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Exploring the Effects of Nitrogen Fertilization Management and Soil Factors on the Yield and Quality of Flue-Cured Tobacco in China—A Quantitative Research

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Abstract: Tobacco, a pivotal economic crop in China, faces the challenge of securing high-quality raw materials for its industry due to unbalanced and inefficient nitrogen (N) application. To assess the impact of fertilizer management and soil factors on the yield and quality of flue-cured tobacco (FCT), a meta-analysis was conducted across 82 peer-reviewed research studies. The findings demonstrated that both fertilizer management and soil properties exerted a significantly greater influence on yield (63.13% and 62.05%, respectively) than the proportion of superior and medium tobacco (PSMT) (23.57% and 23.83%, respectively). Multiple models were conducted to analyze the N application rate for maximum yield and PSMT, respectively, resulting in an optimum range from 90 to 100 kg N ha^{-1}. The highest yield and PSMT increments were observed with fertilizer timing (FT) applied twice, a basal fertilizer ratio (BFR) exceeding 50%, and a soil pH below 6.5. The nicotine content escalated with increasing N application rates (NR) and soil nitrogen content, peaking at NR over 120 kg N ha^{-1} and soil total nitrogen (TN) above 2 g kg^{-1}. Stepwise regression modeling indicated that nicotine content was positively influenced by fertilizer management factors (including NR, fertilizer timing, and BFR), as well as initial soil nitrogen content (AN and TN). However, it was negatively correlated with available potassium (AK). Therefore, the results of this meta-analysis suggest that effective fertilizer management, slightly acidic soils enriched with AK, and lower N supply capacity are crucial for enhancing leaf quality while reducing nicotine content. This approach promises improved economic and environmental returns for the tobacco industry in China.

Keywords: flue-cured tobacco; meta-analysis; nicotine; nitrogen; tobacco yield and quality

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1. Introduction

Tobacco is a crucial economic crop in China, contributing significantly to the nation's income and ranking as the world's largest crop by both area planted and total yield [1–3]. However, the cigarette industry necessitates tobacco raw materials of exceptional quality due to intense international competition in tobacco production and health concerns related to smoking [4,5]. A prevailing challenge for China's tobacco industry are high levels of nicotine and carbohydrates, coupled with low potassium content, in tobacco leaves [6]. These characteristics hinder the achievement of high-quality tobacco standards demanded by the cigarette industry. The use of chemical fertilizers offers a direct, swift, and effective method to enhance agricultural productivity and has temporarily mitigated issues related to leaf quality [7]. Among various nutrients, nitrogen stands out as the most critical element influencing tobacco yield and quality, necessitating a substantial N application [8]. Regulating the quantity and timing of N availability is paramount [9]. However, tobacco has many species which are derived from many origins, and may have different requirements of nitrogen for cultivation [10]. Generally, nitrogen demand peaks during the early stages of tobacco growth. Thus, maintaining nitrogen supply during this period is essential for enhancing tobacco production quality [11]. However, beyond this phase, excessive nitrogen fertilization compromises tobacco quality (harsh tissue, darkness, reduction in strip yield) and its commercial value, complicating harvesting and roasting processes [12]. This can lead to nitrogen losses such as water pollution, soil acidification, and air pollution [13,14]. Consequently, an optimal nitrogen fertilizer rate is indispensable for sustainable tobacco production.

The prevailing fertilizer strategy for Chinese tobacco involves the application of 70% at planting and the subsequent top-dressing of the residual 30% one month later [1]. The nitrogen supply pattern does not align with either the nitrogen uptake or demand patterns of the tobacco plant [8]. The primary factor responsible for the degradation of quality in China's tobacco production is the excessive nitrogen uptake during the later stages of the plant's growth cycle [9]. Nitrogen sources for tobacco absorption are primarily soil and fertilizer nitrogen. On one hand, nitrogen availability is influenced by the timing and rate of fertilizer application, which are critical factors in 4R nutrient management [15]. On the other hand, soil nitrogen mineralization under high temperature and humidity conditions can affect the uptake of nitrogen by the tobacco leaf [16,17].

Extensive research has been conducted to enhance tobacco quality, with a particular emphasis on fertilization techniques [9,18,19]. The optimal results can be achieved by modifying fertilizer application strategies, such as the rate of fertilizer application, basal fertilizer ratio, frequency of application, and other measures [20,21]. By adjusting the fertilizer strategy, which includes changing the amount of fertilizer applied, the ratio of base to top-dressing fertilizer, the frequency of application, and other related measures, we can achieve optimal results for crop growth [15]. For instance, enhancing the nutrient supply concentration in specific zones and employing diverse forms of fertilizer use can markedly improve the nutrient uptake efficiency of crops, thereby significantly boosting crop yields [22]. However, the efficacy of these fertilization methods varies significantly across regions [7,23,24]. To some extent, field fertilization tests in various tobacco-growing regions provide partial evidence of the impact on yield and quality within specific regions. Furthermore, there are significant discrepancies and inconsistencies in studies on the effects of nitrogen (N) fertilization on tobacco production due to the diverse physical and chemical properties of tobacco soils in China [25]. This underscores the complexity of N fertilizer's influence on tobacco production, which is influenced by factors such as environmental conditions, soil characteristics, and crop management [7,9,26,27]. Consequently, it remains unclear how effectively tobacco production can be optimized. Currently, there is no comprehensive nationwide report on the combined effect of increased N fertilization on tobacco yield and quality or analysis of the numerous uncertain factors affecting quality and yield improvement in field experiments.

The primary aims of the present study, encompassing 82 original research papers spanning from 1990 to 2022, were twofold: (i) to assess the flue-cured tobacco's yield and leaf quality in response to nitrogen fertilization, and (ii) to investigate the influencing factors on the extent of this response, including fertilizer management techniques and soil characteristics. Additionally, we emphasized several potential areas and research directions to improve tobacco quality.

2. Material and Methods

2.1. Data Collection

A comprehensive literature review was undertaken to gather data on the impact of nitrogen (N) fertilization on the yield and quality of flue-cured tobacco. The review encompassed peer-reviewed scientific journals from the Web of Science (WoS, https://webofscience.com/, accessed on 6 May 2024) and China Knowledge Resource Integrated Databases (CNKI, www.cnki.net/, accessed on 6 May 2024) published between

1990 and 2022. The search was limited to field studies, employing keywords such as "Nitrogen application rates", "Flued-cured tobacco", "Yield", and "Quality". These keywords were amalgamated to retrieve the pertinent literature for detailed analysis. To ensure the accuracy and representativeness of the integrated analysis results, the selected literature must meet the following criteria: (1) studies conducted in mainland China under field conditions, (2) including data for both N application (fertilizer) and control (no N), (3) containing at least three replications for each treatment in the test experiment, and (4) providing mean, standard deviation (SD), and sample size for control and treatment groups. Data were derived either directly from tables or extractable from figures using Web Plot Digitizer 4.2 software; if only the standard error (SE) was reported, SD was calculated as $SD = SE \times \sqrt{n}$; for studies that did not report SD or SE, SD was calculated from 1/10 of the mean values [28,29].

The relevant information encompassed explicit descriptions of regional factors such as mean annual temperature, mean annual precipitation, and tobacco planting area. Fertilizer management practices including N application rates, fertilizer timing (FT), and basal fertilizer ratio (BFR) were also incorporated. Soil properties like soil pH, soil organic matter (SOM), AN, AK, and total N (TN) were taken into account. In total, our meta-analysis incorporated 511 paired comparisons from 82 peer-reviewed studies that fulfilled our specific criteria (please refer to Supplementary Materials: Table S1 and Figure S1). The geographical distribution of the chosen field studies is depicted in Figure 1.

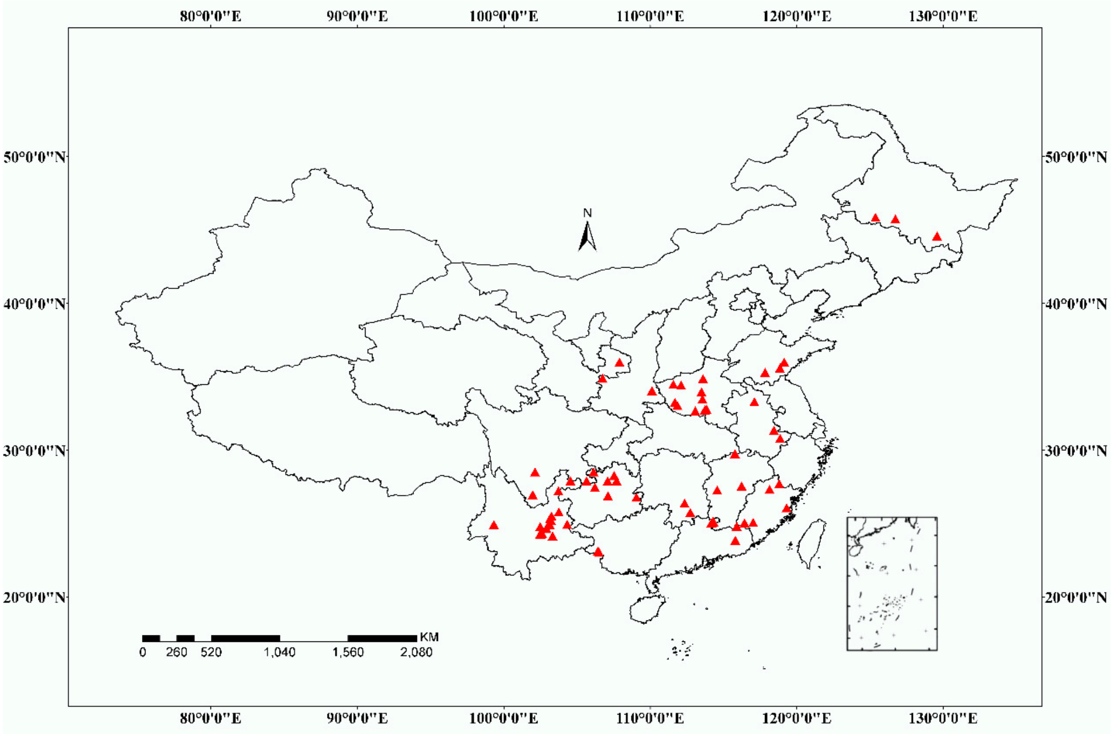

Figure 1. The geographical distribution of the field experiment sites across Chinese upland soils was included in the meta-analysis.

2.2. Data Categorization

To facilitate comparative analysis across studies, the analytical data extracted were categorized based on specific criteria for each attribute. Fertilizer applications were segregated into two groups: those with and without fertilizer. Nitrogen application rates were further divided into six categories: <30, 30–60, 60–90, 90–120, and >120 kg ha^{-1} yr^{-1}. Basal fertilizer ratios were classified into two groups: <50 and > 50 (%). Soil pH was categorized as acidic (<6.5), neutral (6.5–7.5), or alkaline (>7.5) [30]. Soil organic matter was grouped into three categories: <20, 20–30, and >30 (g kg^{-1}). Soil total N was classified as <1.5, 1.5–2, or >2 (g kg^{-1}). Soil available N (AN) was divided into three categories: <60, 60–120, and >120 (mg kg^{-1}). Soil available K (AK) was categorized as <50, 50–150, or >150 (mg kg^{-1}).

2.3. Meta-Analysis

We undertook a meta-analysis to assess the influence of N application rates on tobacco yield and quality, taking into account management, soil, and regional factors. The data were subjected to analysis using the natural logarithm of the response ratio (*lnRR*) [31]:

$$lnRR = \ln\left(\frac{Xt}{Xc}\right) \tag{1}$$

where *Xt* and *Xc* represent the means of nitrogen application treatment and control (without N), respectively. The variable under examination is categorized based on its *lnRR* value: if $lnRR > 0$, it indicates a positive effect on crop yield; if $lnRR < 0$, it signifies a negative effect; and if $lnRR = 0$, it suggests no discernible impact on crop yield or quality.

The variance (V) of each *lnRR* for each study was calculated using the following equation:

$$\mathrm{V} = \frac{S_t^2}{n_t X_t^2} + \frac{S_c^2}{n_c X_c^2} \tag{2}$$

S_t and S_c represent the standard deviations of the treatment and control groups, respectively. Meanwhile, n_t and n_c denote the number of replicates in the respective treatment and control groups.

The weighting factor (*Wij*), weighted response ratio (*R*+), standard error of *R*+ (S), and 95% confidence interval (CI) of *R*+ were calculated as below [32]:

$$W_{ij} = \frac{1}{V} \tag{3}$$

$$R_+ = \frac{\sum_{i=1}^{m}\sum_{i=1}^{k} w_{ij}\,{}^{R_{ij}}}{\sum_{i=1}^{m}\sum_{i=1}^{k} w_{ij}} \tag{4}$$

$$S = \sqrt{\frac{1}{\sum_{i=1}^{m}\sum_{i=1}^{k} w_{ij}}} \tag{5}$$

$$S = \sqrt{\frac{1}{\sum_{i=1}^{m}\sum_{i=1}^{k} w_{ij}}} \tag{6}$$

where '*i*' and '*j*' represent the *ith* and *jth* treatments, respectively. The variables '*m*' and '*k*' denote the number of comparison groups and comparisons within these respective groups, respectively. A significant increase (>0) or decrease (<0) in the treatments was deemed when the 95% confidence interval did not overlap zero for those two variables, as compared to the controls ($p < 0.05$). Furthermore, *Q* statistics were employed to evaluate the heterogeneity of effect sizes in *R* [33]. The total heterogeneity (*Qt*) of effect sizes across studies was divided into within-group (*Qw*) and between-group (*Qb*) heterogeneity. A *Qb* value exceeding a critical threshold suggests a significant difference between groups ($p < 0.05$).

The percentage change (%) for the response of N application effect on crop yield was calculated by the following:

$$Percentage\ change\ (\%) = \left(e^{R_+}\right) \times 100 \tag{7}$$

2.4. Statistical Analysis

Mean effect sizes and 95% CIs were determined by the random-effects model based on a meta-analysis using the "metaphor" package, and to compare the relative importance of nitrogen application on tobacco yield and quality, we created a random-forest model based on machine learning using the "party" package in R (version 3.6.2) software. To further quantify the relative importance of fertilizer management practices and soil properties, a random-forest approach was applied by using the "party" packages (number of trees in each forest = 1000, number of observations in trees' terminal note = 2, and number of entry features = 3) in R software [34].

We employed stepwise linear regression analysis to construct a model delineating the relationships between environmental factors, fertilizer management techniques, and the target variables under nitrogen addition. Utilizing this model, we concurrently identified the explanatory variables that exerted a significant influence on the target variables. We conducted a multi-linear stepwise regression analysis to model the links separately between the explanatory variables ($\log\left(\frac{Xt}{Xc}\right)$) and the effects of leaf nicotine content, as well as fertilizer management or soil factors. The regressions were computed using IBM SPSS 20.0 for Windows. During processing, each coefficient of the parameter in the equation must reach the $p < 0.05$ level of significance. All figures were generated and fitted using OriginPro 2024 (OriginLab Corporation, Northampton, MA, USA). The fail-safe N technique was used to test publication bias.

3. Results

3.1. The Overall Effects of Fertilizer Management and Soil Factors on FCT Yield and Leaf Grades in PSMT

Significant variability was observed in the response ratio (*lnRR*) of tobacco yield and PSMT to N fertilization across various studies conducted in Chinese upland soils. The yield response demonstrated a range from 0.135 to 1.571 (Figure 2a), while the PSMT response exhibited a range from 0.305 to 1.146 (Figure 2b). The frequency distribution analysis demonstrated that *lnRR* can be modeled as a Gaussian normal distribution for both tobacco yield ($R^2 = 0.859$, $p < 0.01$) and PSMT ($R^2 = 0.993$, $p < 0.001$). The N fertilizer application significantly enhanced crop yield. A significant proportion of observations, specifically 97.8% for fertilizer management (Figure 2b) and 97.2% for edaphic factors (Figure 2c), were impacted by the addition of nitrogen fertilizer. Similarly, concerning tobacco PSMT, 78.6% (fertilizer management, Figure 2e) and 79.6% (soil factors, Figure 2f) were affected. Overall, the data indicated that N application resulted in an average increase of 23.57% in leaf grade of PSMT (Figure 2h) due to fertilizer management and 23.83% due to soil factors. Moreover, the positive response of tobacco yield resulting from N addition was more pronounced than that of PSMT, with a crop yield increase of 63.13% influenced by fertilizer management and 62.05% (Figure 2g) by soil factors.

3.2. The Yield of FCT as Affected by Fertilizer Management and Soil Conditions

The impact of nitrogen (N) fertilization on tobacco yield is contingent upon several factors (Figure 3A). The rate of N application significantly influenced the yield response, with a corresponding increase observed as the N rate (NR) escalated. The peak response was noted at N application rates exceeding 120 kg ha^{-1} (89.0%). Specifically, response rates of 34.6%, 58.96%, and 88.15% were recorded for N application rates of 30–60 kg ha^{-1}, 60–90 kg ha^{-1}, and 90–120 kg ha^{-1}, respectively. The lowest yield response was detected when the N application rate remained below 30 kg ha^{-1} (24.2%). The influence of the basal fertilizer ratio (BFR) on the tobacco yield response to N fertilization also demonstrated variability. The most pronounced yield effect was observed with an increase in BFR (an increase of 69.11% at >50% and 43.1% at BFR < 50%, respectively). The yield response increased with FT, with the highest increase observed at two times (an increase of 70.6%), followed by a decrease beyond this number of fertilizer times. A regression analysis of flued-cured yield and N application rates revealed a linear plus plateau model ($R^2 = 0.631$, n = 495), as depicted in Figure 4A. The optimal nitrogen fertilizer application rate is determined to be 100 kg per hectare.

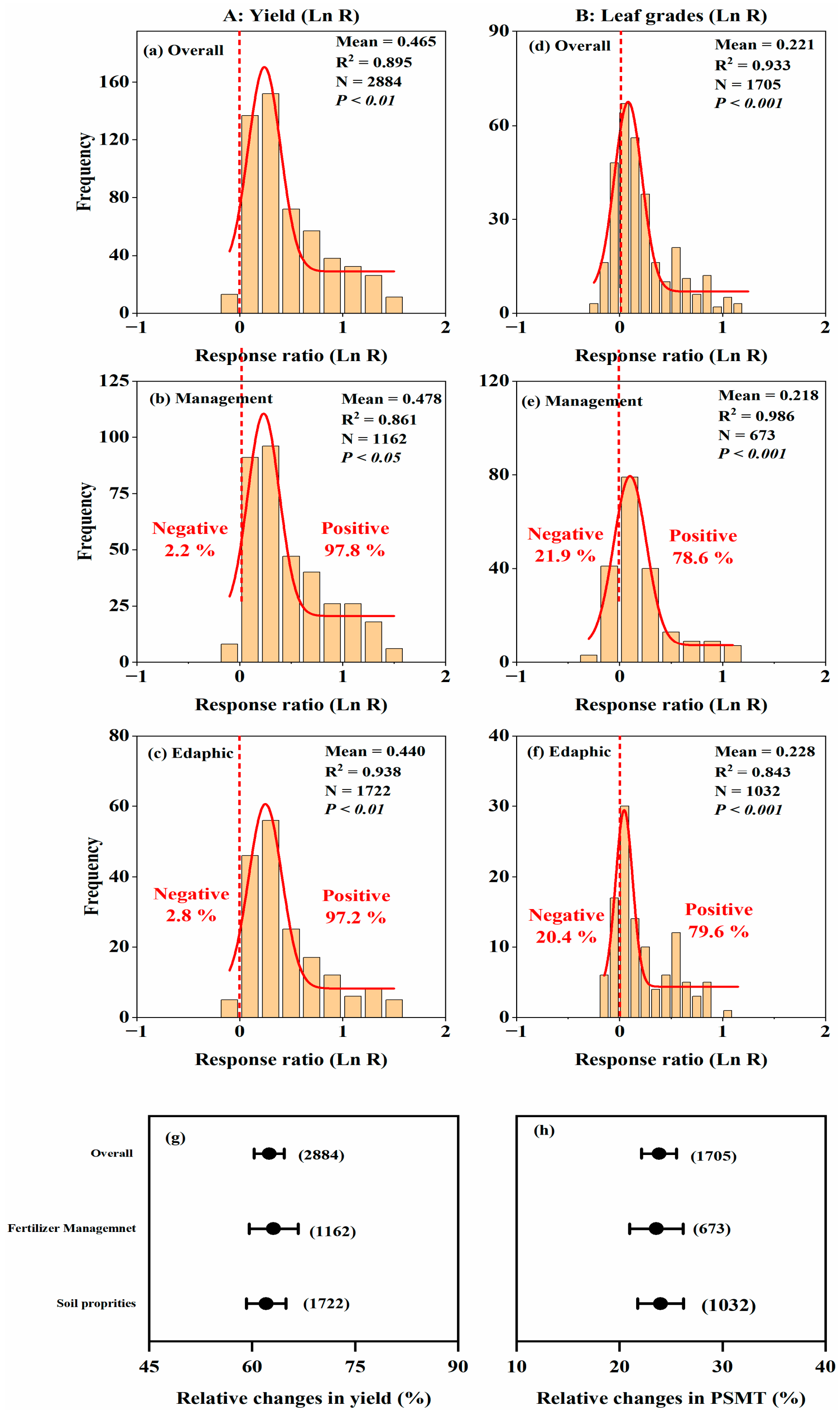

Figure 2. Frequency distributions of response ratio (*lnRR*) (**a**–**f**) and overall effect (**g**,**h**) for tobacco yield responses to fertilizer management and initial soil factors. PSMT: leaf grades in proportion of superior and medium tobacco. For the response ratio, *lnRR* < 0, = 0, and > 0 indicate negative, neutral, and positive, respectively. The numbers in the brackets represent the sample size. Mean effect and 95% confidence interval (CI) are shown. Effects are significant ($p < 0.05$), if the CI does not overlap with 0 line.

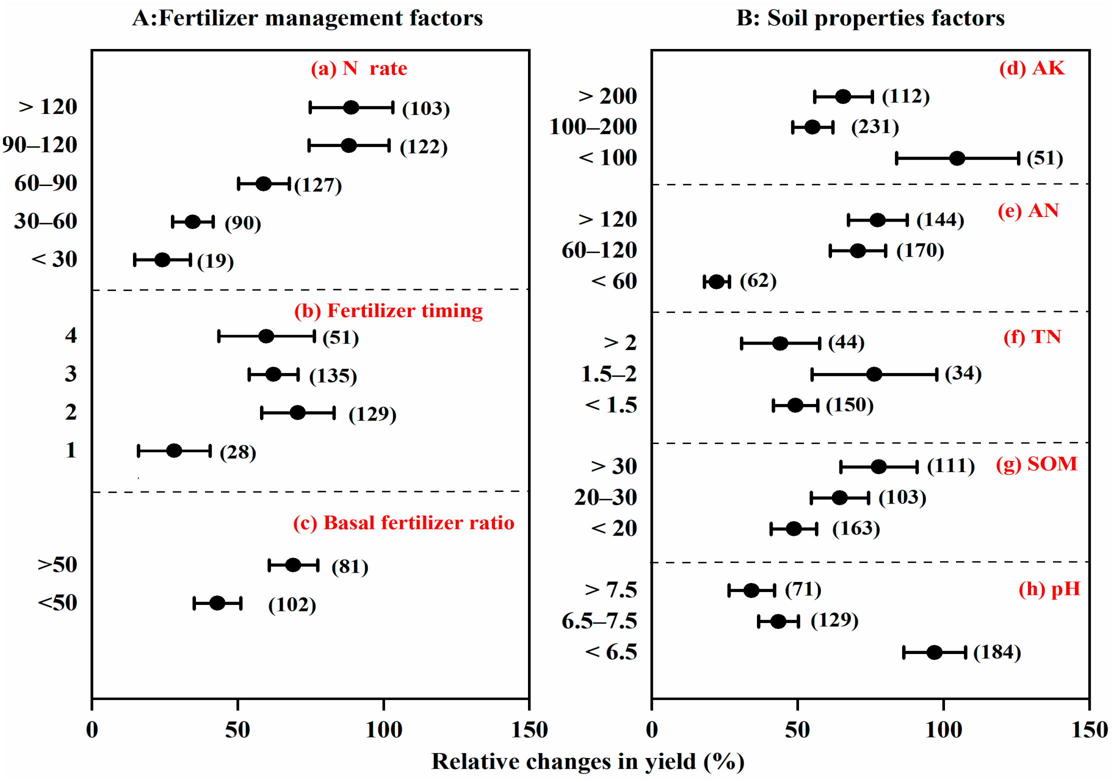

Figure 3. The effect of N fertilization on tobacco yields as affected by fertilizer management factors (**A**), and initial soil factors (**B**); NR: nitrogen rates (kg hm^{-2}); BFR: basal fertilizer ratio (%); AK: available potassium (mg kg^{-1}); AN: available nitrogen (mg kg^{-1}); TN: total nitrogen (g kg^{-1}); SOM: soil organic matter (g kg^{-1}). The error bar and dot represent 95% confidence interval and increase rate, respectively. The number at the right of the error bar indicates the number of samples.

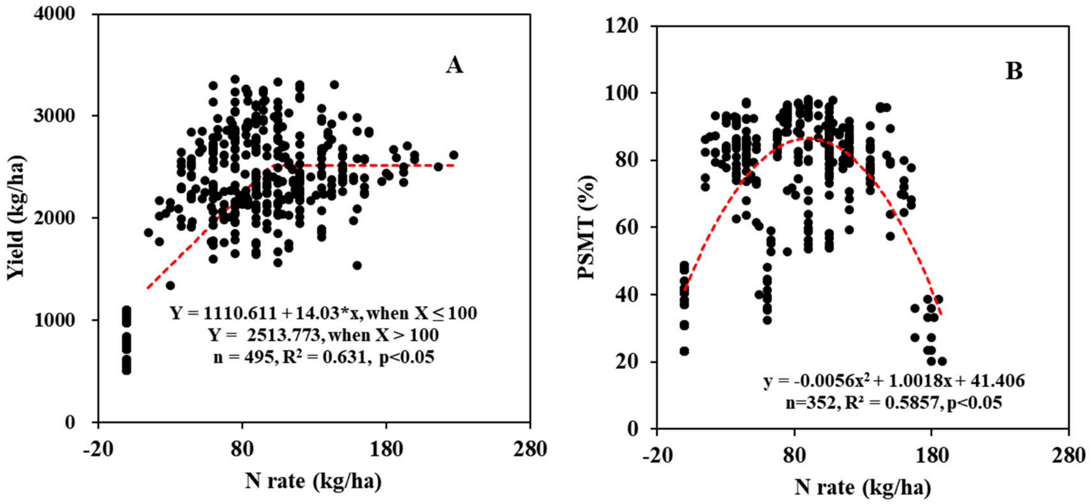

Figure 4. Relationship between N rate and flue-cured tobacco yield (**A**) and leaf grades in the proportion of superior and medium tobacco (PSMT) (**B**).

The influence of edaphic factors on the impact of N fertilization on tobacco yield is illustrated in Figure 3B. At medium (100–200 mg kg^{-1}) and high (>200 mg kg^{-1}) soil AK content, the yield response was notably lower, at 55.21% and 65.71%, respectively. However, the highest yield response (104.83%) was observed at a lower soil AK content (<100 mg kg^{-1}). The yield response ratio exhibited a significant increase with higher soil AN and SOM. For instance, when the soil AN content was <60, 60–120, and >120 mg kg^{-1}, the crop yield increment was 22.3%, 70.69%, and 77.54%, respectively. The highest yield response was recorded at SOM > 30g kg^{-1} (77.89%), followed by 20–30 mg kg^{-1} (64.54%), and <20 mg kg^{-1} (48.74%). In terms of soil pH, the crop yield increase was 34.24% in alkaline (>7.5), 43.46% in neutral (6.5–7.5), and 97.01% in acidic (<6.5) soils. The highest yield response was observed with soil N content of 1.5–2 g kg^{-1} (76.35%), followed by <1.5 g kg^{-1} (49.26%), and >2 g kg^{-1} (44.16%).

3.3. Influence on Leaf Grades in the Proportion of Superior and Medium Tobacco (PSMT) by Fertilizer Management and Initial Soil Properties

Nitrogen fertilization significantly influenced the leaf grades in PSMT, as dictated by fertilizer management (Figure 5A). The impact of N fertilization on PSMT was notably affected by N application rates. The maximum PSMT response was noted at N application rates of 90–120 kg ha^{-1} (26.77%), while the minimum was observed at N application rates exceeding 120 kg ha^{-1} (17.57%). However, these two groups were statistically indistinguishable. Similarly, the highest PSMT response was detected when N was applied twice (40.84%), followed by three times (18.38%) and once (14.51%). A comparatively lower yield response was observed with four applications (13.44%). No significant differences were found between the groups (i.e., one, three, or four times). A more pronounced effect of N fertilization on tobacco PSMT was observed with a basal fertilizer ratio (BFR) greater than 50% (an increase of 33.64%). Regression analysis of the PSMT in proportion to superior and medium tobacco (PSMT) and N rate demonstrated quadratic relationships (R^2 = 0.586, n = 352), as depicted in Figure 4B. It was determined that an optimal nitrogen fertilization application rate is 90 kg per hectare.

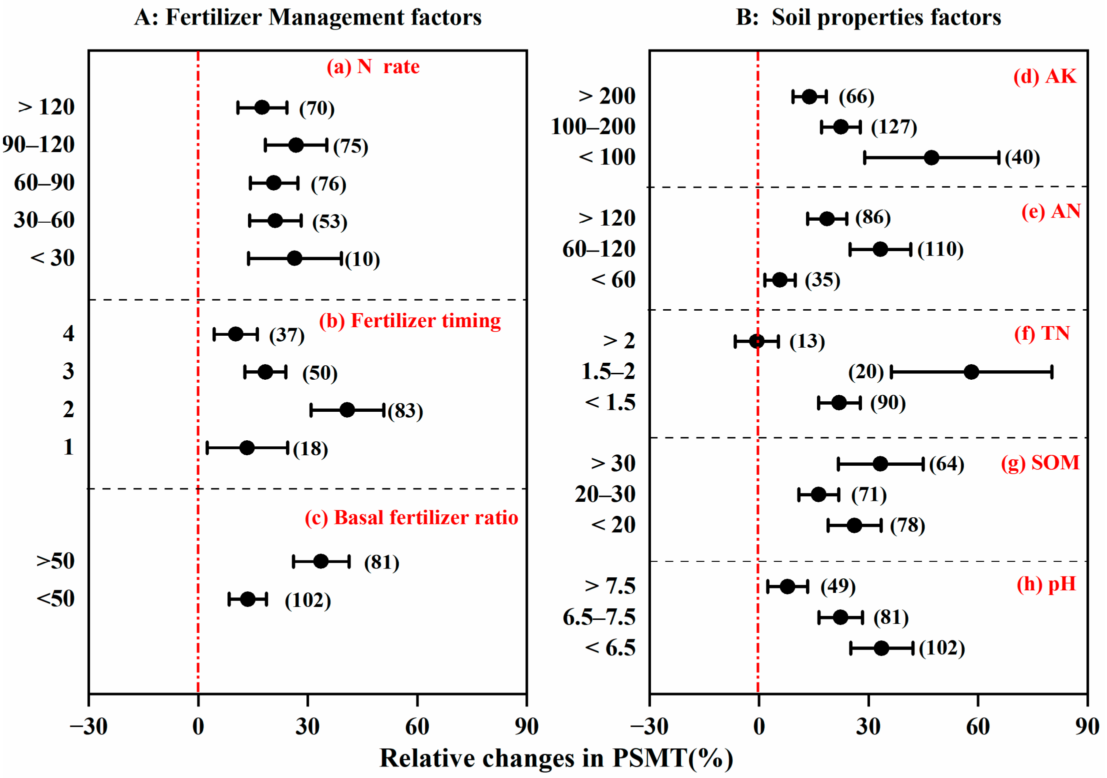

Figure 5. The effect of N fertilization on tobacco leaf grades in proportion of superior and medium tobacco (PSMT) is affected by fertilizer management factors (**A**) and initial soil factors (**B**).

The soil factors markedly impacted the influence of N fertilization on PSMTs in tobacco crops (Figure 5B). The most pronounced PSMT response was noted with a decrease in soil AK content (by 47.34%), followed by medium and high soil AK content (with increases of 22.42% and 13.88%, respectively). Similarly, PSMT exhibited a significant increase with lower and medium soil AN content (by 5.74% and 33.27%, respectively) but a sharp decline with higher AN content (by 18.65%). A positive response in PSMT was observed at low (25.7%) and medium (67.7%) soil TN content, while no significant difference was noted at high content. The highest PSMT response was detected in high SOM (43.2%), followed by low (24.9%) and medium SOM (16.9%). Higher PSMT was observed in alkaline (>7.5), neutral (6.5–7.5), and acidic (<6.5) soils by 10, 25, and 44.3%, respectively. The response of PSMTs escalated with lower and medium TN content, peaking at medium TN content (58.12%), followed by lower TN (21.99%).

3.4. *Effect of N Addition on Leaf Nicotine as Influenced by Fertilizer Management and Edaphic Factors*

The timing of fertilizer application significantly influenced the nicotine content in tobacco (Figure 6A). The maximum nicotine response was noted with four applications of nitrogen (fertilizer timing), yielding a rate of 70.93%. This was followed by one application at 52.72% and three applications at 52.16%. In contrast, the group that received two applications demonstrated a comparatively lower nicotine response of 26.97%. A marked increase in the nicotine content response to nitrogen (NR) was observed, peaking at an NR > 120 kg hm^{-2} (72.76%). The impact of nitrogen fertilization on tobacco nicotine content was more pronounced when the basal area ratio (BAR) was less than 50% (an increase of 54.09%), followed by < 50% (an increase of 35.14%). No significant difference was observed between these two groups. Stepwise regression analysis revealed that factors related to fertilizer management, such as N application rates, fertilizer timing, and basal fertilizer ratio, positively affected leaf nicotine content, with regression coefficients of 0.266, 0.267, and 0.302, respectively (Table 1).

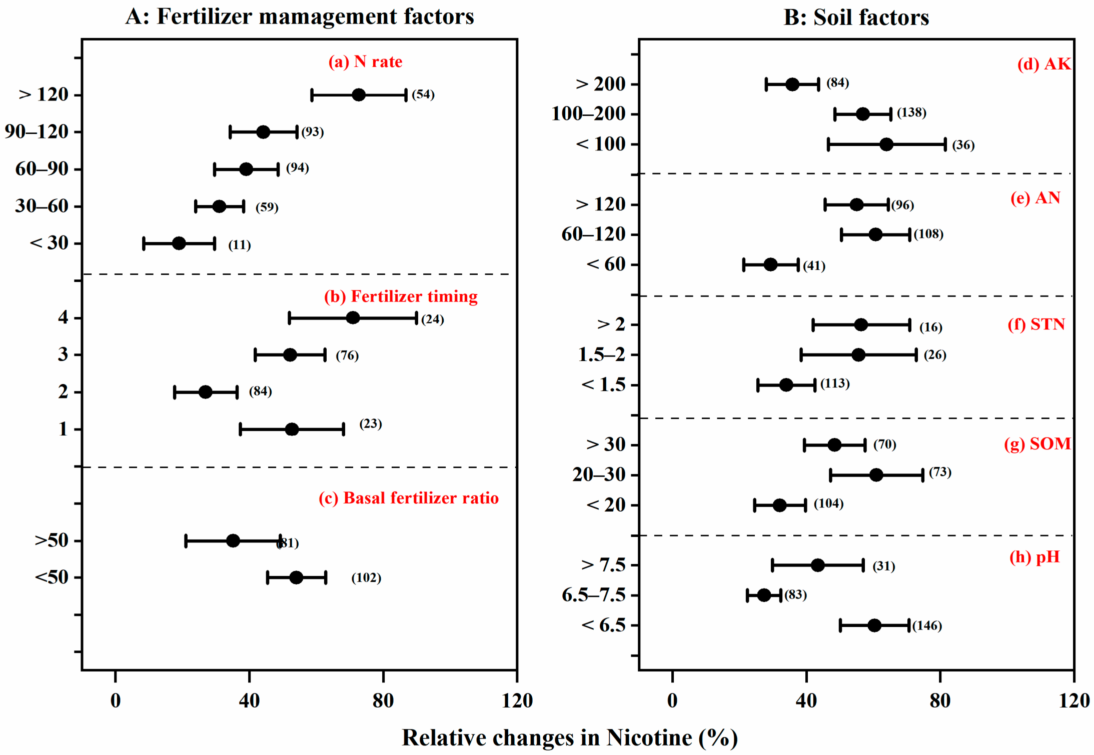

Figure 6. The effect of N fertilization on tobacco leaf nicotine content is affected by fertilizer management factors (**A**), and initial soil factors (**B**).

Table 1. Regression coefficients of nicotine LN (RR) and fertilizer management factors, initial soil factors model based on the multiple stepwise linear regression analysis.

Classification	**Explanatory Variable**	**Nicotine Model**		
		Regression Coefficients	**Standard Error**	***p***
Fertilizer management factors	N application rate	0.266	0.001	0.008 **
	N timing	0.267	0.044	0.011 *
	Basal N application ratio	0.302	0.001	0.02 *
	$R^2(p)$	0.204 (0.000)		
Initial soil factors	AK	−0.292	0.001	0.001 **
	AN	0.400	0.001	0.000 **
	TN	0.246	0.091	0.016 *
	SOM	-	-	-
	pH	-	-	-
	$R^2(p)$	0.343(0.000)		

Dependent variable: Nicotine LN (RR); * $p < 0.05$ ** $p < 0.01$. Note: abbreviations: NR: nitrogen rates (kg hm^{-2}); FT: fertilizer timing, BFR: basal fertilizer ratio (%); AK: available potassium (mg kg^{-1}); AN: available nitrogen (mg kg^{-1}); TN: total nitrogen (g kg^{-1}); SOM: soil organic matter (g kg^{-1}).

Nitrogen fertilization positively influenced tobacco nicotine content, with significant edaphic factors playing a role (Figure 6B). The impact of nitrogen on nicotine content diminished as soil K content increased. The most pronounced response was noted at low K levels (64% increase), followed by medium (56.9% increase) and high (35.84% increase). A notable rise in nicotine content was observed with soil AN, SOM, and TN at lower to medium levels, while a minor decrease in nicotine was noted at higher levels. Increases of 27.36%, 43.44%, and 60.36% were recorded in neutral (6.5–7.5), alkaline (>7.5), and acidic (<6.5) soils, respectively. Stepwise regression analysis revealed that initial soil AN and TN had a positive influence on leaf nicotine content, with regression coefficients of 0.4 and 0.246, respectively. In contrast, the AK regression coefficient was −0.292 ($p < 0.01$), indicating a significant positive effect of soil AK on nicotine content (Table 1).

3.5. Effect of N Fertilization on Leaf Nitrogen Content, as Influenced by Fertilizer Management and Edaphic Factors

N fertilization significantly influences the TN content of tobacco leaves, a phenomenon largely affected by fertilizer management (Figure 7A). The most pronounced response to N fertilization was observed with four applications of N (48.03%), followed by three (46.36%) and one application (25.13%). In contrast, two-time applications demonstrated a comparatively lower response (17.19%). A significant increase in leaf N content was noted at a higher nitrogen rate, although no significant variation was observed between groups. The impact of N fertilization on leaf TN was more pronounced at BFR < 50% (an increase of 34.2%), followed by >50% (25.77%). Stepwise regression analysis revealed that the rate of N application, the timing of fertilizer application, and the basal fertilizer ratio positively influenced the nitrogen content of tobacco leaves, with regression coefficients of 0.267 and 0.236, respectively (Table 1).

Under nitrogen fertilization, edaphic factors positively influenced leaf nitrogen content (Figure 7B). The response of TN in tobacco leaves was amplified with the increase in soil content of AK, AN, TN, and SOM. The highest responses (45.67%, 36.65%, 46.6%, and 41.74%, respectively) were observed in nutrient-rich soils. A decrease in the response of leaf nitrogen to pH was noted (Figure 7h). The highest response was found in acidic soils (35.03%), followed by neutral (27.11%) and alkaline soils (22.06%). A regression analysis was conducted between the effects of leaf nitrogen content and soil factors (pH, SOM, TN, AN, AK). Soil pH and AK were incorporated into the model. The regression coefficients for pH and AK were −0.256 and −0.251, respectively. This indicates a negative correlation between the effect on leaf nitrogen content and both soil pH and AK (Table 1).

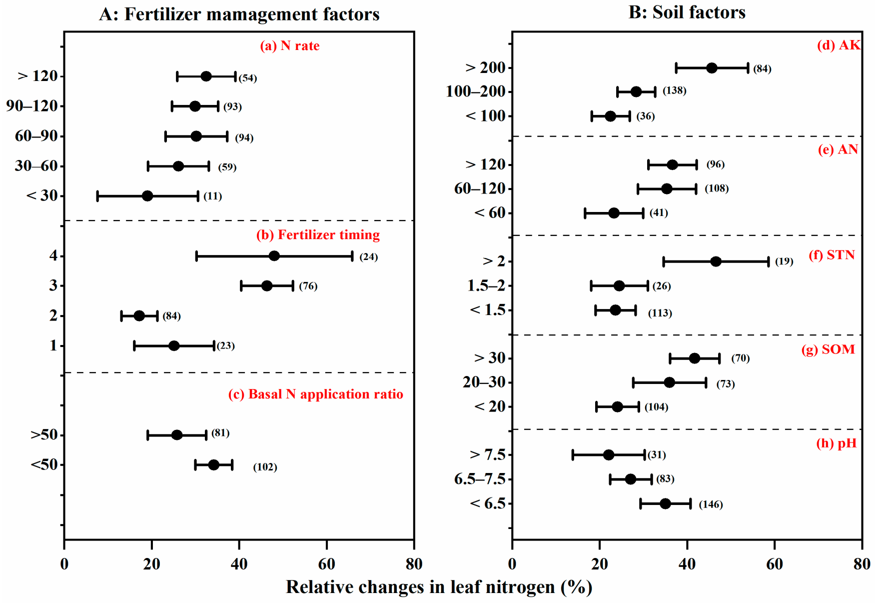

Figure 7. The effect of N fertilization on tobacco leaf nitrogen content is affected by fertilizer management factors (**A**), and edaphic factors (**B**).

3.6. The Relative Importance of Variables on Flued-Cured Yield and Leaf Grades in the Proportion of Superior and Medium Tobacco

In total, 86.98% and 14.02% of the variance in crop yield was attributed to soil and fertilizer management factors, respectively (Figure 8A). The soil TN, pH, and nitrogen application rate were found to be particularly significant in explaining the variation in crop yield, accounting for approximately 23.20%, 49.8%, and 12.37%, respectively. In contrast, 97.2% and 2.86% of the variance in leaf grades (PSMT) was explained by soil factors and fertilizer management strategies, respectively (Figure 8B). The soil AK and pH were identified as particularly important in explaining yield variation, accounting for about 63.26% and 28.80%, respectively.

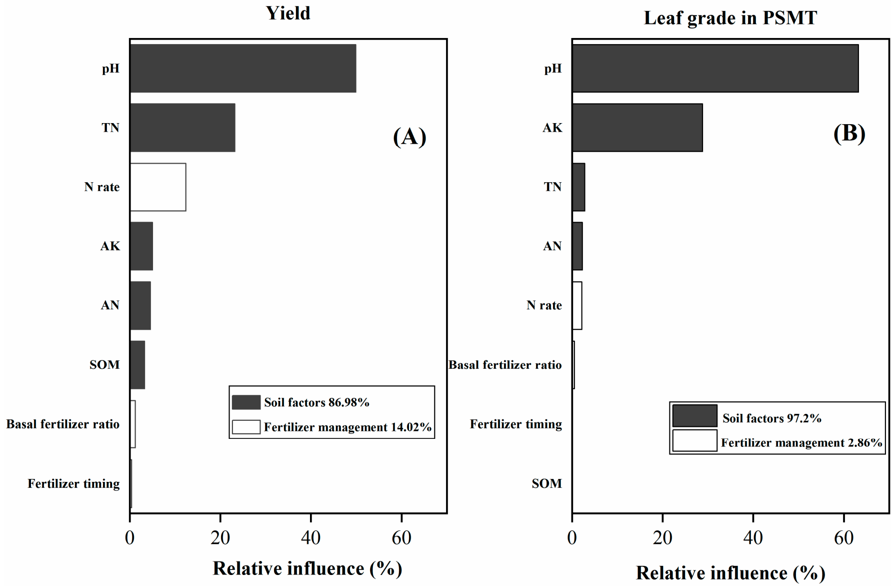

Figure 8. The relative importance (%) of variables for crop yield (**A**) and leaf grades in the proportion of superior—medium tobacco (**B**) response as affected by nitrogen fertilizer rates.

4. Discussion

4.1. Effect of Fertilizer Management on the Yield of Flue-Cured Tobacco

Nitrogen, as the most critical macro-nutrient, significantly influences the yield and quality of flue-cured tobacco [35,36]. Although nitrogen fertilizer is commonly employed in agriculture to boost crop production and economic benefits, its excessive, inefficient, and imbalanced application can result in various environmental and economic consequences [9,12]. This meta-analysis demonstrates that the FCT yield follows a linear plus plateau model, with the nitrogen application rates, reaching a peak response at a nitrogen rate of 100 kg ha^{-1} (Figure 4A). This finding is consistent with prior studies, which observed an initial increase followed by a decrease in FCT yield within a specific range of nitrogen fertilization applications [7]. The primary reason is that an excess of nitrogen leads to increased soil acidity, which in turn increases the levels of soluble manganese and aluminum in the soil. This can result in plant toxicity and nutrient imbalances, ultimately leading to shallow and stunted roots, thus negatively impacting the growth of tobacco plants [20,35]. Additionally, an excessive use of nitrogen fertilizer can lead to an increase in nitrogen metabolism and delayed maturation of tobacco leaves, resulting in poor-quality flue-cured tobacco [37].

Excessive application of base fertilizer or premature top dressing can result in significant nitrogen losses from the soil, thereby diminishing fertilizer efficiency and escalating environmental pollution. López-Bellido et al. underscored that the timing and proportion of base fertilizer are more critical than optimizing nitrogen application [38]. A varied fertilizer supply can augment nutrient absorption by tobacco [22]. Our findings align with these observations, demonstrating that tobacco yield escalates with a higher base fertilizer ratio and increased fertilization frequency ($p < 0.01$). The most substantial increase in tobacco yield (70.6%) was observed when the BFR exceeded 70% (Figure 3c). In line with our results, intensifying root-zone nutrient supply can facilitate crop nutrient absorption [15]. We hypothesize that this phenomenon may be attributed to nitrogen uptake by tobacco plants predominantly occurring during the early stages of crop growth. Consequently, applying a substantial amount of nitrogen at an early stage can amplify fertilizer absorption, thereby enhancing yield and recovery efficiency [39].

Improper timing of nitrogen (N) application significantly impacts the yield of tobacco plants. This analysis revealed that split N application resulted in a dramatic yield increase compared to one-time fertilizer application, with the maximum yield response observed when applying twice (an increase of 70.6%) before decreasing with the timing of fertilizer application (Figure 3b). In accord with our findings, Belete et al. reported that splitting nitrogen applications had greater impacts on yield than one-time application in wheat [40]. This may be due to the fact that better synchronization between high plant N demand and sufficient N availability in the soil at appropriate growth stages accounts for the higher yield response under split applications [41]. Interestingly, one-time root zone fertilization has also been demonstrated to successfully enhance the increase in the production of cotton and rice [42,43]. This suggests that precise nitrogen management in the root zone could provide a higher intensity of nitrogen supply, promoting efficient nutrient absorption by crops [44]. However, there are limited studies (n = 28) on the one-time fertilization of flue-cured tobacco (Figure 3b), suggesting that future studies should focus on this aspect of tobacco yield and quality.

4.2. Edaphic Factors Affecting Yield and Quality of Flue-Cured Tobacco

Soil properties play a pivotal role in determining the significance of soil for crop production and quality [45]. The most pronounced yield response was observed at a SOM level exceeding 30 g kg^{-1}, resulting in a 77.89% increase (Figure 3g). This can be attributed to the fact that elevated soil SOM content enhances water-holding capacity and soil structure, subsequently leading to enhanced crop growth and yield [46]. Furthermore, the peak yield response (76.35% increase) was noted at moderate soil TN levels (1–2%), which then diminished when the initial soil TN exceeded 2% (Figure 3f). This is primarily because early N uptake in tobacco predominantly involves soil mineralization, with over

70% of N sourced from the soil [1]. Given that soil nutrient levels are already high, tobacco attains a considerable level of productivity and quality without additional N fertilizer, making further enhancement in yield and quality challenging [9]. Additionally, higher yield responses were observed in acidic soils (Figure 3h). This could be attributed to the fact that the acidic soils in southern China possess a greater potential for N mineralization, thereby providing more available N for uptake and utilization by tobacco plants [47]. Another plausible explanation could be that Mg and Ca present in alkaline soil inhibit plant nutrient absorption, leading to reduced yields in northern regions [48].

4.3. Effect of Fertilizer Management on the Nicotine Content of Flue-Cured Tobacco

The concentration of nicotine serves as a crucial metric for assessing the quality of tobacco, exhibiting a strong correlation with the quantity of nitrogen supplied [49–51]. The primary accumulation of nicotine in tobacco leaves transpires predominantly during the latter stages of growth, notably after the removal of the apex [52]. The primary determinant of nicotine synthesis in flue-cured tobacco is the intensity of nitrogen supply from both fertilizer and soil. This meta-analysis reveals a significant upsurge in tobacco nicotine content in response to nitrogen application rates (N rates), soil AN, and TN (Figure 6a,e,f). Our results align with recent studies, which demonstrate that nitrogen application rates markedly enhance the content of total nitrogen and nicotine when compared to N0 [9]. We also noted a more pronounced increase in nicotine when the nitrogen timing was at four times (Figure 6b). A potential explanation for this could be attributed to the split application of fertilizer, which augments the intensive supply of nitrogen during the later stages of tobacco production, thereby leading to an increased nicotine content [53]. Additionally, we observed that tobacco nicotine content was significantly influenced by nitrogen fertilization when the basal fertilizer ratio (BFR) exceeded 50% (Figure 6c). This observation aligns with previous research demonstrating a positive correlation between high nitrogen supply and FCT nutrient absorption [54]. We hypothesize that this may be due to the application of high levels of nitrogen fertilizer during the early stages of curing, which stimulates the growth of the flue-cured tobacco and consequently leads to a significant increase in yield. The results of the stepwise regression demonstrated a positive correlation between FCT nicotine content and fertilizer management, including nitrogen application rate, fertilizer timing, and basal fertilizer application ratio. Therefore, we propose a model for fertilizer management based on the effect of nicotine content, represented by the formula Nicotine ($lnRR$) = $0.266 \times \mathrm{R} + 0.267 \times \mathrm{FT} + 0.302 \times \mathrm{BFR}$ ($R^2 = 0.204$, $p < 0.01$).

4.4. Effect of Soil Factors on the Nicotine Content of Flue-Cured Tobacco

SOM serves as a vital reservoir and primary nutrient source for plants, while also acting as a significant indicator of soil health and environmental quality. The influence of N fertilization on nicotine content was observed to be substantial when the SOM content ranged between 20–30 g kg^{-1}. However, this effect diminished once the SOM content surpassed this range, as depicted in Figure 6g. A positive correlation was noted between nicotine content and soil total nitrogen (TN), with the most pronounced response observed at initial TN levels exceeding 2 g kg^{-1} (a 56.43% increase) (Figure 6f). This surge in tobacco nicotine content could potentially be attributed to the high concentration of nitrogen present in the soil, particularly during the advanced stages of tobacco growth [9,18,53]. Furthermore, we noted that the maximum nicotine response (60.67% and 60.97% increase, respectively) was detected at moderate soil AN (60–120 g kg^{-1}), as shown in Figure 6e, which subsequently decreased beyond these thresholds (not statistically significant). This phenomenon may be because elevated soil AN and SOM levels enhance the soil conditions for tobacco cultivation, thereby promoting improved crop growth and yield [46]. We also observed a decrease in nicotine content correlating with soil AK content. Our findings align with a recent study suggesting that potassium might influence nicotine accumulation in tobacco leaves by regulating the expression of the root putrescine N-methyltransferase gene [55–57]. Results from the stepwise regression analysis (Table 1) demonstrate that nicotine content in tobacco leaves is positively associated with soil AN and TN content, but negatively correlated with soil AK content. To enhance the quality of tobacco leaves, it is recommended that soils with higher potassium levels and lower nitrogen levels be chosen for planting.

5. Conclusions

Tobacco, as an important industrial crop, has an irreplaceable supporting role for the national economy. We need to develop the tobacco industry on the basis of giving priority to guaranteeing food security. In this meta-analysis, we analyze the impacts of nitrogen fertilization on the production and quality of flue-cured tobacco in China. On one hand, our findings indicate that N fertilizer management and soil factors equally contribute approximately 60% to gains in yield, respectively. PSMT shows increments of approximately 24% due to those two aspects, respectively, indicating that both of them also play important roles on quality improvement. Notably, the most determinant factors of influences on yield are the N application rates, soil pH, and TN content, while the initial soil pH and AK content are the key factors that shape the effects of N application on leaf quality (PSMT). In consideration of higher yield and better quality, it is crucial to give preference to slightly acidic soil for tobacco cultivation. This practice is essential for selecting the optimal soil pH that supports the healthy growth of tobacco plants and enhances the quality of the leaf yield. Based on linear plus plateau model regression analysis, the optimal nitrogen fertilizer application rates are estimated to be 100 kg per hectare for maximum yield, and the quadratic models showed 90 kg per hectare for optimal PSMT. Therefore, balancing both yield and quality, as well as economic viability, we recommend optimal N application rates ranging from 90 to 100 kg per hectare.

On the other hand, stepwise regression modeling reveals that nicotine content is positively influenced by fertilizer management factors such as nitrogen application rate, nitrogen timing, and basal fertilizer ratio, as well as soil AN and TN. However, nicotine content is negatively correlated with soil AK. In general, SOM is crucial for plant growth and soil health by buffering pH and offering vital nutrients (especially N from soil mineralization). Although the increment of yield was observed in high SOM content of soil, the N absorption in the leaves used for nicotinic synthesis also increased in the meanwhile, which serves a disadvantage factor for tobacco quality. Therefore, in order to optimize both yield and quality of tobacco plants, a moderate level of SOM is necessary for tobacco planting. Overall, to improve leaf quality, reduce nicotine content, and enhance economic as well as environmental gains in China, effective N management is crucial, particularly in slightly acidic soils enriched with AK and with lower N supply capacity.

Our national meta-analysis suggests that site-specific factors have an impact on the yield and quality of flue-cured tobacco. Despite some limitations, such as the lack of data for the assessment of certain variables, precipitation, temperature, and other relevant factors should be taken into account for sustainable tobacco production. Future studies are urgently needed to fully understand their impact. Notably, one-time fertilization management in the rootzone is gaining more attention in China due to the evident drawbacks of conventional fertilization processes. However, only 28 observations from 9 studies covering one-time fertilization were included in our database, which may have led to some controversial results based on the inadequate and inconsistent data. Thus, under friendly environmental conditions, further studies are necessary to not only improve yield and quality but also to reduce fertilizer application rate and frequency.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14071365/s1, Figure S1: Flowchart diagram of the process applied for the meta-analysis; Table S1: Bibliography for studies included in the meta-analysis.

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