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# Multiobjective Optimization of Chlorine Fertilization Enhances Yield and Quality in Cigar Tobacco

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## Abstarct

Chlorine (Cl) is a critical but understudied micronutrient of cigar tobacco (*Nicotiana tabacum* L.), influencing both yield and leaf quality. This study evaluated the effects of exogenous Cl application on yield, physical traits, and chemical quality of two cigar tobacco varieties, CX-26 and CX-14, under field conditions in China. A six-level Cl gradient was applied, and phenotypic and chemical analyses were conducted over two consecutive years. Principal component analysis was used to synthesize multiple chemical quality indicators into a single comprehensive score, and regression modeling and multiobjective optimization were used to determine optimal Cl application rates that balance yield and quality. Results showed different varietal responses. CX-26 benefited from moderate Cl input, achieving peak growth and yield at intermediate rates, whereas CX-14 was more sensitive to Cl, with growth and yield reduced at higher rates. For both varieties, the Cl content increased with Cl application, concurrently reducing the potassium-to-chlorine (K/Cl) ratio. Glycoalkaloid content and reducing sugar were also affected by Cl addition but their responses varied with varieties. The comprehensive chemical quality score peaked at intermediate Cl levels but decreased sharply at high Cl rates, underscoring the detrimental impact of excessive Cl on the overall chemical quality of cigar tobacco. Based on the combined evaluation of yield and quality, the recommended Cl application rates were 47.43 kg/hm$^2$ for CX-26 and 44.50 kg/hm$^2$ for CX-14. This study pioneers the multiobjective optimization of cigar tobacco yield and chemical quality, offering practical Cl fertilization guidance and new insights into Cl nutrition.

Keywords:Chlorine fertilization ; Cigar tobacco; Yield; Quality; Multiobjective optimization

## Introduction

Chlorine (Cl) is an essential nutrient for the growth and development of tobacco, playing a direct role in plant photosynthesis and serving as a key factor in the physiological functioning of tobacco plants. Adequate Cl supports physiological metabolism, increases leaf protein content, and contributes to potassium (K) accumulation in tobacco leaves, which is an important aspect of plant development(Ishizaki and Akiya, 1978). Despite its significance, tobacco has long been considered a Cl-sensitive crop, leading to cautious use of Cl-containing fertilizers. This caution arises from the plant's tendency for luxurious absorption, as excessive Cl uptake can adversely affect crop health. Therefore, a comprehensive understanding of Cl's impact on tobacco growth and quality is critical for advancing cultivation practices and improving leaf quality.

Appropriate Cl levels promote tobacco growth through several physiological mechanisms, as observed in other crops(Rosales et al., 2020). Cl is indispensable in the water-splitting reaction during photosynthesis, enhancing photosystem activity and light energy conversion efficiency. This facilitates increased accumulation of photosynthetic products and supplies the energy and materials required for robust growth(Bové et al., 1963). Additionally, Cl regulates stomatal movement. Under environmental stress such as drought, moderate Cl levels help maintain optimal stomatal aperture, ensuring carbon dioxide supply while minimizing water loss and enhancing drought resistance(Zhang et al., 2022). Huang et al.(Huang et al., 2022) demonstrated that chlorine dioxide treatment significantly alleviated drought-induced premature senescence in tobacco plants.

Conversely, excessive Cl inhibits tobacco growth by damaging leaf cell structure and function, impairing chlorophyll synthesis and stability, and reducing photosynthetic efficiency, ultimately leading to toxic symptoms and diminished yield and quality(Hoyos C et al., 2015; Wu et al., 2024). Zehler et al.(Zehler et al., 1981) classified cured tobacco leaves by Cl content as excellent (<1%), good to satisfactory (1%–2%), unsatisfactory (2%–3%), and poor (>3%). High Cl levels reduce leaf flammability and increase hygroscopicity, posing challenges during drying(Ishizaki and Akiya, 1978). Excess Cl results in muddy, uneven leaf color(McCants and Woltz, 1967) and increases Cl content, while elevates reducing sugars(Tiecher et al., 2023). Due to these potential negative effects, Cl management remains a focus for tobacco agronomists and producers. Although research on Cl's effects on tobacco has advanced, recommended application rates are typically based on yield or a

single quality indicator. Few studies have determined optimal exogenous Cl rates by integrating both yield and quality metrics. Additionally, most existing research focuses on flue-cured tobacco, with limited attention to cigar tobacco.

Cigar tobacco (*Nicotiana tabacum* L.) is distinguished by its cultural heritage and unique flavor profile. In recent years, rising cigar demand has driven expanded cultivation worldwide, with major producers including Brazil, Cameroon, Cuba, the Dominican Republic, Honduras, Indonesia, Mexico, Nicaragua, the United States, and China. In China, research on cigar tobacco cultivation began relatively recently, creating an urgent need for region-specific nutrient management(Chen et al., 2024).

This study aims to systematically investigate the effects of Cl application on the yield, physical properties, and chemical quality of cigar tobacco in China. Furthermore, optimal Cl rates are determined by jointly considering yield and quality indicators through a multiobjective optimization approach. This work provides both theoretical and practical guidance for scientific fertilization practices in cigar production, supporting the sustainable and efficient development of the industry.

## Methods

### Study sites

The experiment was conducted in 2022 and 2023 in Xijiadian Town, Danjiangkou, northwestern Hubei Province (32°46'N, 111°10'E). This area serves as a critical link between the Jianghan Plain and the Qinba Mountains. It has a subtropical monsoon climate, with annual average temperature of 21.6°C and annual precipitation of 750–900 mm. Two fields were used for planting two cigar varieties separately, with corn as the previous crop.

### Experimental Design

Six exogenous Cl addition levels (0, 22.5, 45, 67.5, 90, and 112.5 kg/hm², labeled Cl0–Cl112.5) were established using a dry blend containing potassium chloride (KCl) and potassium sulfate ($K_2SO_4$) with total K input held constant across treatments. Ammonium sulfate was used as the nitrogen (N) source and dihydrogen phosphate as the phosphorus (P) fertilizer. N, P, and K fertilization rates conformed with local practice. N fertilizer was applied in two splits: May 15 and June 3 in 2022, and May 15 and June 2 in 2023, while the full dose of P, K, and Cl was applied as the basal fertilizer. Each treatment was replicated three times in a randomized complete block design. Two cigar tobacco (*Nicotiana tabacum* L.) varieties, Chuxue 26 (CX-26) and Chuxue 14 (CX-14), developed and provided by the Hubei Academy of Tobacco Sciences (Wuhan, Hubei, China), were used in the experiment. Transplanting was conducted on April 19, 2022, and April 16, 2023. Field management practices, including soil preparation, thinning, seedling replenishment, pest control, and insect trapping, were performed in accordance with standard agronomic requirements for cigar tobacco cultivation.

### Measurements

#### Soil properties

Pre-planting soil samples (0–20 cm) in 2022 were collected using an "S"-shaped pattern, air-dried, and sieved. The soil pH value was measured using a pH electrode at a water/soil ratio of 2.5:1(Xu et al., 2006); organic matter was determined using the chromic acid titration method(Salomon, 1953); the total N was determined using the Kjeldahl acid-digestion method(Alcock, 1946); the Olsen-P value was measured using the NaHCO3 method(Bao, 2000); the available K was measured using a flame photometer method(Bao, 2000); water-soluble Cl by silver nitrate titration(Taseska, 1989). The soil properties for CX-26 and CX-14 experiments are presented in Table 1.

**Table 1** Soil properties for CX-26 and CX-14 experiments.

| Cultivar | Organic matter (g/kg) | Total N (g/kg) | Available P (mg/kg) | Available K (mg/kg) | PH | Soluble Cl (mg/kg) |
|---|---|---|---|---|---|---|
| CX-26 | 13.97 | 0.68 | 17.69 | 222.40 | 6.63 | 21.12 |
| CX-14 | 9.71 | 0.68 | 13.50 | 229.50 | 6.96 | 20.09 |

#### *Physical properties, dry matter, and yield*

At harvest, three representative plants were selected from each plot. Plant height, maximum leaf length and width, and stem diameter were measured using a ruler and caliper following standard tobacco agronomic protocols. Harvesting followed an 'under-ripe' method, starting from the bottom of the plant and proceeding upwards. Approximately three to four leaves were harvested every seven days, leaving two to three basal leaves unharvested. After harvest, both cigar leaves and stems were oven-

dried at 105°C for 30 minutes to remove surface moisture, then further dried at 60°C until a constant weight was reached. The dry weight of leaves and stems was then measured separately. The aboveground dry matter accumulation was determined as dry weight of the sum of leaves and stems per unit are. Total yield was expressed as dry weight of all the harvested leaves per unit area.

### *Chemical composition analysis*

Chemical composition analysis of cigar leaves included determination of nicotine, total sugar, reducing sugar, Cl-, total N, and K contents. Selected leaf samples were dried, ground, and passed through a 0.45 mm sieve before being precisely weighed at 0.0500 g for analysis. Total N content was determined via continuous flow analysis(YC/T 161-2002 )and K content was measured using a flame photometer(YC/T 173-2003 ). Reducing sugar, nicotine, and Cl- were quantified using continuous flow methods, based on standard tobacco analysis procedures(YC/T 159-2002 , YC/T 160-2002 , YC/T 162-2011 ). The glycoalkaloid ratio is the ratio of total sugar to nicotine, the K/Cl is the ratio of K to Cl, and the N-alkali ratio is the ratio of N to nicotine. Based on the $Cl^-$ content, Cl accumulation was calculated as dry matter content × $Cl^-$ content.

### *Principal component analysis*

Principal component analysis (PCA) is a multivariate statistical technique used to reduce the dimensionality of complex datasets by transforming multiple correlated variables into a smaller set of uncorrelated principal components(Demšar et al., 2013). These principal components are constructed as linear combinations of the original variables and are mutually independent, allowing for effective data interpretation with minimal loss of information. PCA is especially useful when the dataset contains variables with significant intercorrelation. In this study, PCA was applied to synthesize multiple chemical quality indicators into a comprehensive score, enabling an integrated evaluation of how exogenous Cl application affects the chemical quality of tobacco leaves.

Prior to conducting PCA, all chemical quality parameters were normalized using the Z-score method. In this study, PCA was performed on an m×n matrix X, with m treatment groups and n variables for each cigar variety. The component scores ($S_k$) for each measurement on component k (whose eigenvalues exceed unity) were computed. The weight ($W_k$) for the kth component was calculated as:

$$W_k = \frac{\lambda_k}{\sum_{j=1}^{j=n} \lambda_j} \quad (1)$$

where is the eigenvalue for kth principal component and is the sum of eigenvalues of n components with eigenvalues exceed 1. A final comprehensive chemical quality score (C) was computed for each treatment group with equation (2), providing a quantitative basis for comparison(Muema et al., 2018).

$$C = \sum_{k=1}^{k=n} W_k S_k \quad (2)$$

### *Regression modeling of chemical quality score and yield*

After deriving the comprehensive chemical quality score using PCA, quantitative relationships were established between the Cl application rates and two outcomes: the chemical quality score and cigar leaf yield. For each outcome, nonlinear regression model employing polynomial functions was constructed. Model performance was evaluated using the coefficient of determination ($R^2$) to ensure the reliability and accuracy of the regression fits. For each variety, the Cl application rate that maximizes either yield or chemical quality score was also determined by identifying the critical point of the fitted regression function.

### *Multiobjective optimization*

To determine the optimal Cl application rates that simultaneously maximize both yield and chemical quality, the two regression functions derived above were employed as objective functions within a multiobjective optimization framework. The problem was formulated as:

$$Maximize\ f1(x) = predicted\ chemical\ quality\ score \quad (3)$$

$$Maximize\ f2(x) = predicted\ yield \quad (4)$$

subject to:

$$0\ kg/hm^2 < x < 112.5\ kg/hm^2 \quad (5)$$

where x is Cl application rate.

Optimization was performed using the Non-dominated Sorting Genetic Algorithm II (NSGA-II), a widely recognized evolutionary algorithm for multiobjective optimization. The algorithm began by generating a random population of candidate Cl application rates within defined bounds and iteratively refined these candidates through tournament selection, simulated binary crossover, and polynomial mutation(Zheng et al., 2022). At each generation, non-dominated sorting was used to categorize solutions into Pareto fronts, while crowding distance helped maintain diversity among solutions. Key algorithm parameters, including population size, crossover probability, mutation probability, and the number of generations, were optimized based on preliminary experiments to achieve a balance between convergence and solution diversity.

The output of NSGA-II was a Pareto front representing trade-offs between chemical quality and yield across the Cl application range(On et al., 2024). From this set, the optimal solution was determined using a compromise programming approach, selecting the point closest to the ideal (i.e., maximum predicted quality and yield) in the normalized objective space as the recommended Cl application rate.

#### *Statistical analysis*

For each variety, the two-year data was categorized by Cl application rate, and the mean and standard deviation were computed for Cl application rate. Data analysis was performed in SPSS and graphs were plotted using Origin 2023b.

## Results

### Effects of exogenous Cl addition on cigar physical properties

The physical properties of CX-26 variety exhibited a unimodal response to increasing Cl addition. Leaf length, leaf width and plant height all increased with Cl application, reaching their peak at 67.5 kg/hm$^2$ before declining at higher rates. In contrast, high Cl level (Cl112.5) reduced plant height by 4 cm (a 3.43% decrease) and leaf width by up to 2.75 cm. The Cl45 treatment increased plant height by 3.33 cm and stem diameter by 1.47 mm.

The physical properties of CX-14 increasing continuously with Cl addition. At CI67.5 treatment, the leaf length and plant height reached the maximum, which were 6.69 % and 2.31 % higher than the Cl0 treatment, respectively. High Cl112.5 treatment reduced the stem diameter by 1.06 mm.

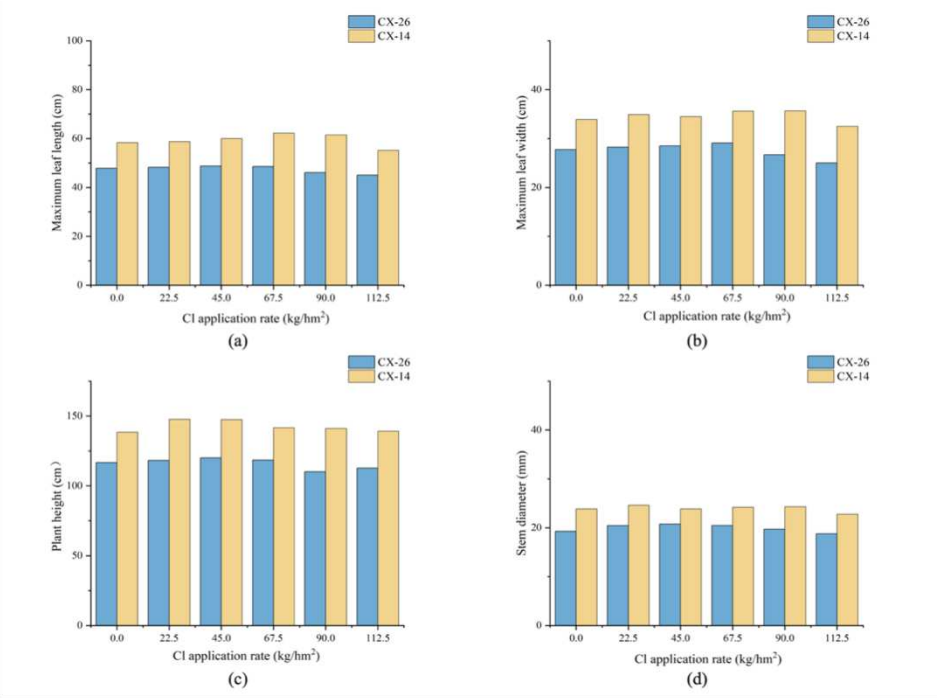



**Figure 1** Maximum leaf length (a), leaf width (b), plant height (c), and stem diameter (d) of cigar leaves under varying Cl application rates.

### Effect of exogenous Cl addition on aboveground dry matter and yield

Significant variety differences were observed in dry matter accumulation in response to exogenous Cl addition. In CX-26, increasing exogenous Cl addition led to a gradual decline in total aboveground dry matter (Figure 2 (a)). Each treatment group showed a 3.17%–18.29% decrease in aboveground dry matter compared to the Cl0 treatment. Leaf dry matter exhibited a unimodal pattern. At application rates of 22.5–90 kg/hm², leaf dry matter significantly increased by 32.14–125.29 kg/hm² (a 1.98%–7.71% rise), peaking in the Cl67.5 treatment. However, at the highest application rate (112.5 kg/hm²), leaf dry matter decreased by 79.22 kg/hm² (a 4.87% decrease) compared to the Cl0 treatment. Stem dry matter consistently declined with increasing Cl, decreasing by 12.39%–33.27%.

For CX-14, dry matter accumulation displayed a threshold effect. Total aboveground dry matter increased with Cl addition up to 45 kg/hm², but declined when rates exceeded this threshold (Figure 2 (b)). Notably, changes in dry matter were primarily driven by leaf dry matter accumulation, while stem dry matter varied much more widely than leaf dry matter.

For both cigar varieties, yield first increased and then decreased as exogenous Cl addition rose (Figure 3). The relationship between the Cl application rate and yield can be fit with a polynomial function. CX-26 achieved the maximum yield of 2061.52 kg/hm² at the Cl rate of 47.42 kg/hm², while the yield of CX-14 peaked at 2822.00kg/hm² at the Cl rate of 44.44 kg/hm².

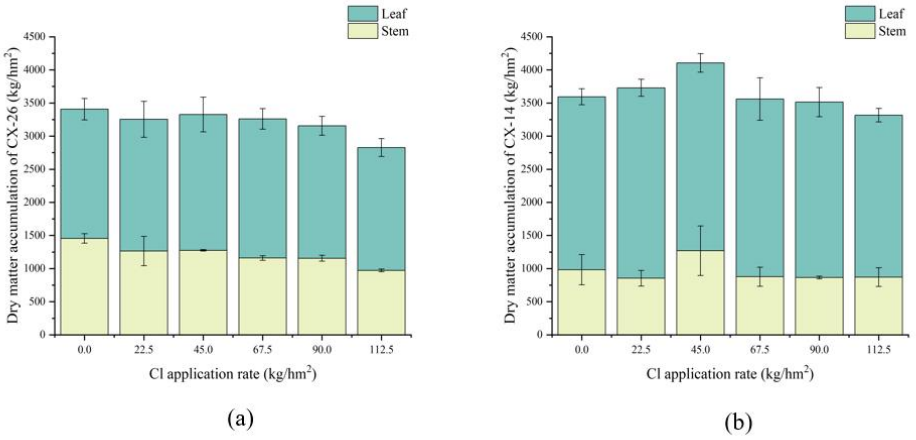



**Figure 2** Aboveground dry matter in cigar varieties CX-26 (a) and CX-14 (b) under varying Cl application rates

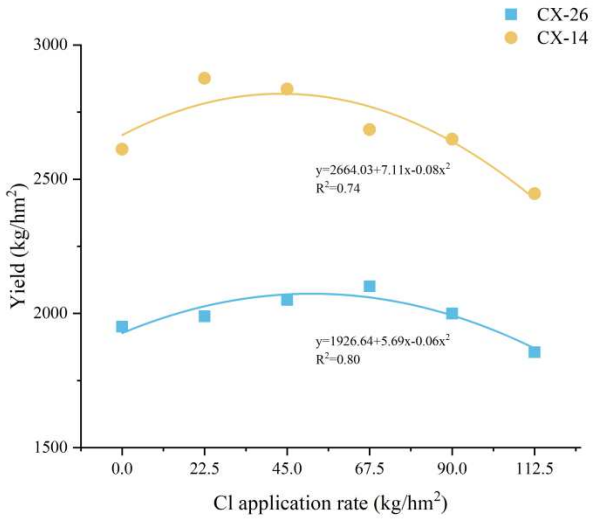



**Figure 3** Relationship between Cl application rates and yield.

### Effect of exogenous Cl addition on cigar Cl accumulation

Exogenous Cl addition affected total Cl accumulation differently in the two cigar varieties. In CX-26, total Cl accumulation showed a threshold response. It increased with Cl input up to 90 kg/hm², and then slightly decreased at higher rates (Figure 4 (a)). Organ-specific analysis showed that, compared to the Cl0 treatment total Cl accumulation under exogenous Cl treatments increased by 14.24%–42.03%. Leaf Cl accumulation rose by 10.98%–32.14%, while stem Cl increased by 1.91%–42.63%. Both stem Cl and total accumulation peaked at 90 kg/hm².

By contrast, CX-14 showed a continuous increase in total Cl accumulation with higher Cl additions (Figure 4 (b)). This trend was primarily due to increases in stem Cl, as leaf Cl levels remained relatively unchanged across treatments.

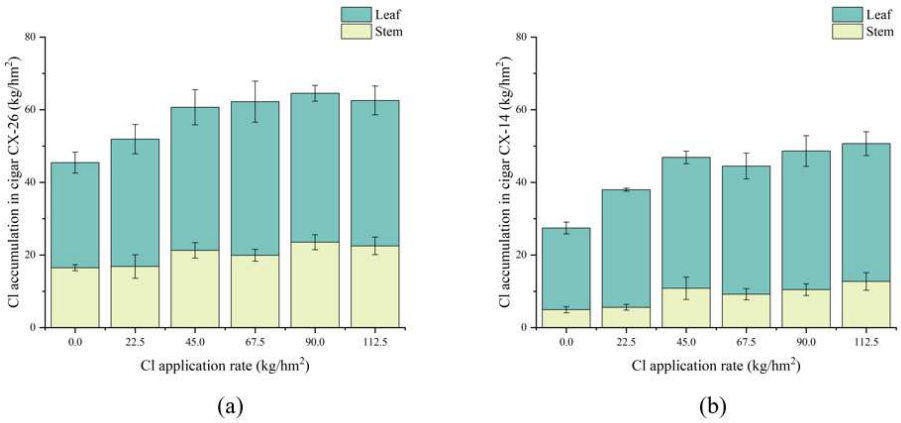



**Figure 4** Cl accumulation in cigar varieties CX-26 (a) and CX-14 (b) under varying Cl application rates

### Effects of exogenous Cl addition on chemical quality

Significant differences in chemical quality were observed between the two varieties. With increasing Cl addition, CX-26 showed dynamic shifts in chemical quality. Nicotine content increased from 4.78% to 4.92% and then decreased to 4.27%, and both reducing sugar and glycoalkaloid ratio increased first and then decreased at high Cl rates. The K/Cl ratio dropped from 0.89 to 0.60, indicating that Cl addition inhibited K accumulation. However, Cl addition did not affect total N content, and K content only slightly decreased at the Cl rate of 112.5 kg/hm2 (Table 2).

CX-14 responded differently as Cl application rates increased. Nicotine content remained stable (5.13%–5.36%), reducing sugar reached a maximum of 1.56% at the Cl rate of 112.5 kg/hm², and the K/Cl ratio dropped from 1.48 to 0.96 (Table 2). Cl content in both varieties increased with higher Cl input. CX-14 generally had lower N and Cl content but higher reducing sugar, K content, and a higher Glycoalkaloid ratio compared to CX-26. This suggests that CX-14 may offer a richer flavor profile. The N-alkali ratio rose to 1.00 in CX-26 but remained at 0.62 in CX-14, highlighting distinct metabolic mechanisms between the varieties.

To comprehensive assess the response of cigar quality parameters to varying Cl application rates, the chemical quality score was calculated for each variety. The relationship between this score and Cl application rates is presented in Figure 5. The chemical quality score reached the maximum at Cl application rates of 44.05 kg/hm² for CX-26, and it peaked at rates 43.73 kg/hm² for CX-14 (Figure 5). Beyond these rates, the chemical quality score decreased sharply, indicating that excessive Cl is detrimental to the overall chemical quality of cigar tobacco.

**Table 2** Variations of cigar leaf chemical quality parameters under different Cl application rates.

| Variety | Treatment | Nicotine (%) | Reducing sugar (%) | Cl (%) | Total N (%) | K (%) | K/Cl | Glycoalkaloid ratio | N-alkali ratio |
|---|---|---|---|---|---|---|---|---|---|
| CX-26 | Cl0 | 4.78 | 0.83 | 1.80 | 4.04 | 1.77 | 0.89 | 0.24 | 0.84 |
| | Cl22.5 | 4.69 | 0.91 | 2.04 | 3.86 | 1.94 | 0.87 | 0.33 | 0.82 |
| | Cl45 | 4.86 | 0.91 | 2.28 | 4.07 | 1.80 | 0.73 | 0.34 | 0.84 |
| | Cl67.5 | 4.92 | 0.88 | 2.33 | 3.95 | 1.80 | 0.71 | 0.39 | 0.81 |
| | Cl90 | 4.85 | 0.53 | 2.41 | 4.18 | 1.71 | 0.66 | 0.26 | 0.86 |
| | Cl112.5 | 4.27 | 0.61 | 2.55 | 4.27 | 1.65 | 0.60 | 0.22 | 1.00 |
| CX-14 | Cl0 | 5.13 | 1.42 | 1.67 | 3.17 | 2.47 | 1.48 | 0.46 | 0.62 |
| | Cl22.5 | 5.09 | 1.42 | 1.84 | 3.43 | 2.56 | 1.39 | 0.42 | 0.68 |
| | Cl45 | 5.08 | 1.29 | 2.01 | 3.30 | 2.43 | 1.22 | 0.42 | 0.65 |
| | Cl67.5 | 5.01 | 1.43 | 2.09 | 3.42 | 2.51 | 1.20 | 0.59 | 0.68 |
| | Cl90 | 5.38 | 1.54 | 2.32 | 3.34 | 2.39 | 1.03 | 0.49 | 0.62 |
| | Cl112.5 | 5.36 | 1.56 | 2.40 | 3.33 | 2.31 | 0.96 | 0.52 | 0.62 |

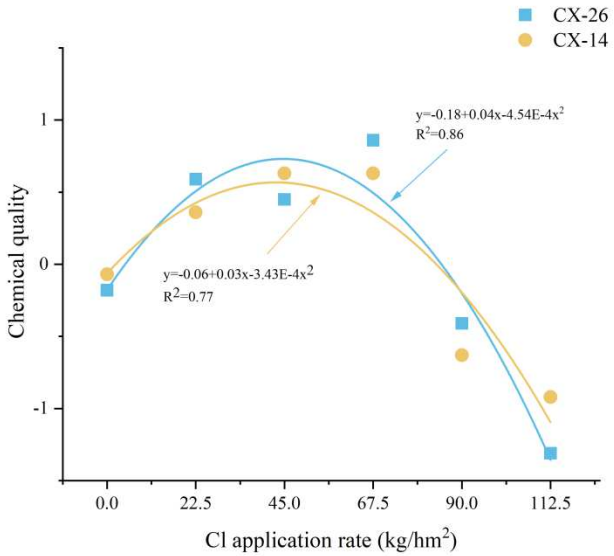



**Figure 5** Relationship between Cl application rates and chemical quality score.

### The optimal Cl application rate

The optimal Cl application rates for CX-26 and CX-14 were identified as those that simultaneously maximize yield and chemical quality scores, based on the NSGA-II algorithm and the objective functions illustrated in Figures 3 and 5. For CX-26, the algorithm recommended an exogenous Cl rate of 47.43 kg/hm², which resulted in a yield of 2,061.54 kg/hm² and a chemical quality score of 0.70. For CX-14, the optimal rate was 44.50 kg/hm², yielding 2,822.01 kg/hm² with a chemical quality score of 0.60.

## Discussion

The observed differences in cigar plant physical properties and yield between CX-26 and CX-14 emphasize the importance of genotype-specific nutrient management. CX-26 exhibited a classic unimodal response to Cl addition, with physical properties such as leaf length, width, and plant height peaking at intermediate Cl application rates. This result suggests that moderate Cl levels can stimulate vegetative growth, possibly by enhancing photosynthetic efficiency and regulating stomatal conductance, as supported by previous physiological studies(Xiang et al., 2006). However, yields declined at higher Cl inputs, underscoring the potential for toxicity or metabolic disruption when exceeding varietal tolerance thresholds(Huang et al., 2022).

In contrast, CX-14 demonstrated continuous inhibition of growth and yield with increasing Cl application rates, suggesting that CX-14 was more sensitive to exogeneous Cl compared with CX-26. It appears less tolerant to Cl stress and lacks comparable adaptive capacity. These findings align with Jinlong et al.(Jinlong et al., 2011)and Tiecher et al.(Tiecher et al., 2023)'s study that showed the improvement of appropriate Cl applications (ranging from 22 to 45 kg/hm²) on tobacco yield but the excess Cl inhibit tobacco growth. Importantly, the distinct responses of these two varieties reinforce the need for precision fertilization and adaptive management strategies.

Beyond agronomic performance, chemical quality is crucial to the value of cigar tobacco. Cl addition was found to regulate key indices, including the nicotine content, K/Cl ratio, and glycoalkaloid content. In CX-26, the K/Cl ratio decreased substantially at higher Cl levels, potentially reducing combustibility and smoke quality. Meanwhile, CX-14 maintained a more favorable glycoalkaloid profile, which may contribute to richer flavor and improved sensory attributes.

Leaf Cl content in both varieties exceeded the typical 1% threshold for most tobacco leaves(Zehler et al., 1981), but it remained within the reasonable range of these varieties(Dai et al., 2021). Leaf Cl content in both varieties increased pronouncedly with exogenous Cl input, which explained the decreased K/Cl ratio. However, maintaining K/Cl balance is essential for leaf burning properties and overall quality.

The use of multiobjective optimization in this study allowed for a balanced recommendation that addresses both yield and quality, providing a more holistic guideline for growers. An optimal exogenous Cl input is recommended as 47.43 kg/hm² for CX-26 and 44.50 kg/hm² for CX-14, which is higher than the recommended rates of previous studies(McCants and Woltz, 1967; Tiecher et al., 2023). However, to our knowledge, this is the first study to derive the recommended Cl rates for cigar plants.

Analysis was based on data collected from two years of experiment conducted at one location that may not fully capture the effect of interannual climate variability or regional differences in environmental condition. Recommendations of Cl application rates did not consider soil and climate information. Future research should focus on integrating varietal tolerance data with site-specific soil and climate information for optimizing cigar fertilization management while minimizing environmental risk. Additionally, the observed decline in stem dry matter with increasing Cl in CX-26 raises questions about carbon allocation and internal nutrient partitioning, highlighting the need for further investigations into physiological and molecular mechanisms underlying Cl tolerance and quality formation.

## Conclusions

This study systematically evaluated the effects of exogenous Cl application on the yield, physical properties, and chemical quality of two cigar tobacco varieties, CX-26 and CX-14, under field conditions in China. The results demonstrated clear varietal differences in response to Cl input. CX-26 benefited from moderate Cl levels, exhibiting peak growth and yield at intermediate application rates, while CX-14 was more sensitive, with growth and yield inhibited by higher Cl doses. Chemical quality indices, including the K/Cl ratio and glycoalkaloid content, were significantly influenced by Cl addition, underscoring the importance of balancing yield and quality in fertilization strategies. By integrating PCA, regression modeling, and multiobjective optimization, the study identified optimal Cl application rates of 47.43 kg/hm² for CX-26 and 44.50 kg/hm² for CX-14. These recommendations offer a balanced fertilization approach to maximizing both yield and quality of cigar tobacco. This study provides a practical foundation for enhancing fertilization practices, improving resource use efficiency, and improving product quality in the cigar industry.

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## Author contributions statement

J. Y. and S. L. wrote the main manuscript text; J. Y., S. L., and L. Z. conducted the experiment and collected data; S. L. and L. X. analyzed data; L. X. prepared figures; X. C. prepared tables and administered the funding; X. L. and S. L. edited the manuscript.

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## Data declaration

The data supporting the findings of this study are available from the funding provider but are not publicly accessible due to ownership restrictions. Data can be obtained from the authors upon reasonable request and with permission from the funding provider.