Article

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Abstract

To investigate the impacts of combining controlled-release urea (CRU) with controlled-release potassium chloride (CRK) on nutrient leaching and use efficiency in wheat fields, we carried out experiments spanning three consecutive years from 2022 to 2024, utilizing a split-plot design. In this study, the control plot received neither nitrogen nor potassium applications (Control). The main plots were designated based on nitrogen fertilizer types: controlled-release urea (CRU) and conventional urea (Urea). The sub-plots were assigned potassium fertilizer rates using CRK, specifically 50 kg ha^{-1} (LCRK), 75 kg ha^{-1} (MCRK), and 100 kg ha^{-1} (HCRK). The findings revealed that the nutrient release pattern of CRU combined with CRK aligned well with wheat's nutrient uptake requirements. Notably, the wheat yields in CRU treatments witnessed a significant average increase of 2.2% from 2022 to 2024 compared to ordinary urea treatments. In the final season, nitrogen recovery efficiency augmented by 10.9%. Furthermore, CRU treatments significantly boosted the number of effective wheat spikes and grains per spike but had no notable influence on wheat's thousand-grain weight (TGW). Consequently, the yield enhancement observed in CRU treatments was primarily attributed to an increase in wheat's effective tiller count. CRU also markedly elevated inorganic nitrogen levels in the plow layer soil during wheat's mid to late growth stages, effectively mitigating nitrate nitrogen leaching into deeper soil layers. The application of CRU×MCRK notably and significantly improved wheat leaf photosynthesis during its mid to late growth stages, yielding substantial economic benefits and theoretical significance.

Keywords: controlled-release urea; controlled-release potassium chloride; nutrient leaching; nutrient use efficiency; yield

1. Introduction

Wheat used to stand as the globe's foremost food crop, with a consistent rise in yield being the paramount approach to fulfilling market demands and safeguarding food security (Mottaleb et al., 2022). However, the scope for expanding or even maintaining the existing arable land dedicated to food production was severely limited, and in some instances, it even experienced a decline. The productivity and quality of wheat were shaped not only by the genetic traits of the cultivar but also by the intricate interplay between the ecological environment and agricultural practices (Guarin et al., 2022). Among the various agricultural strategies employed, the application of chemical fertilizers proved to be the most rapid, effective, and crucial means of enhancing crop yields. It played a pivotal role in ensuring both food production safety and achieving high yields (Jiang et al., 2021).

Nitrogen was a vital nutrient in the growth trajectory and development of wheat, playing a pivotal role in fostering robust root systems and facilitating the accumulation of essential elements like carbon and potassium (de Oliveira Silva et al., 2020). When nitrogen fertilizer was judiciously applied, it boosted wheat chlorophyll levels, enhanced photosynthetic processes, augmented the accumulation of photosynthetically derived products, extended the functionality of green leaves, and ultimately led to higher wheat yields (Liu et al., 2024). In parallel, potassium emerged as another indispensable nutrient crucial for plant growth and development (Wang et al., 2020). The application of potassium fertilizer invigorated plant root systems, enhanced the uptake and accumulation of nitrogen and phosphorus, facilitated the efficient transportation and distribution of assimilates towards ear organs, amplified sucrose supply and starch accumulation within grains during the grain-filling phase, and ultimately elevated economic yields (Khan et al., 2022).

Nevertheless, achieving high yields often came at the expense of unreasonable fertilization practices. These practices not only resulted in the squandering of resources and a decline in fertilizer utilization efficiency but also triggered a cascade of adverse effects, including plant diseases, soil acidification, agricultural non-point source pollution, and heightened greenhouse gas emissions (Guo et al., 2021). Specifically, excessive nitrogen application led to substantial losses via ammonia volatilization, nitrate leaching, and denitrification processes. Consequently, this excessive application translated into higher fertilizer costs, reduced crop yields, escalated production expenses, and severe environmental pollution (Yang et al., 2024). Conversely, as nitrogen and phosphorus fertilizers became increasingly prevalent in farmland and crop yields soared, the demand for soil potassium by crops also saw a marked increase (Chen et al., 2024). Simultaneously, the persistent neglect of potassium fertilizer application resulted in a chronic deficiency of soil potassium (Das et al., 2021). In many areas, the area of soil potassium deficiency was gradually expanding, the de. In numerous regions, the extent of soil potassium deficiency was progressively expanding, the severity of the deficiency was intensifying, and the benefits of crop potassium application were becoming increasingly pronounced.

The direction of future fertilizer research ought to concentrate on enhancing fertilizer efficiency and utilization, rather than merely escalating fertilization levels (Martínez-Dalmau et al., 2021). The rise of controlled-release fertilizers stand as a pivotal trend in the evolution of fertilizer technology, promising to bolster fertilizer utilization efficiency, mitigate environmental pollution stemming from fertilization, and facilitate single-application convenience (Vejan et al., 2021). These innovative fertilizers operated by employing polymer coatings and other mechanisms to achieve nutrient release according to a predefined pattern, thereby aligning with the nutrient absorption patterns of crops.

Controlled-release fertilizers were widely utilized in cereal crops, including corn, wheat, and rice, highlighting their benefits in conserving both fertilizer and labor (Fan et al., 2021; Govil et al., 2024). These fertilizers, specifically those with controlled-release nitrogen, fostered enhanced root development, augmented wheat's capacity to absorb soil nutrients, mitigated nitrogen losses, and bolstered overall fertilizer use efficiency (Liu et al., 2023; Xiang et al., 2025). When compared to conventional urea, controlled-release nitrogen fertilizers elevated the SPAD values and photosynthesis rates of wheat leaves, ultimately leading to increased crop yields (Ma et al., 2021). Additionally, controlled-release potassium fertilizers markedly boosted the levels of available potassium in the soil. In accordance with wheat's growth and developmental nutrient requirements, potassium was steadily released from the soil, ensuring a continuous supply to sustain normal wheat growth (Li et al., 2021). The synergistic interaction between nitrogen and potassium further optimized the utilization efficiency of these nutrients in wheat and facilitated enhanced uptake of nitrogen, phosphorus, and potassium by both wheat grains and straw (Badawy et al., 2021).

Controlled-release fertilizers were at that time a prominent area of interest in international fertilizer research and were seen as a crucial path for future development in the fertilizer industry (Channab et al., 2023). During that period, the majority of research conducted both domestically and internationally centered on the impacts of individually applying controlled-release nitrogen fertilizer or controlled-release potassium fertilizer on wheat growth. Nonetheless, there were no published

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studies detailing the effects of combining controlled-release potassium fertilizer with controlled-release nitrogen fertilizer on wheat yield and soil fertility. Consequently, the purpose of this study was to examine the influence of combining controlled-release nitrogen fertilizer with controlled-release potassium fertilizer on various aspects: (i) photosynthetic properties, (ii) nitrogen and potassium utilization efficiency, (iii) soil nutrient movement, (iv) wheat yield, and (v) economic advantage. This study sought to explain the physiological and biochemical rationale behind the combined use of controlled-release nitrogen and controlled-release potassium to enhance wheat yield, thereby furnishing a theoretical framework for achieving high-yield wheat cultivation.

2. Materials and methods

2.1. Experimental Site and Material

The experimental endeavor was carried out between the years 2022 and 2024 in Guxian Village, located in Zhongce County, Jining City, Shandong Province, China (N 35°69′22″; E 117°27′26″). This locale featured a warm temperate monsoon climate characterized by seasonal precipitation concentration. Precipitation was predominantly observed during the months of July and August, while the annual mean temperature hovered around 15.7 °C, as depicted in Figure 1. According to the USDA classification system (Soil Survey Staff, 1999), the soil type at the experimental site was identified as Typic Hapludalf. Prior to wheat cultivation, soil samples from the 0-20 cm depth were gathered using the 5-point sampling technique within the experimental plot to ascertain the fundamental soil characteristics, as summarized in Table 1. Notably, the experimental area had been previously utilized for food crop cultivation, maintaining uniform soil conditions.

The wheat variety chosen for planting was “Jimai 22”. The fertilizers under investigation encompassed controlled-release fertilizers and traditional fertilizers. The controlled-release fertilizer consisted of polymer-coated urea (CRU, containing 41% N, with nutrient release spanning nearly four months in 25 °C static water) and polymer-coated potassium chloride (CRK, containing 55% K_2O, with nutrient release spanning nearly four months in 25 °C static water), both supplied by Kingenta Ecological Engineering Group Co., Ltd., China. Additionally, the traditional fertilizers included urea (containing 46% N) and calcium superphosphate (containing 14% P_2O_5).

2.2. Experimental Design

The experiment employed a split-plot design, assigning nitrogen fertilizer type as the main plot factor and potassium fertilizer rate as the subplot factor, both arranged at random with four repetitions. The main plots featured two nitrogen fertilizer types: controlled-release urea (CRU) and conventional urea (Urea). Within the subplots, potassium fertilizer rates (CRK) were allocated at 50 kg ha^{-1} (LCRK), 75 kg ha^{-1} (MCRK), and 100 kg ha^{-1} (HCRK). A control plot was also established, devoid of nitrogen and potassium applications. Each subplot measured 25 m^2 (5m wide and 5m long). Urea fertilizers were applied in two installments: 40% pre-planting and 60% as topdressing at the jointing stage, while all other fertilizers were applied once prior to planting. The application rates amounted to 225 kg ha^{-1} N and 150 kg ha^{-1} P_2O_5.

To mitigate the impact of water and fertilizer infiltration across subplots, each subplot was delineated by a cement board with a thickness of 80 mm and buried to a depth of 1 meter. Each subplot hosted 20 wheat rows, alternating between wide and narrow rows, with widths of 25 cm and 15 cm, respectively. Fertilization was conducted in furrows within the central strip of the wide rows. Wheat was sown at a rate of 120 kg ha^{-1}, with seeds buried 3 cm deep. Fertilizers were buried in trenches within the wide rows, spanning 10-15 cm in depth. The ratio of wheat rows to fertilizer rows was maintained at 2:1. Consistent with local agricultural practices, all other agricultural management measures were uniformly implemented.

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2.3. Sampling and Measurement

2.3.1. N and K release rates of CRU and CRK

The nutrient extraction technique, which involved utilizing static water within an indoor incubator maintained at a constant temperature of 25 °C, was established in accordance with the industry standard titled "Controlled Release Fertilizer" (HG/T 4215-2011). For the nutrient release process of bags buried in field soil, a plastic sealing machine was employed to compress a nylon mesh, featuring a pore size of 1 mm, into a bag measuring 12 cm in length and 10 cm in width. Subsequently, 10.0 grams of the coated CRU or CRK sample was weighed, placed into the prepared mesh bag, sealed using the plastic sealing machine, and buried 15 cm deep in the field soil. Regarding the collection of fertilizer bags, during the wheat-growing season, they were retrieved at intervals of 10 days, 20 days, 30 days, and so forth, up to 240 days after burial. On each occasion, three bags were collected and transported back to the laboratory. These bags were then meticulously rinsed with pure water, dried in a 60 °C oven for 48 hours, cooled in a dryer, and subjected to analysis. The total nitrogen content was determined using the semi-micro Kjeldahl method, while the total potassium content was measured using the flame method. The nutrient release rate at each time point was calculated by subtracting the total nutrient content of the retrieved fertilizer bag from the initial nutrient content at the time of burial, and then dividing this difference by the initial nutrient content of the buried bag.

2.3.2. Soil Sampling and Measurement

Wheat crops were cultivated on October 14th, 2022, and October 17th, 2023. Throughout specific growth stages of the wheat, namely, the tillering stage (38 days post-sowing), the jointing stage (179 days post-sowing), the heading stage (213 days post-sowing), and the maturity stage (235 days post-sowing)—soil samples were gathered from the 0-20 cm soil layer during the second cultivation season. In each plot, a five-point sampling technique was employed to collect and combine the soil samples. Subsequent to natural air drying, the soil samples underwent grinding and sieving processes, utilizing sieves with mesh sizes of 2 mm and 0.2 mm, to prepare them for analysis and chemical testing. Using 0.01 M $CaCl_2$, the samples were extracted and filtered, and the soil inorganic nitrogen content (NO_3^--N and NH_4^+-N) was analyzed with an AA3-A001-02E automatic analyzer. Additionally, the samples were treated with 1 mol/L NH_4OAc, and the soil's available potassium content was determined through the flame photometry method, as outlined by Zheng et al. (2016).

2.3.3. Plant Sampling and Measurement

After 38 days of wheat planting, distinctive plants within each experimental plot were designated as fixed observation points for monitoring wheat tillering. Subsequently, the number of wheat tillers was meticulously observed and documented every 14 days, continuing until the waxing stage. Upon harvest, representative wheat samples measuring 1 m^2 were gathered. These samples were air-dried and threshed post-seeding, with the grains and straw subsequently separated to determine the wheat yield. Additionally, five representative plants were collected at harvest time, categorized into straw and grain samples, and dried at 80 °C until they attained a consistent weight. These samples were then finely ground and sieved, enabling the calculation of biomass and the measurement of total nitrogen and potassium content. Ultimately, the methodologies for computing nitrogen recovery efficiency (NRE), nitrogen agronomic efficiency (NAE), potassium recovery efficiency (KRE), and potassium agronomic efficiency (KAE) were detailed by Yang et al. in 2016.

(1) NRE (%)=(cumulative plant N uptake from N treatment- cumulative plant N uptake from the Control treatment)/the amount of N fertilizer applied×100%;

(2) NAE (kg N kg^{-1})=(the yield in the N treatment-the yield in the Control treatment)/the amount of N fertilizer applied;

(3) KRE (%)=(cumulative plant K uptake from K treatment- cumulative plant K uptake from the Control treatment)/the amount of K fertilizer applied×100%;

(4) KAE (kg K_2O kg^{-1})=(the yield in the K treatment-the yield in the Control treatment)/the amount of K fertilizer applied;

(5) Net profit ($ ha^{-1} $year^{-1}$)=the yield×wheat price-fertilizer costs-other costs-labor costs.

The mean prices of fertilizers and other non-labor expenses in China (US dollars per metric ton): polymer coated urea $348.4, polymer coated potassium chloride $485.6, calcium superphosphate $149.3, urea $238.8, wheat $403.8. Other costs included machinery, plastic film, irrigation, pesticides, insecticides, seeds, and other materials and services. Mean cost of labor in China: $12.80 for one employee/day/ha.

2.3.4. Photosynthetic Detection of Wheat

At the jointing stage of wheat, which occurred 179 days after sowing, measurements were taken of chlorophyll content, photosynthesis, and chlorophyll fluorescence parameters. Specifically, two rows of plants from each experimental center were randomly selected for these assessments. The SPAD value was determined using a chlorophyll meter, model SPAD-502, manufactured by Minolta in Tokyo, Japan. Additionally, the net photosynthetic rate (P_n), stomatal conductance (G_s), intercellular carbon dioxide concentration (C_i) and transpiration rate (T_r) were all measured utilizing the Li-6400 portable photosynthetic apparatus, produced by LI-COR in Lincoln, Nebraska, USA. Furthermore, the primary light energy conversion efficiency (F_v/F_m), non-photochemical quenching coefficient (q_N), photochemical quenching coefficient (q_P), and effective quantum yield of PSII photochemistry (ΦPSII) were all evaluated using the FMS2 portable fluorescence system, a product of Hansatech Instruments based in Kings Lynn, Norfolk, UK.

2.4. Statistical Analyses

The data were preprocessed using Microsoft Excel 2010. Subsequently, multiple comparisons were conducted using the LSD method within SPSS 19.0 statistical software, alongside an analysis of variance. All data presented in this article represent the average of three replicates. The processed data were then graphically represented using SigmaPlot software, specifically version 10 (MMIV, Systat Software, San Jose, CA, USA).

3. Results

3.1. Nutrient Release Characteristics of CRU and CRK in 25 °C Static Water and Field Soil

During static water extraction conducted at 25 °C, the nitrogen release profiles of CRU exhibited an “S” shaped pattern (Figure 2). Initially, nitrogen release was gradual over the first 30 days, peaking between days 40 and 80, and then gradually tapering off between days 90 and 120. Meanwhile, the potassium release profiles of CRK mirrored those of CRU but occurred at a quicker pace (Figure 3). After 120 days under these conditions, the nitrogen release of CRU and the potassium release curves of CRK amounted to 92.31% and 96.33%, respectively. Notably, the nitrogen release of CRU nutrient release was 4.02% higher than the potassium release curves of CRK at this 120 day mark.

The soil temperature in the 0-15 cm layer during the wheat season in this experiment averaged 10.73 °C, considerably cooler than the 25 °C of the static water extraction setup (depicted in Figure 1). Consequently, the nutrient release dynamics of CRU and CRK in the soil during the wheat season unfolded in three distinct phases (Figure 2 and 3). Prior to wheat entering its overwintering stage (within the first 30 days), nutrients were swiftly released, followed by a “lag period” spanning from day 30 to day 120. During this period, wheat was in its overwintering stage, with an average soil temperature dipping below 6 °C. Subsequently, from day 120 to day 210, as soil temperatures climbed, the controlled-release fertilizers accelerated their nutrient release until reaching peak levels. Between the two types, CRK exhibited the fastest nutrient release compared to CRU. By day 240, the cumulative nutrient release rates for CRU and CRK had reached 96.21% and 98.22%, respectively.

3.2. Soil Inorganic Nitrogen Content

The levels of NO_3^--N in the soil of each nitrogen application treatment rose notably when compared to the non-nitrogen application treatment (Control). Across all fertilization methods, the application of controlled-release nitrogen fertilizer led to a substantial increase in nitrate nitrogen compared to the conventional urea treatment, highlighting that varying fertilization quantities influenced the nitrogen residuals in the soil (Figure 4). Specifically, in the 0-20 cm soil layer, wheat seedlings treated with ordinary urea exhibited a significantly higher NO_3^--N content than those treated with controlled-release urea. This was attributed to immediate fertility of the urea, resulting in a rapid surge in NO_3^--N levels upon soil application. However, NO_3^--N carried a negative charge, and the adsorption capacity of soil for it was limited, which heightened the risk of NO_3^--N leaching and subsequently led to nitrogen losses and environmental contamination. As wheat grew, the NO_3^--N content in this soil layer decreased significantly, indicating that controlled-release fertilizer effectively retained soil nitrogen and mitigated the risk of NO_3^--N leaching.

Similarly, the Control treatment resulted in a marked decrease in soil NH_4^+-N content (Figure 4). During the wheat seedling and heading stages, soil treated with ordinary urea had significantly higher ammonium nitrogen levels compared to various controlled-release urea treatments, potentially accelerating ammonium volatilization and leaching, thereby causing nitrogen losses. During the wheat seedling stage, nitrogen-fertilized soil had relatively high NH_4^+-N content, whereas NH_4^+-N levels remained relatively stable in soil during other growth stages. In the 0-20 cm soil layer, during the wheat greening period, each controlled-release urea treatment had a higher soil NH_4^+-N content than the ordinary urea treatment. This was due to the peak release of controlled-release urea occurring around the wheat greening period. Conversely, during the winter wheat seedling stage, urea-treated soil had a higher NH_4^+-N content than soil treated with controlled-release nitrogen fertilizer. However, in later wheat growth stages, there were no significant differences in soil NH_4^+-N content among controlled-release urea treatments.

3.3. Soil Potassium Form

The contents of soil available K, water soluble K, exchangeable K and nonexchangeable K were notably influenced by the quantity of CRK administered. Throughout various stages of development, the Control treatment exhibited the lowest concentrations (Figure 5). During the initial phase of wheat growth, alterations in the soil available K, water soluble K, and nonexchangeable K contents were relatively minor, attributed to limited the potassium absorption of wheat at this stage. Upon reaching the jointing stage, wheat transitioned into a period of rapid growth, resulting in a substantial decline in the concentrations of various potassium components. Generally, the levels of soil available K, water soluble K, and nonexchangeable K in the soil progressively declined, whereas exchangeable K exhibited a fluctuating pattern. Irrespective of the nitrogen fertilizer type utilized, an increase in the CRK application rate led to an elevation in the soil available K, water soluble K, and exchangeable K contents, with significant variations observed among different potassium fertilizer treatments.

3.3. Photosynthetic Detection of Wheat Leaves

The effects of various fertilization treatments on the SPAD values of wheat leaves were depicted in Figure 6. During the tillering stage of wheat, the SPAD values observed in the urea treatments surpassed those in the CRU treatments. Across the wheat's entire growth period, the SPAD values initially rose and subsequently declined, peaking during the jointing stage, a time of vigorous nutritional growth. Notably, in the middle and later stages of wheat growth, the SPAD values associated with CRU treatments were higher compared to those of urea treatments. Under three levels of CRK fertilizer application, the SPAD value of the LCRK treatment remained lower throughout the growth cycle, suggesting that inadequate potassium utilization had a discernible impact on the SPAD value. The CRU×HCRK treatment boasted the highest SPAD values during the middle and later stages of wheat growth, while the influence of nitrogen fertilizer on the SPAD value was more pronounced in the later stages. When compared to conventional urea, the application of CRU exhibited greater advantages in enhancing SPAD values.

In the past two years, the control treatment exhibited the lowest net photosynthetic rate (P_n), stomatal conductance (G_s) and transpiration rate (T_r), while the intercellular carbon dioxide concentration (C_i) was the highest, as indicated in Table 2. No significant interaction effect between nitrogen (N) and potassium (K) was observed on the photosynthesis indicators. Among the treatments, the CRU×MCRK and CRU×HCRK treatments demonstrated the most favorable performance in terms of wheat leaf photosynthesis. In comparison to the urea treatments, the CRU treatments showed a significant increase in photosynthetic factors. As the potassium fertilizer dosage increased, there was no notable difference in P_n among treatments using the same type of nitrogen fertilizer. Furthermore, no significant difference was found in G_s, T_r and C_i between the MCRK and HCRK treatments, but these values were significantly higher than those of the LCRK treatment. Both nitrogen fertilizer types and potassium fertilizer rates influenced the photosynthesis indicators, yet their interaction effects did not yield a significant difference.

Over the course of these two years, the control treatment exhibited the lowest effective quantum yield of PSII photochemistry (ΦPSII), primary light energy conversion efficiency (F_v/F_m), photochemical quenching coefficient (q_P), while the non-photochemical quenching coefficient (q_N) was the highest, as detailed in Table 2. Notably, there was no significant N×K interaction effect on the fluorescence indicators. However, both the type of nitrogen fertilizer and the rate of potassium fertilizer had significant impacts on these indicators. When compared to the urea treatments, the CRU treatments showed a marked increase in fluorescence factors. Moreover, as the dosage of potassium fertilizer increased, no significant difference was observed among treatments using the same type of nitrogen fertilizer. The types of nitrogen fertilizer and CRK rates influenced the fluorescence indicators, but their interaction effects did not yield a significant difference. Notably, the CRU×MCRK treatments helped delay leaf senescence and ensured a steady supply of photosynthetic products necessary for wheat growth over these two years.

3.4. Nutrient Absorption and Utilization Efficiency

The application of nitrogen fertilizer led to a significant enhancement in wheat's nitrogen absorption, as shown in Table 3. Specifically, the CRU treatments exhibited significantly higher nitrogen uptake, nitrogen agronomy efficiency (NAE), and nitrogen recovery efficiency (NRE) compared to the urea treatments. No notable interaction was observed between nitrogen fertilizer type and potassium fertilizer rate in terms of nitrogen uptake, NAE, and NRE. Overall, the CRU×MCRK treatment demonstrated the highest nitrogen absorption and utilization efficiency.

Similarly, the application of potassium fertilizer significantly boosted wheat's potassium absorption, as indicated in Table 4. The potassium absorption increased with the rise in CRK dosage. However, the trends for potassium agronomy efficiency (KAE) and potassium recovery efficiency (KRE) were inverse. No significant interaction between nitrogen (N) and potassium (K) was observed in relation to potassium uptake, KAE, and KRE. Overall, the CRU×LCRK treatment showed the highest nutrient absorption and utilization efficiency among all treatments.

3.5. Yield and Net Profit

The wheat yield and its components under various fertilization treatments have been summarized in Table 5. There was no significant difference in wheat yield between the 2022-2023 and 2023-2024 seasons. However, nitrogen application treatments significantly boosted wheat yield compared to treatments without nitrogen application. Specifically, when compared to ordinary urea treatments, the CRU treatment led to a notable increase in wheat yield. In both 2022-2023 and 2023-2024, the wheat yield under CRU treatments was 1.5% and 2.0% higher, respectively, than that under urea treatments. Furthermore, the CRU application significantly increased the number of spikes, grains per spike, and thousand-grain weight (TGW) of wheat. Nevertheless, there was no significant difference between the MCRK and HCRK application treatments, both of which showed a marked increase compared to the LCRK application treatments. In both years, no significant interaction effect between N×K was observed on wheat yield and its components.

The average annual income, cost, and net profit for various treatments in 2023 and 2024 were computed, revealing that the Control treatment had the lowest values, as indicated in Table 6. The results of the economic analysis showed that, despite the higher fertilizer input cost of CRU treatments compared to ordinary urea treatments, the benefits associated with CRU application were significantly greater. This was attributed to the higher yields obtained with CRU treatments, leading to increased total benefits. Additionally, CRU treatments resulted in savings on labor costs due to reduced fertilizer input requirements. The findings indicated that, in comparison to urea treatments, CRU treatments increased net profit by 2.0% in 2023 and 3.3% in 2024. Regardless of the type of nitrogen fertilizer used, the MCRK dosage provided the highest economic benefits compared to LCRK and HCRK treatments. Overall, the CRU×MCRK treatment offered the greatest economic advantages.

4. Discussion

4.1. Nutrient Leaching

Long-term utilization of ammonium nitrogen fertilizer or urea nitrogen fertilizer often resulted in imbalanced anion and cation absorption by soil roots, ultimately causing soil acidification (Klimczyk et al., 2011). When NO_3^--N and NH_4^+-N were the primary forms of nitrogen uptake, the total amount of absorbed cations surpassed that of anions, contributing to soil acidification (Yang et al., 2022). Soil acidification had both direct and indirect effects on crop nutrient absorption and nitrogen utilization efficiency by modulating nutrient availability, crop growth, biomass, and yield. In this study, the application of ordinary urea, in contrast to CRU, not only decreased the pH of the topsoil but also reduced the concentration of soil base ions. This might be attributed to the rapid hydrolysis of ordinary urea, which intensified nitrate leaching (Cui et al., 2020). Furthermore, once NH_4^+-N was adsorbed by the soil, H^+ was displaced into the soil solution, elevating soil acidity. Consequently, other cations were displaced from the soil and either released into the soil solution or leached into deeper soil layers. However, the controlled release of nitrogen by CRU effectively mitigated the intensity of this process. As a result, the exchangeable K content in the CRU treatments was lower than that in the ordinary urea treatments, likely because the CRU treatments achieved higher yields and biomass, thereby enhancing the absorption of soil potassium.

4.2. Nutrient Use Efficiency

As agricultural production continually advanced and the reliance on fertilizers grew, the issue of enhancing nutrient use efficiency emerged as a pressing concern in contemporary agricultural practices (Salim et al., 2020). Various experiments conducted in the past had demonstrated that the utilization of controlled-release urea (CRU) could elevate both the crop yields and nutrient use efficiency in wheat and corn (Zhu et al., 2020; Zhang et al., 2022; Hou et al., 2024). Specifically, when compared to traditional urea applications, CRU treatments were found to improve nitrogen use efficiency by 28.5%. Remarkably, even with a reduction of one-third in nitrogen application, wheat yields still managed to increase by 6.5% (Sapkota et al., 2023). In our experiment, CRU treatments notably augmented nitrogen uptake, nitrogen agronomic efficiency (NAE), and nitrogen recovery efficiency (NRE) compared to standard urea treatments, all while maintaining the same nitrogen application rate. This led to higher wheat yields. It was also observed that the efficiency of potassium fertilizer usage was not influenced by the type of nitrogen fertilizer employed. Potassium uptake rose in tandem with increased potassium fertilizer application, yet both potassium agronomic efficiency (KAE) and potassium recovery efficiency (KRE) decreased. High wheat yields were predicated on high biomass levels, and the application of CRU effectively bolstered nitrogen absorption, which in turn increased the aboveground biomass of wheat. Among the treatments tested, the combination of CRU with medium-rate controlled-release potassium (MCRK), denoted as CRU×MCRK, exhibited the most favorable application effects, suggesting its optimal suitability for wheat growth.

4.3. Multidimensional Correlation Analysis Between Yield and Various Indicators

Nitrogen emerged as the pivotal factor influencing wheat growth. Throughout its entire growth cycle, wheat's nitrogen demand exhibited an S-shaped pattern, underscoring the crucial importance of tailoring nitrogen applications to align with varying nitrogen requirements of wheat at different stages for optimal yields (Zhou et al., 2023). The nutrient release profile of controlled-release fertilizers was governed by soil temperature and moisture content. Under the experimental conditions, the average soil temperature prior to overwintering period of wheat was recorded at 10.25 °C (Figure 1). During this initial stage, the nutrients released by CRU adequately met wheat's nitrogen needs (Fan et al., 2022). Conversely, during the overwintering period, when the average soil temperature dipped below 0.5 °C, nutrient release virtually ceased. Upon the onset of the turning green period, soil temperatures rose, accelerating the release of nutrients from CRU. This nutrient release culminated at the booting stage, precisely catering to wheat's nitrogen demand during its period of maximum nitrogen efficiency. Consequently, this played a pivotal role in facilitating the "nitrogen fertilizer migration" observed in high-yield wheat fields. In summary, the nitrogen release characteristics of CRU in field settings were in harmony with diverse nitrogen requirements of wheat across its various growth stages.

The wheat yield per unit area was determined by a combination of factors, including the number of spikes, grains per spike, and thousand-grain weight (TWG), as previously observed by Cossani et al. (2021). During this experiment, an increase in potassium application rates led to a gradual rise in the number of spikes per unit area, suggesting that the controlled-release urea (CRU) treatments were more effective in enhancing spike numbers compared to urea treatments. Additionally, CRU treatments showed a significant positive impact on improving TWG relative to urea treatments. However, despite achieving a high number of spikes under high CRK conditions, the resulting grain weight was notably lower than that of other treatments.

Through multidimensional correlation analysis (Figure 7), which showed that soil nutrient indicators such as soil available K, water soluble K, exchangeable K and nonexchangeable K, NO_3^--N, NH_4^+-N and photosynthetic physiological indicators including P_n, G_s, T_r, SPAD value and chlorophyll fluorescence parameters including ΦPSII, F_v/F_m and q_P all showed a strong positive correlation with nitrogen and potassium use efficiency, reaching a significant level ($P < 0.05$). At the same time, the q_N had a significant positive correlation with C_i ($P < 0.05$). Except for exchangeable K, yield showed a significant positive correlation with soil nutrient supply, photosynthetic efficiency, and fluorescence parameters ($P<0.05$). Among the various factors influencing yield, adopting an appropriate nitrogen source and CRK application rate (CRU×MCRK) was advantageous for balancing the development of spike number, grains per spike, and TWG, ultimately aiming to attain super high yields.

5. Conclusions

The nutrient release pattern of controlled-release fertilizers was primarily influenced by temperature, along with the coating material used. Consequently, when choosing the suitable type of controlled-release fertilizer, it was crucial to take into account both the growth cycle of crop and the soil temperature conditions in the planting area. In this study, a comparison was made between conventional urea application and a single application of controlled-release urea (CRU). Results indicated that during the 2023-2024 seasons, wheat yields increased significantly by 0.6% to 2.3% with CRU application, and similarly, by 0.3% to 3.5% during the 2023-2024 seasons. Notably, the combination of CRU with a moderate level of potassium (CRU×MCRK) exhibited the most favorable effects. This treatment not only significantly enhanced soil fertility and mitigated soil acidification but also improved nutrient use efficiency and promoted wheat growth compared to the standard urea treatment.

Conflicts of Interest: The authors declare no competing financial interests.

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