Relationship Between Fertilizer Efficiency of Novel Slow-Release Urea and Functional Material Dosage (Postprint)

Authors: Zhenyu Wu, Yang Yang, Zhou Zijun, Ni Xiaoyu, Lixiang Yu, Lu Hewei, Liu Binmei, Yuejin Wu, Wang Yu

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Abstract

This study employed the coal gasification urea production process to prepare six modified slow-release urea formulations (with functional adsorbent material addition rates of 1%, 2%, 3%, 4%, 5%, and 6%, respectively). Through sand column leaching, ammonia volatilization chamber experiments, and field maize trials, using conventional urea as a control, we analyzed the relationship between functional adsorbent material addition rate and urea slow-release characteristics as well as field fertilizer efficiency, explored the optimal addition rate of functional adsorbent material for modified slow-release urea in maize production, and provided a reference for the research and development and agricultural application of matrix slow-release fertilizers. The results showed that the nitrogen release characteristics in slow-release urea could be fitted using the first-order kinetic equation Nt=N0(1 e bx), with the nitrogen release rate constant (b) decreasing by 67.4%~82.6% compared to conventional urea, and cumulative ammonia volatilization loss decreasing by 15.8%~39.3%. In the maize cultivation experiment, the available nitrogen content in the topsoil showed an increasing trend with the increase of functional adsorbent material addition rate, while the chlorophyll content and nitrate reductase activity in maize leaves also showed increasing trends. Using a unary cubic model to fit the relationship between maize yield traits and functional adsorbent material addition rate, it was found that slow-release urea with functional adsorbent material addition rates of 5.28%, 4.80%, 5.24%, and 4.76% could obtain theoretical maximum maize biological yield (15 829 kg · hm), aboveground biomass (164.0 g · plant 1), root biomass (26.9 g · plant-1), and grain yield (6 769 kg · hm-), respectively. In summary, the functional adsorbent material in matrix-type slow-release urea has good effects on reducing nitrogen leaching and ammonia volatilization, improving maize nitrogen nutrition, and increasing maize yield, and the 5% addition rate is more conducive to increasing maize biomass and yield.

Full Text

Effects of Adding Proportions of Functional Absorption Materials on Performance of New Slow-Release Urea

WU Zhenyu[1], YANG Yang[2], ZHOU Zijun[2], NI Xiaoyu[2], YU Lixiang[2], LU Hewei[1], LIU Binmei[2], WU Yuejin[2], WANG Yu[1]

[1]School of Resources and Environmental Engineering, Anhui University, Hefei 230601, China
[2]Institute of Technical Biology & Agriculture Engineering, Hefei Institutes of Physical Science, Chinese Academy of Sciences, Hefei 230031, China

Abstract

Nitrogen fertilization enhances crop productivity, yet conventional nitrogen fertilizers suffer from significant drawbacks, including high risks of nitrogen leaching and ammonia volatilization, which create environmental and economic problems. The development and application of new high-efficiency fertilizers, such as matrix-based slow-release fertilizers, offer a promising solution to these challenges. Matrix-based slow-release fertilizers feature simple production processes, low costs, and stable performance. However, the proportion of modified functional absorption materials added substantially affects fertilizer performance, effective component content, and production costs. Despite this importance, little is known about the relationship between functional absorption material addition rates and slow-release urea performance. This study aimed to evaluate how different proportions of functional absorption materials affect the performance of a novel materials-based slow-release urea.

The nitrogen loss characteristics and field crop performance of functional absorption material-based slow-release urea (SRU) were analyzed using sand leaching columns, ammonia emission chambers, and field maize experiments. Experimental treatments included common urea (CU) as a control and six SRU formulations with 1%, 2%, 3%, 4%, 5%, and 6% functional absorption materials, respectively. Nitrogen release characteristics were described using a first-order kinetic model. Under field conditions, soil from the plough layer (0–20 cm) and maize ear leaves were sampled at the silking stage to measure soil available nitrogen concentration, leaf chlorophyll content, and nitrate reductase activity. The optimal addition proportion of functional absorption materials in slow-release urea was calculated using a polynomial model.

Results showed that the highest nitrogen leaching ratio occurred during the first leaching event—81.6% for common urea versus 27.7%–42.8% for SRU treatments. The cumulative nitrogen leaching ratio in the common urea treatment reached 100% by the sixth leaching, while SRU treatments required twelve leaching events to reach 90%. Slow-release urea with 6% functional absorption materials demonstrated the best performance in reducing nitrogen leaching. Nitrogen release characteristics were well-fitted by the first-order kinetic equation

$N_t = N_0(1 - e^{-bx})$, where N_t is the cumulative nitrogen release ratio, N_0 is the maximum cumulative nitrogen release ratio, b is the nitrogen release rate constant, and x is the number of leaching events. The nitrogen release rate constant (b) of SRU treatments was 67.4%-82.6% lower than that of the CU treatment, while cumulative ammonia emission from SRU treatments was 15.8%-39.3% lower than that from CU.

Available nitrogen content in the plough layer of maize fields increased with increasing proportions of functional absorption materials, which also enhanced leaf chlorophyll content and nitrate reductase activity in maize. SRU increased maize biomass and grain yield. Based on polynomial model calculations, the highest plant biomass (15,829 kg · hm ^{2}), shoot biomass (164.0 g · plant ^{1}), root biomass (26.9 g · plant ^{1}), and grain yield (6,769 kg · hm ^{2}) were obtained with SRU treatments containing 5.28%, 4.80%, 5.24%, and 4.76% functional absorption materials, respectively.

Overall, slow-release urea with 5% functional absorption materials demonstrated superior performance in reducing nitrogen losses through leaching and ammonia emission, improving maize nitrogen nutrition, and increasing maize biomass and grain yield.

Keywords: Slow-release urea; Functional absorption materials; Optimum adding proportion; Nitrogen release rate; Cumulative ammonia emission; Grain yield; Maize

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Introduction

Excessive nitrogen fertilizer application and nutrient loss in agricultural production cause severe resource waste and environmental hazards. Developing and applying new types of slow- and controlled-release fertilizers represents an important pathway to improve crop fertilizer use efficiency and reduce nutrient losses. Urea supplies over 60% of nitrogen fertilizer in China, making the development of various slow- and controlled-release urea formulations a persistent research focus. Coated and stabilized urea fertilizers effectively control nutrient release and transformation through physical coating and biological inhibition principles. However, coated fertilizers involve complex processes and high costs, while stabilized fertilizers exhibit poor stability in waterlogged soils, limiting their agricultural application.

Matrix-based slow-release fertilizers control nutrient transport and loss by adding functional absorption materials with strong ion-exchange properties. Although matrix slow-release fertilizers have shorter nutrient release periods than coated controlled-release fertilizers, their lower costs offer broad agricultural application prospects. Functional materials added to matrix slow-release fertilizers are typically prepared by modifying natural minerals with layered or reticular structures and adsorption sites—such as zeolite and bentonite—

using organic polymer compounds. These materials form complex triangular network structures through the combination of silicon-oxygen tetrahedra and aluminum-oxygen octahedral crystal sheets in layered silicate minerals. Through isomorphic substitution of cations in the octahedra, adsorption charges are generated, and combined with large specific surface areas (600–800 m^{2} · kg ^{1}), they enable three types of adsorption: physical, chemical, and ion exchange, thereby controlling fertilizer nutrient release.

The capacity of matrix slow-release fertilizers to control nutrient loss is closely related to functional material properties. Previous studies using first-order kinetic models to compare effects of different functional materials on nitrogen release characteristics showed that matrix slow-release fertilizers with added vermiculite (83.1%) and bentonite (87.2%) had relatively low maximum cumulative nitrogen release rates. This capacity also depends heavily on functional material addition rates. One study set the functional material addition rate at 59.0% and found that materials like vermiculite, bentonite, and zeolite significantly controlled nitrogen release from fertilizers. However, excessive functional material addition reduces effective nutrient content and increases production and transportation costs, creating substantial limitations for industrial production and agricultural application. Another attempt reduced the functional material addition rate to 5% and found that the resulting matrix fertilizer still exhibited significant effects in controlling nitrogen release. Yet, how further reduction in functional material addition affects matrix fertilizer performance remains poorly documented.

Determining appropriate functional materials and optimal addition rates represents a critical prerequisite for developing and promoting matrix slow-release fertilizers. This study utilized coal gasification urea production technology to prepare modified slow-release urea with different functional material addition rates. Through laboratory simulation experiments, we evaluated nitrogen leaching and ammonia volatilization loss characteristics, analyzed effects on soil available nitrogen, maize nitrogen nutrition, and yield through field experiments, and explored optimal functional material addition rates for maize production based on function fitting and extremum calculations. The results aim to provide guidance for developing and applying matrix slow-release fertilizers in agriculture.

Materials and Methods

1.1.1 Fertilizer Materials Both laboratory and field experiments used conventional urea (control) and six types of slow-release urea with modified functional material addition rates of 1%, 2%, 3%, 4%, 5%, and 6% (assisted production by Henan Xinlianxin). Functional materials used zeolite, bentonite, and other minerals with layered chain structures and reticular adsorption sites as matrix materials. These were modified through polymer compounding to enhance ion-exchange performance and slow-release effects, then mixed into urea granules via spray application during granulation. Field experiments used calcium superphosphate (containing 16% P O , produced by Shandong Luke Chemical) as phosphorus fertilizer and potassium sulfate (containing 51% K O, produced by Zhongyan Anhui Hongsifang) as potassium fertilizer.

1.1.2 Field Conditions and Experimental Crop The experimental area receives average annual precipitation of 950 mm. The tested soil type was yellow-brown soil with basic chemical properties: total nitrogen 0.96 g $\cdot$ kg^{1}, total phosphorus 1.31 g $\cdot$ kg^{1}, total potassium 16.1 g $\cdot$ kg^{1}, organic matter 20.5 g $\cdot$ kg^{1}, and pH 6.83. The maize (*Zea mays* L.) variety tested was 'Fengnuo 476' .

1.2.1 Sand Column Leaching Experiment Seven treatments were established: common urea (CU) and six slow-release urea formulations with 1%, 2%, 3%, 4%, 5%, and 6% functional material addition (1%SRU, 2%SRU, 3%SRU, 4%SRU, 5%SRU, and 6%SRU). Quartz sand (0.25–0.42 mm) served as the leaching medium, washed and dried at 100°C. The leaching method involved packing glass leaching tubes (3.2 cm diameter, 14.5 cm height) with three layers: 60 g quartz sand at both top and bottom, with 0.93 g N of test urea in the middle layer. A peristaltic pump at the tube bottom operated at 90 r $\cdot$ min^{1} for reverse leaching. Leachate was collected every 25 mL, with 12 collections total. Each treatment had three replicates.

1.2.2 Ammonia Volatilization Experiment Eight treatments were established: no-urea control (CK), common urea (CU), and six slow-release urea formulations with 1%, 2%, 3%, 4%, 5%, and 6% functional materials (1%SRU, 2%SRU, 3%SRU, 4%SRU, 5%SRU, and 6%SRU). Test soil was air-dried and passed through a 2 mm sieve. Ammonia volatilization was measured using a closed intermittent ventilation method: 800 g air-dried soil was placed in a sealed chamber (22 cm height, 15 cm diameter, 4 L volume), mixed with 240 mL distilled water and incubated for 24 h. Then 0.93 g N of test urea was evenly spread on the soil surface, covered with 200 g soil, and 60 mL distilled water was added. The system was incubated at (23±2)°C. A gas pump, timer, and ammonia capture bottle (10 cm height, 7 cm diameter, 400 mL volume, containing 100 mL of 20 g $\cdot$ L^{1} boric acid as ammonia absorbent) were used to capture volatilized ammonia. Ventilation occurred daily at 2:00, 8:00, 14:00, and 20:00, lasting 20 minutes each time. Samples were collected over 14 days, with ammonia absorption measured every 2 days. Each treatment had three replicates.

1.2.3 Field Experiment A field maize experiment was conducted from June 23 to September 23, 2016, at the experimental base of Hefei Institutes of Physical Science, Chinese Academy of Sciences. Eight treatments were established: no-urea control (CK), common urea (CU), and six slow-release urea formulations with 1%, 2%, 3%, 4%, 5%, and 6% functional materials (1%SRU, 2%SRU, 3%SRU, 4%SRU, 5%SRU, and 6%SRU). All nitrogen fertilizer treatments received 195 kg(N) $\cdot$ hm^{2}. All treatments received 45 kg(P O) $\cdot$ hm^{2} calcium superphosphate and 45 kg(K O) · hm ^{2} potassium sulfate. All fertilizers were applied as basal fertilizer and incorporated into the 0–20 cm plough layer before sowing. The experiment used a randomized block design with 16 m^2 plots (4 m × 4 m) and three replicates per treatment. Maize row spacing was 40 cm and plant spacing 30 cm, with conventional field management for pest, disease, and weed control.

At the silking stage, ear leaves were collected (five leaves per plot), washed with distilled water, blotted dry, cut into pieces, and mixed for chlorophyll content and nitrate reductase activity measurements, with three replicates per treatment. Simultaneously, soil samples from the plough layer (0–20 cm) were collected from five points per plot using a soil auger (5.5 cm diameter) in a W-shaped pattern. Soil samples from each plot were mixed (~5 kg), and approximately 1 kg was taken using the quartering method for available nitrogen measurement, with three replicates per treatment. At maturity, yield components were measured from 20 plants per plot, including grain number per ear, thousand-grain weight, grain yield, and biological yield.

1.3 Measurement and Analysis Methods Urea content in leaching samples (converted to pure N) was determined using the p-dimethylaminobenzaldehyde colorimetric method. Ammonia content in absorption solutions was measured by titration with 0.005 mol · L ^{1} dilute sulfuric acid standard solution. Soil available nitrogen (NO -N) was determined using UV absorption and indophenol blue colorimetric methods. Maize leaf chlorophyll content and nitrate reductase activity were measured using spectrophotometric methods. Grain number per ear, thousand-grain weight, grain yield, and biological yield were determined using conventional methods.

1.4 Data Analysis Methods Data processing and statistical analysis were performed using SAS 9.1 software, with multiple comparisons conducted using LSD method (= 0.05). Based on sand column leaching data, Origin 2015 software was used to construct the first-order kinetic model $N_t = N_0(1 - e^{-bx})$ to analyze nitrogen release kinetics of slow-release urea. In the equation, N_t represents cumulative nitrogen release ratio, N_0 represents maximum cumulative nitrogen release ratio, b represents nitrogen release rate constant, and x represents leaching frequency.

Results

2.1 Nitrogen Leaching Characteristics of Slow-Release Urea in Sand Columns The effect of functional materials on nitrogen leaching loss was evaluated through sand column leaching [Figure 1: see original paper]. All treatments showed peak nitrogen leaching loss rates during the first leaching event. Common urea exhibited an 81.6% nitrogen leaching loss rate in the first leaching, while slow-release urea with 1%–6% functional materials showed values of 27.7%–42.8%, representing a 47.6%–66.0% reduction compared to common urea.

Common urea nitrogen leached rapidly, reaching a cumulative nitrogen loss rate of 98.8% by the second leaching. In contrast, slow-release urea showed relatively slower nitrogen leaching loss, with cumulative nitrogen loss rates of 46.6%-66.4% by the second leaching. By the sixth leaching, common urea reached 100% cumulative nitrogen loss, whereas slow-release urea with 4%-6% functional materials reached only about 70%, and approximately 90% by the twelfth leaching. Slow-release urea with 6% functional materials exhibited the slowest nitrogen leaching loss.

2.2 Kinetic Characteristics of Nitrogen Release from Slow-Release Urea The kinetic characteristics of nitrogen release from slow-release urea were analyzed using the first-order kinetic equation $N_t = N_0(1-e^{-bx})$, with good fitting results (r = 0.983-0.999, $P < 0.05$). Based on the maximum cumulative nitrogen release rate (N_0) and nitrogen release rate constant (b) derived from the first-order kinetic equation (Table 1), common urea and slow-release urea with 1%-3% functional materials showed maximum cumulative nitrogen release rates of approximately 100%, while slow-release urea with 4%-6% functional materials showed values of approximately 90%. The nitrogen release rate constant for common urea was 1.72, while values for slow-release urea with 1%-3% functional materials (0.54-0.56) were reduced by 67.4%-68.6%, and values for slow-release urea with 4%-6% functional materials (0.30-0.33) were reduced by 80.8%-82.6%.

2.3 Ammonia Volatilization Loss Characteristics of Slow-Release Urea Based on intermittent ventilation incubation, the dynamic characteristics of soil ammonia volatilization loss were compared among different urea treatments (Table 2). Peak ammonia volatilization for most urea treatments occurred on days 1-2, but for slow-release urea with 6% functional materials, the peak appeared on days 3-4. Thereafter, ammonia volatilization gradually decreased, dropping below 0.2 mg N by days 13-14. Ammonia volatilization loss from all urea treatments remained significantly higher than the no-urea control ($P < 0.05$). Slow-release urea showed significantly lower ammonia volatilization loss than common urea on days 1-2 and 5-6 ($P < 0.05$). Peak ammonia volatilization for slow-release urea ranged from 14.09-21.26 mg N, representing a 20.0%-47.0% reduction compared to common urea (26.59 mg N), with the lowest peak (14.09 mg N) observed for slow-release urea with 6% functional materials.

Total cumulative ammonia volatilization loss was compared by summing losses across time periods (Table 2). Cumulative ammonia volatilization loss from urea treatments ranged from 34.3-56.5 mg N, accounting for 3.69%-6.08% of total nitrogen applied (930 mg), all significantly higher than the no-urea control ($P < 0.05$). Slow-release urea reduced cumulative ammonia volatilization loss by 15.8%-39.3% compared to common urea ($P < 0.05$). Slow-release urea with 6% functional materials showed the lowest cumulative ammonia volatilization loss (34.3 mg N), significantly lower than slow-release urea with 1%-3% functional materials ($P < 0.05$).

2.4 Response of Available Nitrogen in Plough Layer to Slow-Release Urea at Maize Silking Stage The nitrogen leaching resistance of different urea treatments under field conditions was compared based on available nitrogen in the plough layer at maize silking stage (Figure 2 [Figure 2: see original paper]). Available nitrogen content in the plough layer for urea treatments ranged from 15.0-17.9 mg(N) · kg^{1}, significantly higher than the no-urea control ($P < 0.05$). As functional material addition rate increased, available nitrogen content in the plough layer for slow-release urea treatments showed an increasing trend. Specifically, slow-release urea with 3%-6% functional materials significantly increased available nitrogen content by 8.7%-19.3% compared to common urea ($P < 0.05$), with the highest value observed for slow-release urea with 6% functional materials.

2.5 Response of Leaf Chlorophyll Content and Nitrate Reductase Activity to Slow-Release Urea at Maize Silking Stage Maize nitrogen nutritional status under different urea treatments was compared using leaf chlorophyll content and nitrate reductase activity at silking stage (Table 3). Leaf chlorophyll content for urea treatments ranged from 1.92-2.54 mg · g^{1}(FW), significantly higher than the no-urea control ($P < 0.05$). Slow-release urea treatments showed leaf chlorophyll content of 1.99-2.54 mg · g^{1}(FW), significantly higher than common urea by 3.65%-32.29% ($P < 0.05$). Leaf nitrate reductase activity for urea treatments ranged from 20.66-29.60 g(NO) · g^{1} · h^{1}, significantly higher than the no-urea control ($P < 0.05$). All slow-release urea treatments showed higher nitrate reductase activity than common urea, with slow-release urea containing 2%-6% functional materials showing activity of 22.51-29.60 g(NO) · g^{1} · h^{1}, significantly higher than common urea by 9.0%-43.3% ($P < 0.05$).

2.6 Effects of Slow-Release Urea on Maize Yield and Yield Components The effects of different urea treatments on maize growth were compared through biological yield, grain yield, and yield components (Table 4). All urea treatments showed significantly higher biological yield, grain yield, grain number per ear, and thousand-grain weight than the no-urea control ($P < 0.05$). Slow-release urea with 2%-6% functional materials significantly increased biological yield by 5.6%-16.4% compared to common urea ($P < 0.05$). Slow-release urea with 4%-5% functional materials significantly increased grain yield by 12.3%-13.5% compared to common urea ($P < 0.05$). Compared to common urea, slow-release urea did not significantly affect grain number per ear ($P > 0.05$). Slow-release urea with 3%-5% functional materials significantly increased thousand-grain weight by 5.5%-11.8% compared to common urea ($P < 0.05$).

2.7 Model Optimization of Functional Material Addition Rate in Slow-Release Urea Based on Maize Biomass and Yield The relationship between maize yield parameters and functional material addition rate in slow-release urea was fitted using a cubic polynomial model (Figure 3 [Figure

3: see original paper]). The functional relationship models between maize yield parameters and functional material addition rate were significant ($P < 0.01$ or $P < 0.05$), with functional material addition rate explaining 93.7%-99.5% of variation in maize yield parameters. Through extremum calculations on fitted curves, theoretical maximum values were determined: maize biological yield 15,829 kg · hm ^{2}, shoot biomass 164.0 g · plant ^{1}, root biomass 26.9 g · plant ^{1}, and grain yield 6,769 kg · hm ^{2}, corresponding to theoretical optimal functional material addition rates of 5.28%, 4.80%, 5.24%, and 4.76%, respectively.

Discussion

3.1 Effects of Functional Absorption Materials on Nitrogen Release

Leaching represents a major pathway for nitrogen fertilizer loss. Functional absorption materials, based on layered structures composed of numerous montmorillonite unit cells, enable three types of adsorption—physical, chemical, and ion exchange—demonstrating excellent ion-exchange performance that effectively controls fertilizer nutrient release. However, unmodified functional absorption materials have limited layered structure dispersion and ion-exchange performance due to interlayer cation types and environmental solution conditions. The modified functional absorption materials used in this study exhibited improved environmental adaptability and ion-exchange performance. Sand column leaching experiments demonstrated that slow-release urea with added functional materials showed relatively slow nitrogen leaching loss. Slow-release urea with 4%-6% functional materials exhibited maximum cumulative nitrogen release rates of approximately 90%, lower than common urea (100%), while their nitrogen release rate constants were reduced by over 80% compared to common urea. Zhang et al. also found through sand column leaching experiments that matrix-based slow-release fertilizer using functional materials had a maximum cumulative nitrogen release rate of 87%, lower than conventional fertilizer (100%), with nitrogen release rate constants reduced by over 64% compared to common urea. Sun et al. similarly demonstrated through soil column leaching experiments that slow-release urea prepared with functional material coatings had far lower cumulative nitrogen dissolution rates than common urea. These findings collectively indicate that slow-release urea with added functional absorption materials effectively controls nitrogen leaching losses.

In addition to leaching losses, ammonia volatilization represents another important pathway for nitrogen fertilizer loss, positively correlated with soil ammonium content. This study demonstrated that adding functional absorption materials to urea significantly regulated the dynamic characteristics of ammonia volatilization loss, with cumulative ammonia volatilization loss from slow-release urea significantly lower than that from common urea ($P < 0.05$). The mechanism for reduced ammonia volatilization may involve: (1) the layered reticular structure of functional materials effectively adsorbing ammonium produced from urea hydrolysis, reducing ammonium concentration in soil solution; and (2) modified functional materials possessing good swelling and flocculation properties that alter soil pore structure, reducing gas exchange channels between soil and atmosphere, thereby decreasing ammonia volatilization.

3.2 Effects of Functional Absorption Materials in Urea on Maize Nitrogen Nutrition Improving soil available nitrogen content through nitrogen fertilization represents an important approach to enhance maize nitrogen nutritional status. This study found that compared to common urea, slow-release urea with added functional materials increased available nitrogen content in the plough layer, with slow-release urea containing 3%–6% functional materials showing significant differences from common urea ($P < 0.05$). These results align with laboratory simulation experiments demonstrating that slow-release urea reduces nitrogen leaching and ammonia volatilization losses, while also proving that matrix-based slow-release fertilizers using functional absorption materials, similar to coated controlled-release fertilizers, can increase available nitrogen content in maize plough layers. Overall, functional absorption material-based slow-release urea maintains nutrient loss control characteristics under complex field conditions, demonstrating agricultural application value.

Leaf greenness and nitrate reductase activity serve as excellent indicators of plant nitrogen nutritional status. Under nitrogen deficiency, maize leaf chlorophyll content and nitrate reductase activity typically decrease. This study found that applying slow-release urea with added functional materials increased maize leaf chlorophyll content and nitrate reductase activity, further confirming that functional material addition to urea improves maize nitrogen nutrition. Wang et al. similarly found that functional material-coated urea increased chlorophyll content in pakchoi leaves, reflecting improved plant nitrogen nutrition from this slow-release urea.

3.3 Relationship Between Functional Absorption Material Addition Rate in Slow-Release Urea and Maize Yield The aforementioned results demonstrate that functional materials added to slow-release urea reduce nitrogen losses and improve maize nitrogen nutritional status. Subsequent yield results showed that slow-release urea increased maize biological yield by 0.2%–16.4% and grain yield by 0.2%–13.5%. Sun et al. also found that functional material-coated controlled-release fertilizer increased maize biological yield by over 8%. Functional absorption materials possess strong ion-exchange capacity that significantly affects nutrient release, and only appropriate addition rates can control nutrient losses while avoiding impacts on fertilizer nutrient availability and crop uptake. This study revealed differential maize yield responses to functional material addition rates in slow-release urea. Wang et al. also demonstrated that adjusting functional material addition rates in coated urea could regulate crop yield. To explore optimal functional material addition rates for maize production, a cubic polynomial model was used to fit the relationship between maize yield and functional material addition rate. Extremum calculations indicated that functional material addition rates of 4.76%–5.28% in slow-release urea could achieve higher maize biological and grain yields.

Conclusion

Slow-release urea with added modified functional absorption materials effectively reduces nitrogen leaching and ammonia volatilization losses. The nitrogen release kinetics of slow-release urea can be fitted by the first-order kinetic equation $N_t = N_0(1 - e^{-bx})$, with nitrogen release rate constants (b) 67.4%-82.6% lower than those of common urea, and cumulative ammonia volatilization loss reduced by 15.8%-39.3%. As functional material content in slow-release urea increased, available nitrogen content in the plough layer increased, thereby improving leaf chlorophyll content and nitrate reductase activity in maize. A functional material addition rate of approximately 5% in slow-release urea achieved higher maize biological yield and grain yield.

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