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A Meta-Analysis of the Effects of Different Fertilization Treatments on Rice Yield and Nitrogen Accumulation

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Abstract. This study uses a meta-analysis to integrate published literature data, aiming to clarify how different fertilization management practices affect rice yield and nitrogen accumulation. Results show that various fertilization treatments significantly boost rice yield and total nitrogen accumulation, with pooled effect sizes of 0.232 and 0.202 respectively. Fertilizer application rates impose differential regulatory impacts on yield and total nitrogen. High fertilization levels (N4 and N5) generate notable positive effects, and the effect size of N5 on total nitrogen accumulation reaches 0.9856. Fertilization methods do not significantly alter yield, yet controlled-release fertilizers markedly increase soil total nitrogen content, with an effect size of 0.2105. Splitting fertilizer into multiple applications significantly promotes yield and total nitrogen accumulation compared with single application, with effect sizes of 0.2479 and 0.4384 respectively. High heterogeneity exists across included studies, suggesting that moderator variables deserve further investigation.

Keywords: Fertilization practices, rice yield, nitrogen accumulation, meta-analysis

1. Introduction

Balanced application of nitrogen (N), phosphorus (P) and potassium (K) stands as one of the most critical management measures for rice to finish its growth cycle and achieve high yield and good quality [1]. Proper combination of these three nutrients directly supports rice growth from vegetative to reproductive stages, and strongly affects nitrogen accumulation and translocation efficiency within plants, which ultimately determines yield and quality [2]. For this reason, scientific NPK application has become a core strategy to safeguard food security and improve rice quality.

However, rice responses to NPK application—including growth, total nitrogen use efficiency, yield and quality changes—are often jointly regulated by regional climate, soil background properties, rice varieties and specific field management practices [3]. Such influencing factors lead to obvious regional differences and inconsistent conclusions among different experimental results.

Some studies point out that long-term NPK fertilization can significantly enhance rice yield accumulation and improve the absorption and utilization efficiency of total nitrogen (TN) [4]. Other experiments find that single application of NPK fertilizer does not effectively promote rice growth; instead, organic fertilizer performs better in increasing seed setting rate and improving rice appearance quality [5]. These inconsistent results are not accidental, but reflect complex interactions among regional environment, basic soil fertility and agricultural management measures [6].

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Therefore, it is difficult to form a unified understanding of NPK regulatory effects only relying on local or short-term test results [7]. There is an urgent need to conduct systematic and quantitative analysis of nutrient regulation mechanisms on rice growth, yield and quality at a larger regional scale [8].

To overcome limitations of single-site or short-term experiments and better understand general rules of combined NPK application on rice growth, yield and quality, this study focuses on how NPK affects rice growth, total nitrogen accumulation, yield and quality. We systematically collect and sort published field test data at home and abroad, and quantitatively evaluate how different NPK application rates and ratios influence rice yield and nitrogen accumulation characteristics.

2. Materials and methods

2.1. Data sources and literature screening

Data in this study were retrieved from two academic databases: China National Knowledge Infrastructure (CNKI) and Web of Science [9]. We conducted systematic searches using keywords related to fertilization methods, rice yield and nitrogen use efficiency [6], and collected peer-reviewed journal papers published before December 31, 2025. To ensure data quality and analytical reliability, included literature must meet the following criteria. First, the study must be a field experiment covering at least one complete rice growing season, with observed data on growth, nitrogen use efficiency, yield and quality. Second, the experiment must contain different NPK application treatments differing in rate, timing or ratio, with clear records of fertilizer type, application rate and frequency. Third, each experiment must set a non-fertilized control group, with replications and standard deviation for each treatment, or data from at least two consecutive growing seasons.

Following these screening rules, we finally obtained 133 valid paired experimental data from 10 research papers. Extracted indicators mainly include mean values and standard deviations of rice yield and nitrogen use efficiency, as well as detailed fertilization management information.

2.2. Classification and coding of fertilization treatments

To facilitate subsequent meta-analysis, we classified all fertilization treatments into three groups based on experimental designs of original studies.

The first category is fertilizer type. Referring to common terms in existing literature, this study divides fertilization methods into four types: conventional fertilization (CF), controlled-release fertilizer (CRF), organic fertilizer (OF) and stabilized fertilizer (SF). These four types cover major fertilizers widely used in rice production.

The second category is fertilization level, which is divided into five gradients according to nitrogen application rate: N1 (60–120 kg ha^{-2}), N2 (121–180 kg ha^{-2}), N3 (181–240 kg ha^{-2}), N4 (241–300 kg ha^{-2}) and N5 (≥301 kg ha^{-2}).

The third category is application frequency, including single application and multiple applications.

Data under this classification system were used to systematically analyze effects of different fertilization treatments on rice yield and nitrogen use efficiency.

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2.3. Calculation of the effect size

This study used the response ratio as a measure of effect to evaluate the impact of different fertilization treatments on rice yield and N use efficiency compared to the no-fertilizer control [10]. The formula for calculating the natural logarithm of the response ratio is as follows:

$$\ln RR = \ln\left(\frac{\overline{X}_t}{\overline{X}_c}\right) = \ln\overline{X}_t \ln\overline{X}_c \tag{1}$$

Here, $\overline{X}_t$ represents the mean for the fertilization treatment group, and $\overline{X}_c$ represents the mean for the non-fertilization control group.The corresponding formula for calculating the variance of the effect size is:

$$Var(\ln RR) = \frac{SD_t^2}{n_t\overline{X}_t^2} + \frac{SD_c^2}{n_c\overline{X}_c^2} \tag{2}$$

In the formula, SD_t and SD_c represent the standard deviations for the treatment group and the control group, respectively, while n_t and n_c represent the sample sizes (number of replicates) for the two groups, respectively. For studies that did not directly report standard deviations, calculations were adjusted based on standard errors or confidence intervals provided in existing studies. The calculated effect sizes will be used in subsequent meta-analyses.

2.4. Statistical models and heterogeneity analysis

Given the significant differences among the original studies in terms of trial locations, rice varieties, climatic conditions, and field management practices, and considering that some studies did not report standard deviations, resulting in substantial variability in variance across studies, this study employed a random-effects model to pool the overall effect estimates. The fundamental assumption of the random-effects model is that each study not only involves sampling error but also has its own true effect estimate drawn from the population effect distribution; in other words, there is true heterogeneity among the studies [4]. The basic form of this model is as follows:

$$\Theta_i = \mu + \tau_i + \varepsilon_i \tag{3}$$

Here, Θ_i represents the observed effect size for the i-th study, μ is the population mean effect size, τ_i is the random error term between studies, which follows a normal distribution with a mean of 0 and a variance of τ^2, reflecting heterogeneity among studies, and ε_i is the sampling error within studies, which follows a normal distribution with a mean of 0 and a variance of $Var(\Theta_i)$.The Restricted Maximum Likelihood (REML) method is used to estimate the between-study variance component τ^2 .This method provides unbiased and efficient variance estimates and is particularly suitable when the number of studies is small or the variance distribution is uneven.

To assess the degree of heterogeneity in effect sizes across studies, the Cochran Q test and its corresponding I^2 statistic were calculated [9, 10]. The formula for the Q statistic is

$$Q = \sum_{i=1}^{k} w_i(\Theta_i\Theta)^2 \tag{4}$$

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Here, k denotes the number of studies, w_i denotes the weight of the i-th study (typically the inverse of the variance), Θ_i denotes the effect size of the i-th study, and is the estimate of the pooled effect size. Building on the Q-test, the I^2 statistic is further calculated using the following formula::

$$I^2=\frac{Qdf}{Q}\times 100\% \tag{5}$$

In this formula, df represents the degrees of freedom, which is equal to the number of studies minus one. The I^2 value reflects the proportion of total variation attributable to true heterogeneity among studies rather than sampling error. Generally, an I^2 value between 25% and 50% indicates low heterogeneity, between 50% and 75% indicates moderate heterogeneity, and greater than 75% indicates high heterogeneity. If the I^2 value is high and the Q-test is significant, this suggests substantial differences in effect sizes across studies. In such cases, it is not appropriate to rely solely on a single pooled effect size for interpretation; further investigation into the sources of heterogeneity is required.

To identify potential sources of heterogeneity, this study conducted subgroup analyses using a mixed-effects model in addition to the overall random-effects model [1]. The mixed-effects model is an extension of the random-effects model, and its basic structure is as follows:

$$\Theta_{ij}=\mu+\beta X_{ij}+\tau_j+\varepsilon_{ij} \tag{6}$$

Here, Θ_{ij} represents the observed effect for the i-th study in the j-th subgroup; μ is the intercept; β is the fixed-effect coefficient; X_{ij} is the subgroup-level covariate; τ_j is the between-study random effect for the j-th subgroup, following a normal distribution with a mean of 0 and a variance of $\tau^2_{between}$; and ε_{ij} is the within-study sampling error. In this model, the subgroup classification variable is included as a fixed effect, while the studies within each subgroup are treated as random effects, thereby simultaneously controlling for between-group differences and within-group heterogeneity.

2.5. Data analysis

Subgroup analysis focused on several key factors. First, fertilizer type (CF, CRF, OF, SF) was used to compare effects on rice yield and nitrogen use efficiency. Second, five nitrogen application levels (N1–N5) were used to assess how rate gradients affect effect magnitude. Third, application frequency (single vs. multiple) was used to detect differences in treatment effects.This analysis helped identify factors significantly affecting the relationship between fertilization treatments and yield or nitrogen use efficiency, laying a foundation for subsequent meta-regression. Within the mixed-effects model framework, Wald test was used to compare effect sizes among subgroups, and random-effects model was used to calculate pooled effect sizes within each subgroup. Between-study variance component τ^2 was estimated separately for each subgroup to reflect within-subgroup heterogeneity. All analyses were run with meta and metafor packages in R, and significance level was set at $P < 0.05$.

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3. Results

3.1. Overall effects of different fertilization treatments on rice yield and N accumulation

According to the analysis results in Table 1, different fertilization treatments had a vital positive effect on both rice yield and N accumulation. Regarding yield, the pooled effect size based on 123 observations was 0.232, with a 95% confidence interval of 0.192 to 0.272, and was statistically significant. Regarding TN accumulation, the pooled effect size based on 73 observations was 0.202, with a 95% confidence interval of 0.117 to 0.287, which was also statistically significant. No significant effects of publication bias were observed in either analysis; however, high heterogeneity was present across studies, with I^2 values of 100% for both the yield analysis and the nitrogen accumulation analysis, and corresponding tau^2 values of 0.0494 and 0.137, respectively. This indicates the need for further exploration of potential moderating variables.

Table 1. Overall effects of different fertilization treatments on rice yield and N accumulation

Outcome	k	Estimate [95% CI]	*P*	I^2 (%)	tau^2
Yield	123	0.232 [0.192, 0.272]	< 0.0001	100	0.0494
Total Nitrogen	73	0.202 [0.117, 0.287]	< 0.0001	100	0.137

3.2. Effects of different N application rates on rice yield and N accumulation

Mixed-effects model results (Figure 1) show that fertilization level significantly affects both yield and total nitrogen accumulation, but the two indicators show different response patterns. Moderator tests confirm that fertilization level imposes a statistically significant impact on yield.

Compared with the control (N1), N2, N4 and N5 significantly increase yield, with effect sizes of 0.2302, 0.3282 and 0.3895 respectively. N5 shows the strongest effect, and its confidence interval does not include zero. N3 shows a positive trend but does not reach significance.

For total nitrogen accumulation, the model still presents high heterogeneity, and fertilization level as a moderator significantly explains part of the heterogeneity. Compared with the control, N4 and N5 generate highly significant promoting effects, with effect sizes of 0.7338 and 0.9856 respectively, and effect size rises with increasing application rate. N2 is marginally significant for total nitrogen, while N3 shows no significant effect.

Overall, high fertilization levels (especially N4 and N5) exert stable and significant positive effects on both yield and total nitrogen content.

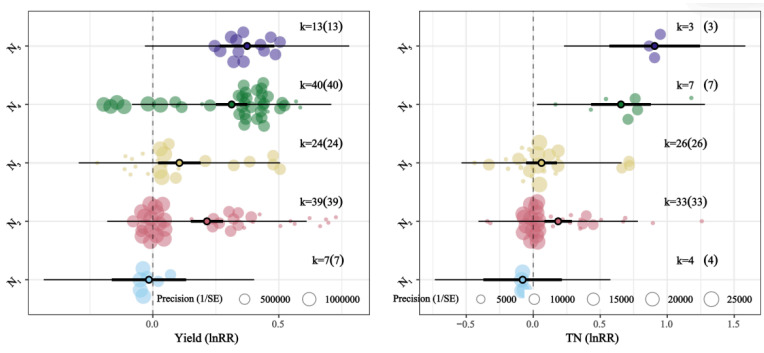

Figure 1. Effects of different N application rates on rice yield and N accumulation

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3.3. Effects of different fertilization methods on rice yield and N accumulation

Mixed-effects model results (Figure 2) indicate that different nitrogen fertilizer types do not cause significant differences in rice yield. Taking conventional fertilization as reference, estimated yield effect sizes of controlled-release fertilizer, organic fertilizer and stabilized fertilizer are −0.0336, −0.1432 and 0.0073 respectively, with all P values > 0.05. This means yield-increasing effects of these three treatments are not significantly different from conventional fertilization.

Model residual heterogeneity test is significant, with I^2 of 100%, suggesting high between-study heterogeneity.

For soil total nitrogen, different nitrogen fertilizer types show significant effects. Controlled-release fertilizer significantly increases soil total nitrogen content, with effect size of 0.2105 and P = 0.0206. Organic fertilizer shows a marginally significant negative effect on total nitrogen, with effect size of −0.3143 and P = 0.0982. Stabilized fertilizer has no significant effect. Moderator analysis shows that nitrogen fertilizer type significantly explains variation in total nitrogen (P = 0.0078).

These results suggest that different nitrogen fertilizers have similar yield-enhancing effects, while controlled-release fertilizer has obvious advantages in increasing soil total nitrogen.

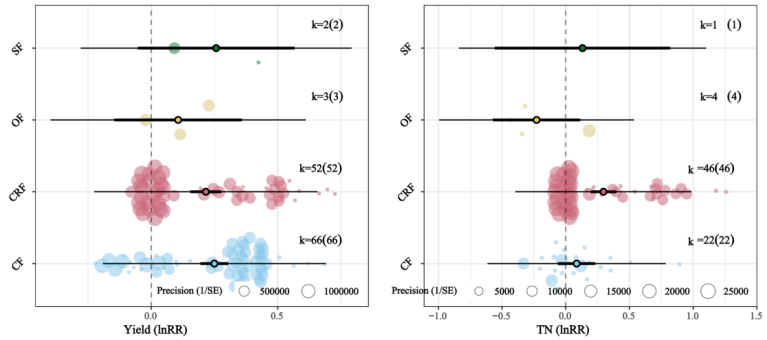

Figure 2. Effects of different nitrogen application rates on rice yield and nitrogen accumulation

3.4. Effects of different fertilization frequencies on rice yield and nitrogen accumulation

Mixed-effects model analysis (Figure 3) shows that for yield, the intercept (0.0831) is significantly non-zero, representing a meaningful baseline level. Compared with single application, multiple applications significantly improve yield (estimate = 0.2479, SE = 0.0345, Z = 7.1897, P < 0.0001; 95% CI: 0.1803–0.3155). Unexplained heterogeneity (τ^2 = 0.0336) is significant, and the model explains 31.99% of total heterogeneity.

For total nitrogen, the intercept (0.0630) is not significant. Multiple applications also show significant positive effects (estimate = 0.4384, SE = 0.0783, Z = 5.5995, P < 0.0001; 95% CI: 0.2850–0.5919). The model τ^2 is 0.0959, explaining 29.98% of heterogeneity.

In general, increasing fertilization frequency significantly and positively affects both yield and total nitrogen accumulation, with a stronger impact on total nitrogen.

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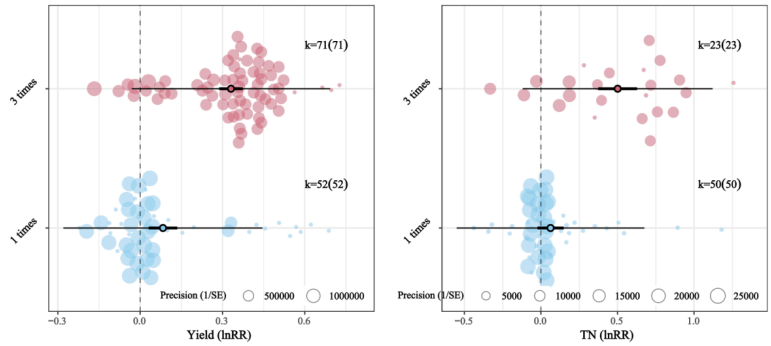

Figure 3. Effects of different N application rates on rice yield and N accumulation

4. Conclusion

This meta-analysis systematically evaluates how fertilization management regulates rice yield and nitrogen accumulation. The main conclusions are as follows.First, most fertilization treatments significantly improve rice yield and nitrogen accumulation, but high between-study heterogeneity indicates that moderators such as application rate, method and frequency play important roles. Second, fertilization rate shows a clear threshold effect. High levels N4 and N5 significantly increase both yield and total nitrogen, and total nitrogen responds more strongly to N5. N3 has no significant effect, suggesting that nitrogen accumulation is more sensitive to application rate than yield. Third, fertilization methods show asynchronous effects. Controlled-release fertilizer and organic fertilizer do not outperform conventional fertilization in yield improvement. However, controlled-release fertilizer significantly increases soil total nitrogen, while organic fertilizer shows a slight negative trend. Fourth, increasing fertilization frequency significantly promotes both yield and nitrogen accumulation, and the effect on total nitrogen is nearly twice that on yield, indicating that nitrogen accumulation is more sensitive to application frequency. The model explains about 30% of heterogeneity, implying that soil background fertility and climate conditions also contribute to variation. In summary, appropriately raising nitrogen application rate, popularizing controlled-release fertilizer and increasing application times can synergistically improve rice yield and soil nitrogen retention.

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