study further showed that balanced NPK application can provide a practical basis for improving the growth performance of *S. mukorossi* ‘Yuanhua’ plantations.

The present results also showed that the best-performing treatment differed among growth traits. N₁P₁K₂ produced the greatest mean annual height increment, N₁P₂K₁ produced the greatest ground-diameter increment, and N₂P₂K₁ produced the greatest crown-width increment. This difference indicates that height growth, stem-base growth,

and canopy expansion may respond differently to nutrient combinations. Therefore, vegetative growth should be evaluated using multiple traits rather than a single growth indicator.

4.2. Key Factors Affecting the Growth of ‘Yuanhua’

Site quality, soil nutrient status, and management practices are important factors affecting forest growth. Fertilization can directly modify soil nutrient availability and thereby influence tree growth, but fertilizer responses in forest stands are often delayed and interactive, making formula fertilization more complex than simple single-nutrient application [20,23,25]. In the present study, most fertilized treatments improved growth compared with the unfertilized control, but the magnitude of improvement differed among treatments and traits. This pattern suggests that balanced nutrient supply was more favorable for young tree growth than nutrient deficiency or unbalanced fertilizer application.

The relative responses of different growth traits to fertilization were not identical. Tree height was more responsive to treatments with moderate N and P_2O_5 supply, whereas ground diameter and crown width responded strongly to treatments containing balanced NPK combinations. Similar differences among nutrients have been reported in other tree species. For example, Yang et al. [5] showed that NPK fertilization altered biomass accumulation and nutrient allocation in *Phoebe bournei* seedlings, whereas Erel et al. [37] reported that N and P played stronger roles than K in olive-tree flowering and fruit set [34,38,39]. These differences may be associated with tree species, stand age, soil fertility, and climatic conditions.

Interannual climatic variation may also have affected the fertilizer response. In this study, height and ground-diameter increments in 2022 were lower than those in 2021. From 1 July to 30 October 2022, precipitation at the experimental site was only 50 mm, much lower than the 371.1 mm recorded during the same period in 2021. This drought condition may have limited nutrient uptake and reduced the growth response of ‘Yuanhua’ to fertilization. In addition, the lower height increment under $N_2P_2K_3$ compared with $N_2P_2K_0$ may also be related to environmental stress or limited fertilizer absorption under high K input.

Crown width is closely associated with canopy development, light interception, leaf area, and fruiting capacity, and is therefore an important indicator for evaluating the growth potential of fruit-bearing trees [40–42]. Compared with tree height and ground diameter, crown width may better reflect the productive structure of *S. mukorossi* ‘Yuanhua’. Therefore, crown-width growth can be used as an important indicator for evaluating vegetative performance in this clonal plantation. However, the best-performing fertilization treatment in this study differed from some previous *S. mukorossi* fertilizer-management studies [9,10,43], probably because of differences in stand age, propagation type, site conditions, and evaluation indicators. This indicates that fertilization recommendations for *S. mukorossi* should be adjusted according to cultivar, stand development stage, and production objective.

4.3. Effects of NPK Fertilization on Fruit Yield, Yield Stability, and Gross Output Value of *Sapindus mukorossi* ‘Yuanhua’

In addition to promoting vegetative growth, NPK fertilization markedly improved fruit yield, yield stability, and gross output value in *S. mukorossi* ‘Yuanhua’. Across the three experimental years, all fertilized treatments produced higher yields than the unfertilized control, indicating that nutrient supply was an important limiting factor for fruit production in this plantation. Among the treatments, $N_2P_2K_2$ showed the best overall performance, producing the highest yields in 2021 and 2022, the highest three-year mean yield of $1278.93 \text{ kg ha}^{-1}$, and one of the highest yield stability index values. These results

suggest that an appropriate NPK combination can enhance not only annual yield but also interannual yield stability [10].

The yield response to fertilizer application generally showed a pattern of first increasing and then decreasing with increasing nutrient input. Moderate NPK application may improve soil nutrient availability, promote canopy development, enhance photosynthetic capacity, and increase assimilate accumulation, thereby supporting fruit formation and yield improvement. Similar nonlinear responses to NPK fertilization have been reported in *Phoebe bournei*, satsuma mandarin, and blueberry, where suitable fertilizer combinations improved yield or growth, whereas excessive nutrient input reduced fertilizer efficiency or inhibited plant performance [19,30,34,39,44–46]. Therefore, the yield advantage of formula fertilization depends on maintaining a suitable nutrient balance rather than simply increasing fertilizer rates.

Excessive fertilization may reduce yield by disturbing nutrient balance, lowering nutrient-use efficiency, and limiting root nutrient uptake. Under excessive nutrient input, vegetative growth and reproductive development may become unbalanced, which can reduce carbohydrate allocation to fruits or storage organs [44]. In addition, over-application of fertilizers may impair soil structure and increase environmental risks such as nutrient leaching and soil acidification [26,27,36,45,47,48]. Previous studies have also shown that inappropriate fertilization can increase disease susceptibility or induce adverse physiological responses in crops such as *Panax notoginseng*, coffee, and citrus [39,44,49,50]. These findings support the view that excessive or unbalanced fertilization may negatively affect both short-term yield and long-term plantation sustainability. Long-term responses to fertilization may also depend on changes in soil nutrient status over successive growing seasons. Although the present study focused mainly on tree growth, fruit yield, yield stability, and gross output value, future work should further examine post-experiment soil properties and nutrient dynamics. Such information would help clarify the long-term sustainability of different fertilization regimes and their potential effects on soil fertility in *S. mukorossi* plantations.

Beyond mineral NPK fertilization, sustainable nutrient management should also consider soil fertility dynamics and complementary biological or organic inputs. Biological components, such as nitrogen-fixing bacteria, humic substances derived from organic residues, organic amendments, and foliar biostimulants, have been reported to improve nutrient availability and plant productivity in other cropping systems [51,52]. Therefore, fertilization strategies for *S. mukorossi* should be evaluated not only in terms of short-term fruit yield and gross output value, but also in relation to soil nutrient balance and long-term plantation sustainability.

Gross output value showed a trend similar to fruit yield because it was calculated from annual fruit yield and the corresponding market price. The highest gross output values were observed under $N_2P_2K_2$ in 2021 and 2022 and under $N_2P_2K_1$ in 2023, which was consistent with the annual yield pattern. Because fertilizer, labor, and other production costs were not included, gross output value should be interpreted as gross return before deducting production costs rather than net economic profit.

The superiority of $N_2P_2K_2$ was also supported by the three-year mean yield and SYI results. This treatment combined high annual yield, the highest three-year mean yield, high yield stability, and high gross output value. $N_2P_2K_1$ also performed well, especially in 2023, when it produced the highest annual yield and gross output value. These results indicate that balanced NPK supply, particularly the $N_2P_2K_2$ combination among the tested treatments, was more favorable for stable and productive fruit production than nutrient-deficient or excessive single-nutrient treatments.

Overall, N₂P₂K₂ was the most favorable treatment for achieving high and stable fruit yield and gross output value in *S. mukorossi* ‘Yuanhua’. These findings indicate that fertilization management for this cultivar should integrate vegetative growth, fruit yield, yield stability, and gross output value. A balanced NPK fertilization strategy is therefore essential for improving the productivity and gross returns of *S. mukorossi* plantations [26,27,48].

5. Conclusions

Balanced NPK fertilization effectively improved the vegetative growth, fruit yield, yield stability, and gross output value of six-year-old *Sapindus mukorossi* ‘Yuanhua’ clonal stands. Compared with the unfertilized control, most fertilization treatments promoted tree height, ground diameter, crown width, and fruit yield, although the response varied among fertilizer combinations and growth traits. Among the tested fertilization combinations, N₂P₂K₂ showed the best overall performance, producing the highest three-year mean fruit yield and gross output value while maintaining high yield stability. N₂P₂K₁ also showed good performance, especially in 2023, when it produced the highest annual fruit yield and gross output value. Therefore, N₂P₂K₂ can be considered the most suitable treatment among the tested combinations for six-year-old *S. mukorossi* ‘Yuanhua’ plantations under the conditions of this study. These results provide a practical basis for improving fertilization management in *S. mukorossi* ‘Yuanhua’ plantations and emphasize the importance of integrating vegetative growth, fruit yield, yield stability, and gross output value when developing NPK fertilization strategies.

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