Journal of Integrative Agriculture 2026, 25(7): 2783–2795

Available online at ScienceDirect

Journal of Integrative Agriculture



RESEARCH ARTICLE

An application strategy of combined controlled-release fertilizers can balance the yield and quality of soft wheat while meeting its nutrient requirements

Yingpeng Wang[1, 2*], Yifan Hua[1*], Lanxin Mei[1], Yixuan Meng[1], Yongtao Guo[2], Jian Cai[1], Mei Huang[1], Yingxin Zhong[1], Xiao Wang[1], Dong Jiang[1], Qin Zhou[1#]

[1] *National Technique Innovation Center for Regional Wheat Production/Key Laboratory of Crop Ecophysiology, Ministry of Agriculture and Rural Affairs/ College of Agriculture, Nanjing Agricultural University, Nanjing 210095, China*
[2] *The Kaifeng Seed Industry Development Center, Kaifeng 475000, China*

Highlights

- A combination of different types of slow-controlled release nitrogen fertilizer (BRNF) is recommended for soft wheat production. The N release from BRNF corresponded well to the N demand of soft wheat.
- By providing a continuous and stable supply of nutrients, BRNF can increase the accumulation of photosynthetic products and the contribution rate of post-anthesis dry matter accumulation to grain.
- By reducing the excessive supply of N at the later stages of wheat growth, BRNF can reduce the protein content in wheat grains, thereby maintaining the unique quality of soft wheat.

Abstract

The application of slow-controlled release fertilizer is a simple and labor-saving cultivation technology that can improve the yield and nitrogen use efficiency (NUE) of wheat, although research on the impact of a single application of controlled-release nitrogen (N) fertilizers with different release periods on wheat grain quality is still limited. In this study, urease inhibitor urea (AHA), sulfur-coated urea (SCU), a combination of SCU and AHA fertilizer (BSAF) and blended slow-controlled release fertilizer (BRNF) were used to investigate the effect of slow-controlled release fertilizers on the nutrient release, grain yield, NUE, and protein content of soft wheat. The goal was to determine the effect of a one-time application of controlled release fertilizer on wheat grain yield and protein content and its underlying mechanisms. The results showed that the different slow-controlled release fertilizer treatments had significantly different N release rates. AHA presented a fast release mode, while SCU and BSAF presented slow-release modes, and BRNF presented a controlled release mode. Compared with CK, BRNF increased grain yield and reduced the protein content of soft wheat, with an average increase of 6.73% in grain yield and a reduction of 1.85% in protein content. The higher N absorption of BRNF led to greater NUE, N agronomic efficiency (NAE) and N apparent recovery fraction (NRF). However, AHA, SCU and BSAF all showed the opposite trend. Compared with CK, BRNF improved post-anthesis dry matter accumulation (PDMA) and the contribution rate of dry matter accumulated post-anthesis to the grain (CDA), while reducing post-anthesis N accumulation (PNA) and the contribution rate of post-anthesis N accumulation to grain (CNA). The main reasons for the improvement in yield and reduction in protein content were related to the increases in PDMA and CDA, and the reductions in PNA and CNA, respectively. Therefore, BRNF is an effective agronomic strategy for promoting the coordination of grain yield and quality in soft wheat.

Keywords: soft wheat, slow-controlled release fertilizer, nutrient release, protein content, N use efficiency

Received 9 October 2024; Received in revised form 26 January 2025; Accepted 7 February 2025; Available online 20 February 2025
[#]Correspondence Qin Zhou, Tel: +86-25-84399627, E-mail: qinzhou@njau.edu.cn
[*] These authors contributed equally to this study.

© 2026 CAAS. Publishing services by Elsevier B.V. on behalf of KeAi Communications Co. Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/). Peer review under responsibility of Editorial Board of *Journal of Integrative Agriculture*.
doi: 10.1016/j.jia.2025.02.038

1. Introduction

Soft wheat is suitable for making biscuits, pastries, and other foods since it has less protein in the grain (Morris *et al.* 2020). However, there is a large shortage of soft wheat suitable for making biscuits in the Chinese market (Zheng *et al.* 2021). Therefore, studying production technologies suitable for soft wheat is essential. Studies have shown that grain protein content is significantly influenced by nitrogen (N) fertilizer management and there is a positive correlation between grain protein content and N application rate (Sieling *et al.* 2021; Wang *et al.* 2023). In addition, the reduction of N topdressing at the jointing period is beneficial to the production of biscuit wheat, but the yield also shows a downward trend at the same time (Yu *et al.* 2017; Zheng *et al.* 2020). Meanwhile, the unreasonable application of common urea is widespread, causing environmental pollution and low N use efficiency (NUE) (Yu *et al.* 2022). Therefore, figuring out how to balance the yield and quality and improve the NUE of soft wheat is an important research topic.

Slow-controlled release fertilizer is new type of fertilizer that is attracting more attention because of its long release period, and its nutrient release is synchronized with crop absorption (Lawrencia *et al.* 2021). Previous studies have shown that a one-time basal application of slow-controlled release fertilizers can increase crop yields and NUE, while reducing environmental pollution in rice, maize, and cotton (Yang *et al.* 2017; Ma *et al.* 2023; Gao *et al.* 2024; Jiang *et al.* 2024). In addition, slow-controlled release N fertilizer is also recommended for wheat production. Ma *et al.* (2021) reported that applying slow-controlled release N fertilizer twice before sowing and during re-greening maintained a higher level of soil inorganic N after jointing, which met the need for the second N uptake peak of wheat. Moreover, it is beneficial for delaying leaf senescence and the decline in photosynthetic performance during the later grain-filling stage, and it significantly increases dry matter accumulation after anthesis and grain yield (Ma *et al.* 2022a). Although slow-controlled release N fertilizers have great advantages in terms of yield, NUE, and environmental friendliness, the impact of slow-release fertilizers on the wheat grain protein content is still controversial. For example, Rekowski *et al.* (2020) showed that the addition of urease inhibitor urea can increase the content of protein and composition of wheat due to the improvement of x-type high molecular weight (HMW) gluten subunits. Zhang *et al.* (2022b) showed that a one-time mixed application of controlled-release urea and normal urea can increase the protein content of wheat, while the increase in grain protein content was mainly attributed to elevated post-anthesis N accumulation and its improved contribution to grain N content. However, De Santis *et al.* (2020) showed that a one-time basal application of slow-controlled release fertilizers can reduce the protein content without affecting the wheat yield, mainly because the release characteristics of different slow-controlled release fertilizers are inconsistent.

Slow-controlled release N fertilizers may affect the tillering during early wheat growth and thus panicle number, resulting in lower yields (Shang *et al.* 2021; Ding *et al.* 2023). Moreover, wheat has a long growth duration of more than 210 days, and the effective release cycle of most slow-controlled release fertilizers is shorter, so they cannot meet the N demand of wheat, especially in the later growth stage (Ma *et al.* 2021). A new fertilizer strategy has been proposed that involves blending fertilizers with varying controlled release periods to regulate nutrient release rates at different growth stages (Zheng *et al.* 2016). In addition, the mixed treatments significantly enhance both the quality and quantity of wheat tillering, while also improving the N uptake and utilization efficiency of the wheat. The primary reason for the observed outcomes is that the N release characteristics of the fertilizer mixtures correspond well with the N demands during different growth periods of wheat (Zheng *et al.* 2016). While different formulations of slow-controlled release fertilizer can achieve the synergic increases in yield and NUE of wheat, their effect on the yield and quality of soft wheat is still unclear.

The simultaneous improvement of wheat yield and quality has become an important goal of modern wheat production in China. Slow-controlled release fertilizers can gradually release nutrients according to the growth needs of wheat, and improve fertilizer utilization efficiency, which is of great significance for the growth and quality improvement of soft wheat. Therefore, finding the best slow-controlled release N fertilizer strategy to achieve synergistic improvements in wheat yield and quality is urgently needed. To that end, this study investigated the effects of a one-time application of various combinations of controlled released N fertilizers on wheat yield and quality. In this study, different slow-controlled release fertilizers and combinations were used to study the effects on grain yield, protein content and N absorption and transport in soft wheat. The objective was to investigate the technological ways to achieve a synergistic rise in soft wheat yield and protein quality. In addition, this study aims to furnish a theoretical framework and technical assistance for the cultivation of soft wheat in the middle and lower reaches of the Yangtze River.

2. Materials and methods

2.1. Experimental materials and growth conditions

The field experiments were performed during two wheat growing seasons (2019–2020 and 2020–2021) in the experimental stations of Jiangyan County (32°24′N, 120°3′E) and Jurong County (31°57′N, 119°10′E), Jiangsu Province, China. During the growing seasons of wheat from 2019 to 2021 in the Jurong ecological site, the average daily temperatures were 11.5 and 11.3°C, the total rainfall amounts were 404.0 and 449.6 mm, and the average daily peak sunlight hours were 4.9 and 4.9 h, respectively. During the growing seasons of wheat of the Jiangyan ecological site from 2019 to 2021, the average daily temperatures were 10.9 and 10.4°C, the total rainfall amounts were 309.5 and 339.0 mm, and the average daily peak sunlight hours were 5.0 and 5.0 h, respectively (Appendix A). The soft winter wheat cultivar Yangmai 22, a widely grown soft wheat cultivar in the Yangtze River Downstream area, was used in loam soil (Jiangyan site) and clay soil (Jurong site). The basic soil fertility data for the two test sites before sowing are shown in Appendix B.

The field experiments were laid out in a randomized design with three replicates. This study included five N

fertilizer treatments (Appendix C): urea (CK), sulfur-coated urea (SCU), 26% N, with a fertilizer release duration of 3–4 months), AHA (urease inhibitor urea, 25% N, by adding urease inhibitor to delay fertilizer release, with a fertilizer release duration less than 1 month), BSAF (SCU and AHA blended at ratio of 1:1, with a fertilizer release duration of 3–4 months) and BRNF (blended slow-controlled release fertilizer, 25% N, a mixture of common urea, sulfur-coated urea and polymer-coated urea at ratio of 1:1:1, with a fertilizer release duration of 4–5 months). All the fertilizers were provided by the Hanfeng Slow-Release Fertilizer Company (Jiangsu Province, China).

Ordinary urea (CK) was applied at the sowing and jointing stages with a ratio of 7:3. SCU, AHA, BSAF, and BRNF were applied as basal fertilizers. The N, phosphate (P_2O_5) and potassium (K_2O) fertilizers were applied at rates of 210, 120, and 120 kg ha^{-1}, respectively. A blank treatment without N application (N0) was used to calculate the NUE. Each plot (3 m×5 m) consisted of 12 rows of wheat with row spacing of 25 cm. Sowing dates were 2 November, 2019 and 31 October, 2020 in Jiangyan, and 11 November, 2019 and 11 November, 2020 in Jurong. Harvest dates were 22 May, 2020 and 24 May, 2021 in Jiangyan, and 24 May, 2020 and 29 May, 2021 in Jurong. Other field management was conducted following the local practices.

2.2. Measurements

The N release characteristics of slow-controlled release fertilizers The N release rates of slow-controlled release fertilizers in the field were measured using the embedding bag method (Yang *et al.* 2011). A total of 10 g of fertilizer was placed into a nylon mesh bag (10 cm×5 cm) with a mesh diameter of 1.0 mm, and buried in the field at a depth of 10–15 cm. Three replicates were sampled at 30, 60, 90, 120, 135, and 150 d after incubation. Samples were cleaned with distilled water and then dried in an oven at 30°C to constant weight. The weight of the remaining fertilizer was measured, and the N loss was calculated. The calculation formulas were as follows:

N cumulative release rate (%)=(Total fertilizer weight−Remaining fertilizer weight)/Total fertilizer weight×100 (1)

Interval N release rate (%)=Interval N loss weight/Total fertilizer weight×100 (2)

Inorganic N content Soil samples (0–20 cm) were collected from five locations in each plot using a soil auger. After mixing well, a composite sample from each plot was packaged and stored in a freezer at –40°C. After extraction with 2 mol L^{-1} KCl, the soil NH_4^+−N and NO_3^-−N concentrations were determined using an auto-analyzer (Model AA3-A001-02E, Bran-Luebbe, Norderstedt, Germany) (Wang *et al.* 2021).

Determination of yield and its components At the maturity stage, the number of spikes in a 0.5 m^2 area in the center of each plot was counted. The harvested spikes were threshed, air-dried and weighed to determine the yield and 1,000-grain weight. Both grain yield and 1,000-grain weight were adjusted to a standard moisture content of 13%. The number of kernels per spike for each treatment was taken as an average of 20 consecutive spikes.

Dynamics of tillers and the percentage of productive tillers The number of tillers in the population was counted at key growth stages, including the overwintering, jointing, booting, and anthesis stages. The percentage of productive tillers was calculated as the ratio of the number of effective spikes at the mature stage to the maximum number of tillers at the jointing stage.

Chlorophyll content The relative chlorophyll content (SPAD) was measured in flag leaves using a SPAD chlorophyll meter (SPAD-502, Minolta, Japan) between 9:00 and 11:00 a.m. during the anthesis and grain-filling stages. SPAD values were calculated as the average for the upper, middle, and lower parts of the flag leaves.

Normalized difference vegetation index (NDVI) An EcoDroneUAS-8 Multi-Spectral UAV equipped with Red-Green-Blue (RGB) and multi-spectral sensors (Beijing EcoTech Science and Technology Ltd., China) was used to take photos from 11:00–13:00 on sunny days at the wheat growth stages of jointing, booting, flowering and milking. Pix4Dmapper software was used to splice UAV images and obtain the UAV digital orthophoto image. The five canopy reflectance band values were extracted with ENVI software for processing and analyzing the UAV multi-spectral images. The calculation formula according to Duan *et al.* (2017) was:

$$NDVI=(R_{nir}-R_{red})/(R_{nir}+R_{red}) \quad (3)$$

where R_{nir} and R_{red} are the reflectance spectra of near infrared band and red-light band, respectively.

Contents of protein and wet gluten The grain N content was determined using the micro-Kjeldahl method (Kong *et al.* 2024), which was multiplied by the coefficient of 5.7 to obtain grain protein content. The wet gluten content was measured with a gluten instrument (Perten Instruments AB, Stock-holm, Sweden) according to the method of Zhang *et al.* (2024).

2.3. Accumulation and remobilization of dry matter and N

The dry matter, N accumulation and remobilization were calculated according to Zhang *et al.* (2022a):

Pre-anthesis dry matter remobilization amount (PDRA)=Dry matter accumulation of vegetative organs at anthesis (DMAA)–Dry matter accumulation of vegetative organs at maturity (4)

Post-anthesis dry matter accumulation (PDMA)=Dry matter accumulation at maturity (DMAM)–DMAA (5)

Contribution rate of dry matter remobilized pre-anthesis to the grain (CDP) (%)=PDRA/Grain dry weight×100 (6)

Contribution rate of dry matter accumulated post-anthesis to the grain (CDA)=1−CDP (7)

Pre-anthesis N remobilization amount (NRA)=N accumulation at the anthesis stage (NAA)–N accumulation in vegetative organs at maturity (8)

Post-anthesis N accumulation (PNA)=N accumulation at the maturity stage (NAM)–NAA (9)

Contribution rate of N remobilized pre-anthesis to the grain (CNP) (%)=NRA/Grain N accumulation×100 (10)

Contribution rate of N accumulated post-anthesis to the grain (CNA)=1–CNP (11)

The N use efficiency (NUE; kg kg^{-1}), N agronomic

efficiency (NAE; kg kg^{-1}), N apparent recovery fraction (NRF, %), and N physiological efficiency (NPE; kg kg^{-1}) were calculated according to Ke *et al.* (2023):

$$\text{NUE (kg kg}^{-1}\text{)}=Y_N\times U_N^{-1} \quad (12)$$

$$\text{NAE (kg kg}^{-1}\text{)}=(Y_N-Y_0)\times F_N^{-1} \quad (13)$$

$$\text{NRF (\%)}=(U_N-U_0)\times F_N^{-1}\times 100 \quad (14)$$

$$\text{NPE (kg kg}^{-1}\text{)}=(Y_N-Y_0)\times (U_N-U_0)^{-1} \quad (15)$$

where Y_N and Y_0 are the total yields (kg ha^{-1}) at maturity with and without N fertilizer, respectively; U_N and U_0 are the total N uptake (kg N ha^{-1}) values at maturity with and without N fertilizer input, respectively; and F_N^{-1} is the N fertilizer input amount (kg ha^{-1}). The yield and N accumulation without N fertilizer are shown in Appendix D.

The N nutrition index (NNI) and accumulative N deficit (AND) were calculated according to Yin *et al.* (2018):

$$\text{NNI}=N_a/N_c \quad (16)$$

where N_a is the actual N content (%) and N_c is the critical N content (%).

$$\text{AND (kg ha}^{-1}\text{)}=N_A-N_Ac \quad (17)$$

where N_A is the actual N accumulation (kg ha^{-1}) and N_Ac is the critical N accumulation (kg ha^{-1})

2.4. Statistical analysis of data

Analysis of variance was performed to analyze differences among the various treatments using SPSS version 25.0. (SPSS Statistics, SPSS Inc., Chicago, USA). The means were compared using LSD at P=0.05 and P=0.01 (LSD 0.05 and LSD 0.01). Pearson's correlation analysis was also performed using SPSS 25.0. All figures were drawn with Origin 2021.

3. Results

3.1. The N release rate and inorganic N content in the soil

The N cumulative curves and interval release percentages of different slow-controlled release fertilizers are shown in Fig. 1. According to their release characteristics, they can be divided into three types. AHA showed an explosive release at the early stage and no release at the later stage, exhibiting an inverted "L" type of release mode. There was no significant difference between the two fertilizer treatments of SCU and BSAF, with both showing a slow-release mode. BRNF was partially released at the early stage and continuously released at the middle stage, and the overall release mode was an "S" type. The N cumulative release rate of AHA reached 90.10% at 0–30 d, which was significantly higher than those of SCU, BSAF, and BRNF. The N cumulative release rates of SCU and BSAF were greater than 80% after 90 d of incubation. The N cumulative release rate of BRNF was 58.07% after 60 d of incubation, and nearly 100% at 120 d. The interval N release rates of AHA, SCU and BSAF showed successive reductions at 0–30 d, 30–60 d, and 60–90 d, respectively. The interval N release rates of BRNF at 0–30 d and 30–60 d were 36.43 and 21.63%, respectively. While the interval N release rate showed a downward trend at 60–90 d it then increased at 90–120 d.

The release of N from the different slow-controlled release fertilizers also affected the dynamic changes in the soil inorganic N content during the growth process of wheat (Fig. 2). The soil inorganic N contents of CK, AHA, SCU, and BSAF showed continuous declining trends during the whole growth period. BRNF showed an upward trend from the over-wintering stage to booting stage and then gradually decreased. The content of inorganic N for BRNF was higher than the other treatments from the booting to maturity stages. At the over-wintering stage, the soil inorganic N content of BRNF showed a decreasing trend compared with CK, with an average decrement of 6.36%, but it then increased at the booting, anthesis and maturity stages, with average increments of 9.18, 32.48 and 16.13%, respectively. Compared with CK, the soil inorganic N content of AHA

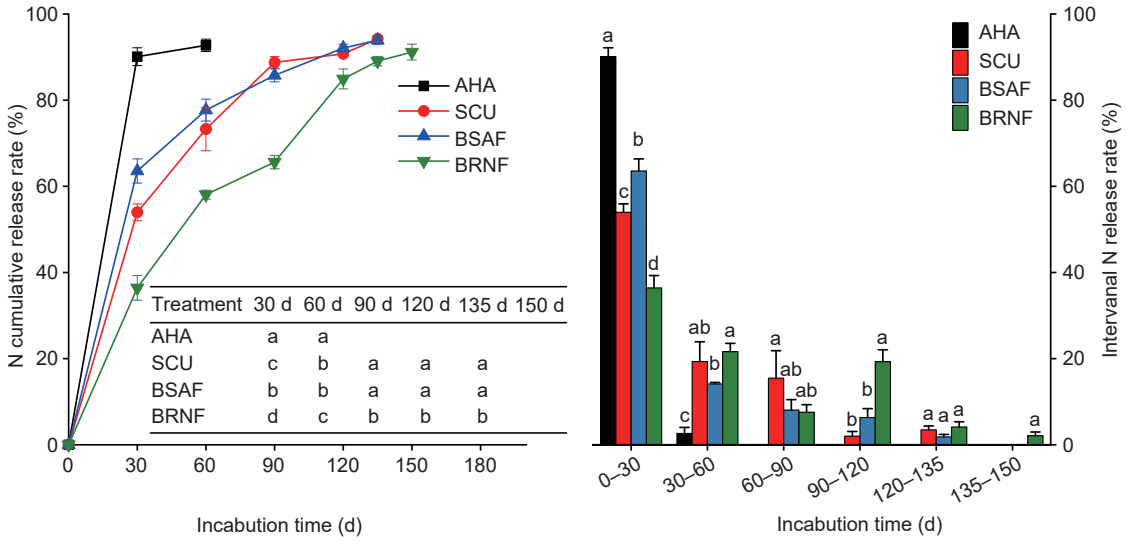


Fig. 1 The N cumulative and interval release rates of different slow-controlled release fertilizers in soil. AHA, urease inhibitor urea; SCU, sulfur-coated urea; BSAF, SCU and AHA blended at 1:1; BRNF, a mixture of common urea, sulfur-coated urea and polymer-coated urea at ratio of 1:1:1. Bars indicate SD of three replicates. Different lowercase letters indicate significant differences at the 0.05 level.

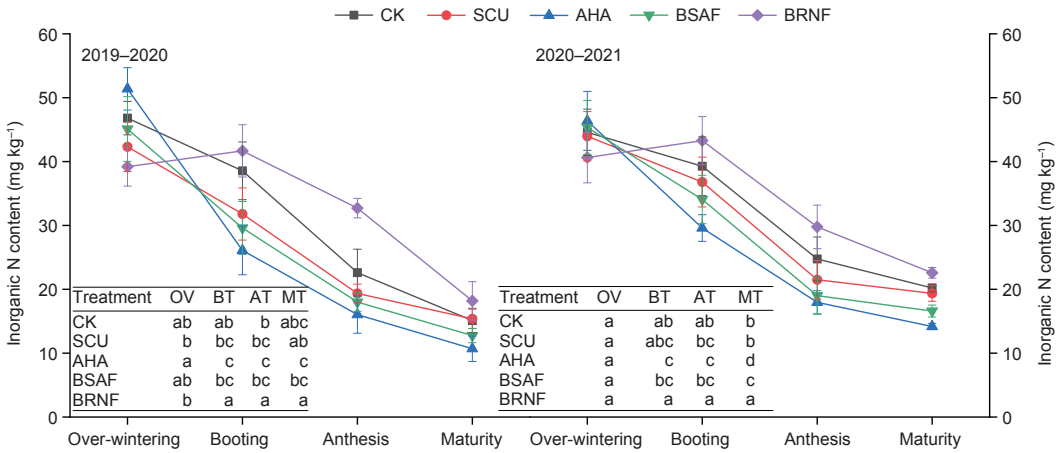


Fig. 2 Effects of different slow-controlled release fertilizers on inorganic N content in the soil (Jurong, Jiangsu Province, China). CK, urea applied at two stages; SCU, sulfur-coated urea; AHA, urease inhibitor urea; BSAF, SCU and AHA blended at 1:1; BRNF, a mixture of common urea, sulfur-coated urea and polymer-coated urea at ratio of 1:1:1. OV, over-wintering; BT, booting; AT, anthesis; MT, maturity. Bars indicate SD of three replicates. Different lowercase letters indicate significant differences at the 0.05 level.

showed an increasing trend at the over-wintering stage, with an average increment of 6.91%, but decreasing trends at the other growth stages. Compared with CK, SCU and BSAF showed decreasing trends at all growth stages.

3.2. Grain yield, dry matter accumulation and remobilization

The effects of different slow-controlled release fertilizers on grain yield and the yield components are shown in Table 1. Compared with CK, the average grain yields of SCU, AHA and BSAF were reduced by 7.28, 16.78 and 3.88% in both years and ecological sites, respectively. In contrast, the average grain yield of BRNF increased by 6.73% in both years and ecological sites. The grain yield at the Jiangyan site was higher than the Jurong site under the same treatment and experimental year, with an average increment of 10.90%. However, BRNF had a higher yield increment in Jurong than Jiangyan compared with CK during the two growing seasons, with an average increment of 6.73%. BRNF increased the grain yield, which was primarily due to increases in the spike number and TGW compared with CK. The yields of SCU, AHA and BSAF showed downward trends compared with CK.

The effects of different slow-controlled release fertilizers on dry matter accumulation and remobilization of soft wheat are shown in Table 2. The DMAA, DMAM, and CDA among different slow-controlled release fertilizers generally showed the order of BRNF>CK>BSAF>SCU>AHA. Compared with CK, BRNF showed increasing trends for DMAM and PDMA, with increase rates of 11.37–14.63% and 9.18–21.28%, respectively. But SCU, AHA and BSAF showed downward trends. Compared with CK, CDA increased in the BRNF treatment, while it decreased in SCU, AHA and BSAF.

3.3. Tiller dynamics, NDVI value and chlorophyll content

The effects of different slow-controlled release fertilizers on tiller number and the percentage of productive tillers of soft wheat are shown in Figs. 3 and 4. The tiller number increased to its maximum at the jointing stage, and then gradually decreased from jointing to the anthesis stage. Compared with CK, AHA had the highest tiller numbers at the over-wintering and jointing stages, with average increments of 6.42 and 4.23%. But BRNF showed a decreasing trend at the over-wintering stage, with an average decrement of 6.36%. In the flowering period, BRNF increased the spikes per unit area by 7.25% compared with CK, while SCU and AHA showed significant downward trends. Compared with CK, the tiller-to-spike ratio of BRNF increased significantly, with an average increment of 4.83%, while SCU and AHA showed significant downward trends.

As the growth process progressed, the NDVI value increased rapidly after the jointing stage, increased to a maximum at the booting stage, and then gradually decreased from booting to the grain-filling stage (Fig. 5). At the booting stage, the NDVI in BRNF was significantly higher than in CK, with an average increment of 8.60%. The NDVI in AHA was significantly lower than in CK, with an average decrement of 14.30%. In the flowering period, compared with CK, the NDVI in BRNF increased by 5.52% on average, and the values of the other treatments decreased by 2.14–15.82%.

Different slow-controlled release fertilizers also affected the chlorophyll content (SPAD) of flag leaves after flowering (Fig. 6). During the flowering period, the SPAD values of AHA and BSAF showed significantly decreasing trends compared with CK, with average decrements of 14.41 and 8.54%, respectively. BRNF also showed a downward trend compared with CK, but there was no significant difference. The SPAD at the filling stage was basically the same as at the flowering stage. Compared with CK, the SPAD values in SCU, AHA and BSAF all showed significant downward trends, with average reductions of 7.66, 14.71 and 10.66%, respectively.

3.4. N accumulation and remobilization, protein content, wet gluten content, and NUE

The N accumulation at anthesis and maturity at the Jiangyan experimental site was higher than at the Jurong experimental

Table 1 Effects of different slow-controlled release fertilizers on the grain yield and yield components of soft wheat[1)]

Year	Site[2)]	Treatment[3)]	Spikes ($\times10^4$ ha^{-1})	GN/spike	TGW (g)	GY (kg ha^{-1})
2019–2020	Jiangyan	CK	464 ab	43.11 a	41.61ab	7,529 ab
		SCU	437 c	42.92 a	41.00ab	6,980 c
		AHA	431 c	43.06 a	40.73 b	6,324 d
		BSAF	444 bc	42.77 a	41.85 ab	7,167 bc
		BRNF	482 a	42.06 a	42.77 a	7,940 a
	Jurong	CK	436 b	41.39 a	40.86 ab	6,760 b
		SCU	403 c	42.58 a	40.63 ab	6,275 d
		AHA	402 c	42.11 a	39.68 b	5,437 e
		BSAF	426 b	41.86 a	39.83 b	6,423 c
		BRNF	467 a	40.82 a	41.98 a	7,398 a
2020–2021	Jiangyan	CK	448 b	43.80 a	40.63 a	7,222 a
		SCU	423 bc	44.30 a	41.03 a	6,547 bc
		AHA	417 c	45.07 a	41.20 a	6,318 c
		BSAF	433 bc	43.60 a	41.07 a	6,863 b
		BRNF	475 a	42.83 a	42.37 a	7,497 a
	Jurong	CK	435 b	44.00 a	38.30 a	6,541 b
		SCU	395 c	42.47 a	39.17 a	6,088 b
		AHA	376 c	43.47 a	39.33 a	5,297 c
		BSAF	405 bc	42.13 a	39.03 a	6,349 b
		BRNF	467 a	41.57 a	40.23 a	7,080 a
F-value						
F_{Y}			10.13**	10.62**	7.42*	21.09**
F_{L}			42.98**	12.35**	26.66**	161.91**
F_{T}			42.11**	3.08*	7.24**	106.12**
$F_{Y\times T}$			0.60 ns	0.62 ns	1.28 ns	0.99 ns
$F_{Y\times L}$			0.04 ns	0.07 ns	2.15 ns	1.09 ns
$F_{T\times L}$			1.25 ns	0.09 ns	0.57 ns	2.30 ns
$F_{Y\times T\times L}$			0.52 ns	0.81 ns	0.40 ns	0.42 ns

[1)] GN, grain number; TGW, 1,000-grain weight; GY, grain yield.
[2)] Jiangyan and Jurong, Jiangsu Province, China.
[3)] CK, urea applied at two stages; SCU, sulfur-coated urea; AHA, urease inhibitor urea; BSAF, SCU and AHA blended at 1:1; BRNF, a mixture of common urea, sulfur-coated urea and polymer-coated urea at ratio of 1:1:1. F_{Y}, F_{L} and F_{T} indicate the main effects of year, location and treatment. $F_{Y\times T}$, $F_{Y\times L}$, $F_{T\times L}$, and $F_{Y\times T\times L}$ indicate the interaction effects between year and treatment, year and location, treatment and location, and year, treatment and location.
Different lowercase letters in the same column within the same year and same site indicate significant differences at the 0.05 probability level. *, ** and ns indicate significant levels of 0.05 and 0.01 and not significant, respectively.

site among all treatments (Table 3). NAA and NAM showed similar trends at the two sites and years. BRNF showed an increasing trend compared with CK, with average increments of 6.87 and 4.09%, respectively. However, SCU, AHA and BSAF showed decreasing trends. Compared with CK, the PNA in treatments with BRNF, SCU, BSAF and AHA decreased, with reductions of 4.72, 28.82, 31.11, and 47.91%, respectively. Compared with CK, all slow-controlled release fertilizers reduced CNA in the order of AHA>BSAF>SCU>BRNF.

Compared with CK, the protein contents of treatments SCU, AHA, BSAF, and BRNF all showed downward trends, with average declines of 5.10, 8.91, 6.80, and 1.85%, respectively (Fig. 7). Similar to the protein contents, the wet gluten contents were also in the order of CK>BRNF>SCU>BSAF>AHA. Compared with CK, AHA showed the largest reduction, with an average of 15.54%, while BRNF showed the smallest reduction, with an average of 2.41%. The ranges of SCU and BSAF decreased from 6.99 to 10.54%.

The NAE, NUE, and NRF showed similar trends for the two years and experimental sites (Table 3). Compared with CK, the NAE, NUE, and NRF in treatment BRNF showed increasing trends, with average increments of 9.68, 6.10 and 7.16%, respectively, but they decreased in treatments SCU, BSAF and AHA. The rankings of NAE, NUE and NRF in these treatments were all BRNF>CK>BSAF>SCU>AHA. Compared with CK, the NPE in treatment AHA significantly increased for the two years and experimental sites, with an average increment of 36.96%. However, there was no significant difference in NPE between BRNF and CK, and the NPE in BSAF and SCU showed increasing trends, ranging from 12.81 to 30.29%.

3.5. N nutrition index and accumulated N deficit

The effects of different types of slow-controlled release fertilizers on the NNI and AND of soft wheat are shown in Fig. 8. At the jointing period, BRNF significantly increased the NNI and AND compared with CK. AHA had the lowest NNI and the highest AND. At the booting stage, the NNI values of CK and BRNF were closer to 1, and the AND values were –1.29 and 5.33 kg ha^{-1}, respectively. Compared with CK, the NNI values of SCU, AHA and BSAF were significantly reduced. At the flowering stage, the NNI values of all treatments were lower than 1. Compared with CK, BRNF showed no significant difference, while the other treatments showed a significantly downward trend.

3.6. Correlation analysis between N accumulation, yield, and protein content

The grain yield and protein content of soft wheat showed significantly positive relationships with the NAA, NAM and PNA in both years and experimental sites (Fig. 9). The coefficient of determination (R^2) for the linear regression equation between grain yield and NAA or NAM were the highest. The coefficient of determination for the linear regression equation for protein content and PNA was the highest. This indicated that PNA is more important for protein content, and NAA and NAM are more important for yield formation. BRNF provides a stable N supply throughout all wheat growth periods, which can stabilize the wheat yield. At the same time, the protein content was decreased by reducing the PNA.

4. Discussion

4.1. The N release characteristics of different slow-controlled release fertilizers, and N absorption and utilization

The N release characteristics of different types of slow-controlled release fertilizer showed significant differences (Fig. 1). SCU showed a slow-release mode, while BRNF had a long effective release period and showed a controlled release mode. The difference is mainly related to the outer material and formulations of the fertilizers. In addition, soil temperature, moisture and microbes are also important factors influencing N release (Yang *et al.* 2011; Geng *et al.*

Table 2 Effects of different slow-controlled release fertilizers on dry matter accumulation and remobilization in soft wheat[1)]

Year	Site[2)]	Treatment[3)]	DMAA (kg ha^{-1})	DMAM (kg ha^{-1})	PDMA (kg ha^{-1})	CDP (%)	CDA (%)
2019–2020	Jiangyan	CK	11,047 b	17,069 b	6,023 b	27.12 bc	72.88 ab
		SCU	11,454 ab	16,641 b	5,187 cd	30.90 ab	69.10 bc
		AHA	10,078 c	14,892 c	4,814 d	33.86 a	66.14 c
		BSAF	11,283 b	17,032 b	5,749 bc	29.28 ab	70.72 bc
		BRNF	12,310 a	19,010 a	6,701 a	24.09 c	75.91 a
	Jurong	CK	9,900 b	15,072 b	5,173 b	27.89 cd	72.11 ab
		SCU	9,667 b	13,910 c	4,243 cd	33.26 ab	66.74 cd
		AHA	8,607 c	12,321 d	3,714 d	37.05 a	62.95 d
		BSAF	9,795 b	14,581 bc	4,786 bc	31.67 bc	68.33 bc
		BRNF	11,012 a	17,276 a	6,264 a	25.28 d	74.72 a
2020–2021	Jiangyan	CK	9,932 bc	15,413 b	5,481 ab	26.79 bc	73.21 ab
		SCU	9,642 cd	14,149 c	4,507 cd	30.10 b	69.90 b
		AHA	9,211 d	13,402 d	4,190 d	37.71 a	62.29 c
		BSAF	10,356 b	15,341 b	4,985 bc	28.69 bc	71.31 ab
		BRNF	11,234 a	17,219 a	5,984 a	24.58 c	75.42 a
	Jurong	CK	9,541 b	14,258 b	4,717 b	28.46 bc	71.54 ab
		SCU	8,703 cd	12,569 cd	3,866 cd	33.18 ab	66.82 bc
		AHA	8,188 d	11,817 d	3,629 d	36.58 a	63.42 c
		BSAF	9,158 bc	13,319 c	4,161 c	31.17 abc	68.83 abc
		BRNF	10,218 a	15,938 a	5,721 a	26.60 c	73.40 a
F-value							
F_Y			25.33**	52.36**	34.20**	0.04 ns	0.04 ns
F_L			62.56**	124.15**	77.76**	11.39*	11.39*
F_T			53.86**	102.91**	65.65**	26.09**	26.09**
$F_{Y\times T}$			1.90 ns	1.64 ns	0.99 ns	0.19 ns	0.19 ns
$F_{Y\times L}$			48.08**	30.78**	1.10 ns	0.19 ns	0.19 ns
$F_{T\times L}$			1.51 ns	1.75 ns	1.61 ns	0.33 ns	0.33 ns
$F_{Y\times T\times L}$			0.35 ns	0.21 ns	0.04 ns	0.01 ns	0.01 ns

[1)] DMAA, dry matter accumulation at anthesis; DMAM, dry matter accumulation at maturity; PDMA, post-anthesis dry matter accumulation; CDP, contribution rate of dry matter remobilized pre-anthesis to the grain; CDA, contribution rate of dry matter accumulated post-anthesis to the grain.
[2)] Jiangyan and Jurong, Jiangsu Province, China.
[3)] CK, urea applied at two stages; SCU, sulfur-coated urea; AHA, urease inhibitor urea; BSAF, SCU and AHA blended at 1:1; BRNF, a mixture of common urea, sulfur-coated urea and polymer-coated urea at ratio of 1:1:1. F_Y, F_L and F_T indicate the main effects of year, location and treatment. $F_{Y\times T}$, $F_{Y\times L}$, $F_{T\times L}$, and $F_{Y\times T\times L}$ indicate the interaction effects between year and treatment, year and location, treatment and location, and year, treatment and location.
Different lowercase letters in the same column within the same year and same site indicate significant differences at the 0.05 probability level. *, ** and ns indicate significant levels of 0.05 and 0.01 and not significant, respectively.

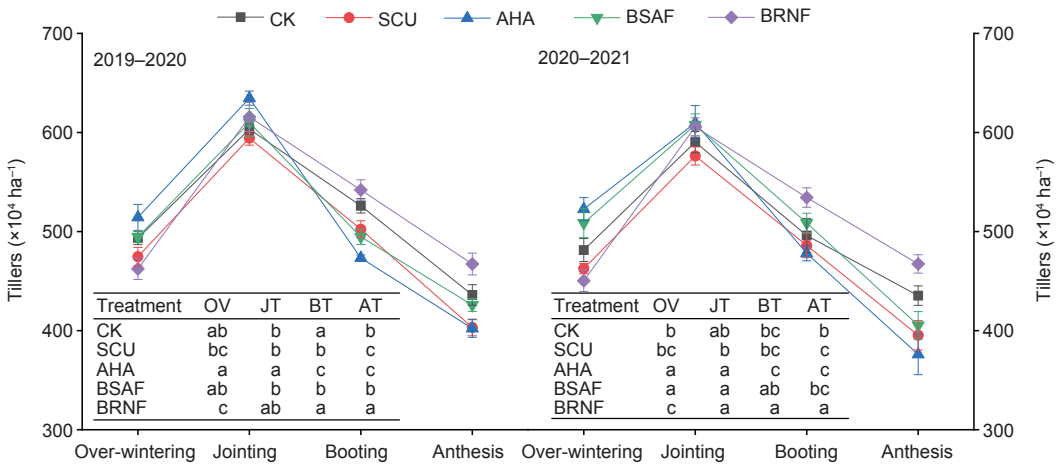


Fig. 3 Effects of different slow-controlled release fertilizers on tiller number dynamics of soft wheat (Jurong, Jiangsu Province, China). CK, urea applied at two stages; SCU, sulfur-coated urea; AHA, urease inhibitor urea; BSAF, SCU and AHA blended at 1:1; BRNF, a mixture of common urea, sulfur-coated urea and polymer-coated urea at ratio of 1:1:1. OV, over-wintering; JT, jointing; BT, booting; AT, anthesis. Bars indicate SD of three replicates. Different lowercase letters indicate significant differences at the 0.05 level.

2016; Naz *et al.* 2016).

The soil inorganic N content can directly affect the growth and development of wheat, and its changes can be used to assess the dynamic relationships between the N supply of fertilizer and N uptake by wheat (Ma *et al.* 2021). Common urea treatment can increase the soil inorganic N content in a short time after the application of basal fertilizer and topdressing at the jointing stage (Shakoor *et al.* 2018). However, slow-controlled release fertilizer can delay N release and reduce the risk of N loss. In this study, soil inorganic N in AHA, SCU and BSAF showed trends of continuous reduction during the whole growth period (Fig. 2). Although the common urea treatment had a topdressing at the jointing stage, it also showed a trend of a continuous reduction during the whole growth period. Therefore, the N supplies in CK, AHA, SCU and BSAF may not meet the N requirement at the later stage of wheat. BRNF showed an upward trend from over-wintering to the booting stage and then gradually decreased. Although BRNF did not show an advantage at over-wintering, it maintained a higher soil inorganic N content from booting to the maturity stage, which could meet the need for N absorption throughout the whole growth period of wheat.

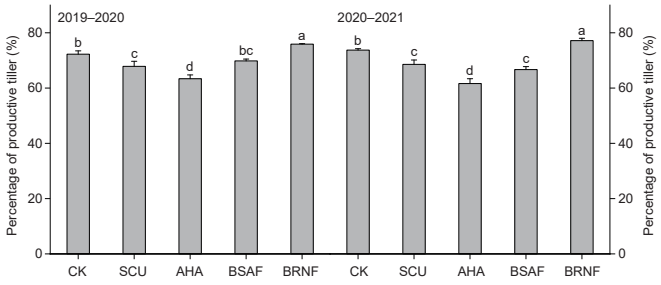


Fig. 4 Effects of different slow-controlled release fertilizers on the percentage of productive tillers in soft wheat (Jurong, Jiangsu Province, China). CK, urea applied at two stages; SCU, sulfur-coated urea; AHA, urease inhibitor urea; BSAF, SCU and AHA blended at 1:1; BRNF, a mixture of common urea, sulfur-coated urea and polymer-coated urea at ratio of 1:1:1. Bars indicate SD of three replicates. Different lowercase letters indicate significant differences at the 0.05 level.

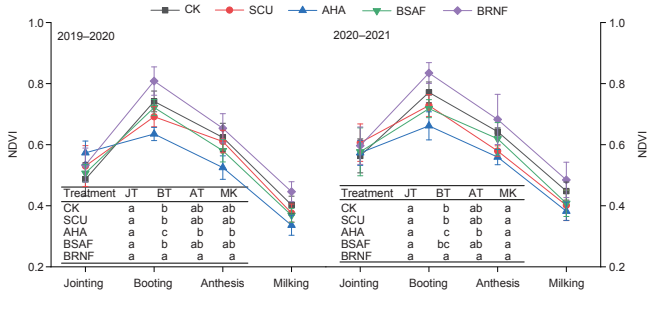


Fig. 5 Effects of different slow-controlled release fertilizers on the normalized difference vegetation index (NDVI) of soft wheat (Jurong, Jiangsu Province, China). CK, urea applied at two stages; SCU, sulfur-coated urea; AHA, urease inhibitor urea; BSAF, SCU and AHA blended at 1:1; BRNF, a mixture of common urea, sulfur-coated urea and polymer-coated urea at ratio of 1:1:1. JT, jointing; BT, booting; AT, anthesis; MK, milking. Bars indicate SD of three replicates. Different lowercase letters indicate significant differences at the 0.05 level.

NNI and AND are commonly used indexes for crop N nutrition diagnosis (Yin *et al.* 2018). Therefore, they can be used to estimate the N nutrition status of crops at critical growth stages. In this study, common urea treatment resulted in N deficiency during the jointing stage and flowering stage, while the N supply was appropriate only after topdressing at the booting stage (Fig. 8). AHA, SCU, and BSAF released more N in the early growth stage of wheat. The amount of N absorbed by wheat at the seedling stage is small, and excessive N will lead to losses. Therefore, the NNI values in AHA, SCU, and BSAF were less than 1 at the jointing, booting and flowering stages, which indicated N deficiency in the later stages of wheat. BRNF had a longer N supply period and could meet the N demand of wheat, so the NNI was closer to 1 at the jointing and booting periods. Although BRNF showed N deficiency in the flowering period, there was no significant difference compared with CK. Compared with CK, the continuous supply of N in BRNF directly promoted N absorption and utilization in wheat (Table 3). Therefore, the NUE, NAE, and NRF in BRNF showed increasing trends, while NPE showed a decreasing trend, which was consistent with previous research (Ke *et al.* 2017).

4.2. Effects of different slow-controlled release fertilizers on yield, dry matter accumulation and remobilization in soft wheat

N fertilizers are the primary factor determining wheat yield (Hu *et al.* 2023). As a new type of N fertilizer, the N release from special slow-controlled release fertilizers can meet the needs for crop N absorption (Ma *et al.* 2021; Zheng *et al.* 2016). Previous studies showed that controlled release N fertilizer has a significant advantage in promoting crop

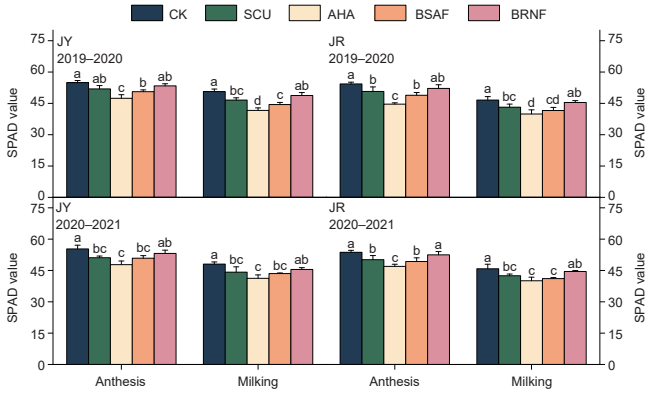


Fig. 6 Effects of different slow-controlled release fertilizers on the SPAD of soft wheat. CK, urea applied at two stages; SCU, sulfur-coated urea; AHA, urease inhibitor urea; BSAF, SCU and AHA blended at 1:1; BRNF, a mixture of common urea, sulfur-coated urea and polymer-coated urea at ratio of 1:1:1. JY and JR represent the Jiangyan site and Jurong site, respectively. Bars indicate SD of three replicates. Different lowercase letters indicate significant differences at the 0.05 level.

Table 3 Effects of different slow-controlled release fertilizers on nitrogen accumulation and remobilization and the N use efficiency (NUE) of soft wheat[1)]

Year	Site	Treatment[2)]	NAA (kg ha^{-1})	NAM (kg ha^{-1})	PNA (kg ha^{-1})	CNP (%)	CNA (%)	NUE (kg kg^{-1})	NAE (kg kg^{-1})	NRF (%)	NPE (kg kg^{-1})
2019–2020	Jiangyan	CK	166.28 b	216.94 a	50.65 a	70.78 c	29.22 a	35.85 ab	20.91 ab	55.31 a	38.01 b
		SCU	147.26 c	183.69 b	36.43 b	73.94 bc	26.06 ab	33.24 c	18.30 c	39.48 b	46.71 ab
		AHA	133.50 d	160.58 c	27.08 c	78.37 a	21.63 c	30.11 d	15.18 d	28.47 c	53.53 a
		BSAF	153.06 c	187.17 b	34.11 b	76.65 ab	23.35 bc	34.13 bc	19.19 bc	41.13 b	46.82 ab
		BRNF	182.17 a	227.71 a	45.54 a	72.83 bc	27.17 ab	37.81 a	22.87 a	60.44 a	37.85 b
	Jurong	CK	140.76 a	180.15 a	39.40 a	72.59 c	27.41 a	32.19 b	20.25 b	51.59 a	39.36 c
		SCU	124.15 b	152.32 b	28.17 b	75.41 b	24.59 b	29.88 d	17.93 d	38.34 b	46.79 b
		AHA	105.30 c	125.06 c	19.76 c	80.22 a	19.78 c	25.89 e	13.94 e	25.36 c	55.07 a
		BSAF	127.39 b	152.77 b	25.38 b	78.52 a	21.48 c	30.59 c	18.64 c	38.55 b	48.70 ab
		BRNF	148.31 a	186.29 a	37.98 a	75.29 b	24.71 b	35.23 a	23.27 a	54.52 a	42.83 bc
2020–2021	Jiangyan	CK	145.58 ab	196.46 a	50.88 a	68.45 c	31.55 a	34.39 a	21.39 a	51.28 a	41.90 b
		SCU	132.39 cd	169.42 b	37.02 b	71.93 bc	28.07 ab	31.17 b	18.17 b	38.40 b	47.27 b
		AHA	124.79 d	153.98 c	29.20 c	76.20 a	23.80 c	30.08 b	17.08 b	31.05 c	55.29 a
		BSAF	142.43 bc	181.27 b	38.84 b	72.43 b	27.57 b	33.95 a	20.95 a	44.04 b	47.48 b
		BRNF	154.43 a	203.40 a	48.98 a	70.32 bc	29.68 ab	35.70 a	22.69 a	54.58 a	41.69 b
	Jurong	CK	128.06 a	171.67 a	43.61 a	67.22 c	32.78 a	31.14 ab	21.54 ab	50.26 a	43.01 b
		SCU	109.52 bc	139.41 b	29.89 b	72.94 b	27.06 b	28.99 b	19.39 b	34.90 b	55.75 a
		AHA	101.73 c	122.38 c	20.65 c	78.66 a	21.34 c	25.22 c	15.62 c	26.79 c	58.13 a
		BSAF	114.73 b	144.15 b	29.42 b	74.27 b	25.73 b	30.23 ab	20.63 ab	37.16 b	56.04 a
		BRNF	136.34 a	179.33 a	42.99 a	71.26 b	28.74 b	32.92 a	23.32 a	53.91 a	43.28 b
F-value											
F_{Y}			73.60**	34.66**	15.51**	42.18**	42.18**	18.27**	11.85**	1.52 ns	8.99**
F_{L}			232.53**	299.85**	141.62**	9.28*	9.28*	172.04**	0.54 ns	14.00**	7.86**
F_{T}			69.80**	126.22**	140.98**	36.91**	36.91**	95.72**	72.66**	132.99**	23.47**
$F_{Y\times T}$			2.84 ns	2.85 ns	0.48 ns	0.88 ns	0.88 ns	0.05 ns	0.79 ns	0.00 ns	1.26 ns
$F_{Y\times L}$			2.11 ns	1.33 ns	0.98 ns	0.92 ns	0.92 ns	1.96 ns	1.48 ns	1.40 ns	0.15 ns
$F_{T\times L}$			0.37 ns	0.25 ns	0.45 ns	0.46 ns	0.46 ns	1.67 ns	1.27 ns	0.26 ns	0.36 ns
$F_{Y\times T\times L}$			0.95 ns	0.93 ns	0.45 ns	0.45 ns	0.45 ns	0.36 ns	0.27 ns	0.98 ns	0.87 ns

[1)] NAA, N accumulation at anthesis; NAM, N accumulation at maturity; PNA, post-anthesis N accumulation; CNP, contribution rate of N remobilized pre-anthesis to the grain; CNA, contribution rate of N accumulated post-anthesis to the grain; NUE, N use efficiency; NAE, N agronomic efficiency; NRF, N apparent recovery fraction; NPE, N physiological efficiency.

[2)] CK, urea applied at two stages; SCU, sulfur-coated urea; AHA, urease inhibitor urea; BSAF, SCU and AHA blended at 1:1; BRNF, a mixture of common urea, sulfur-coated urea and polymer-coated urea at ratio of 1:1:1.

Different lowercase letters in the same column within the same year and same site indicate significant differences at the 0.05 probability level. F_{Y}, F_{L} and F_{T} indicate the main effects of year, location and treatment. $F_{Y\times T}$, $F_{Y\times L}$, $F_{T\times L}$, and $F_{Y\times T\times L}$ indicate the interaction effects between year and treatment, year and location, treatment and location, and year, treatment and location. *, ** and ns indicate significant levels of 5% and 1% and not significant, respectively.

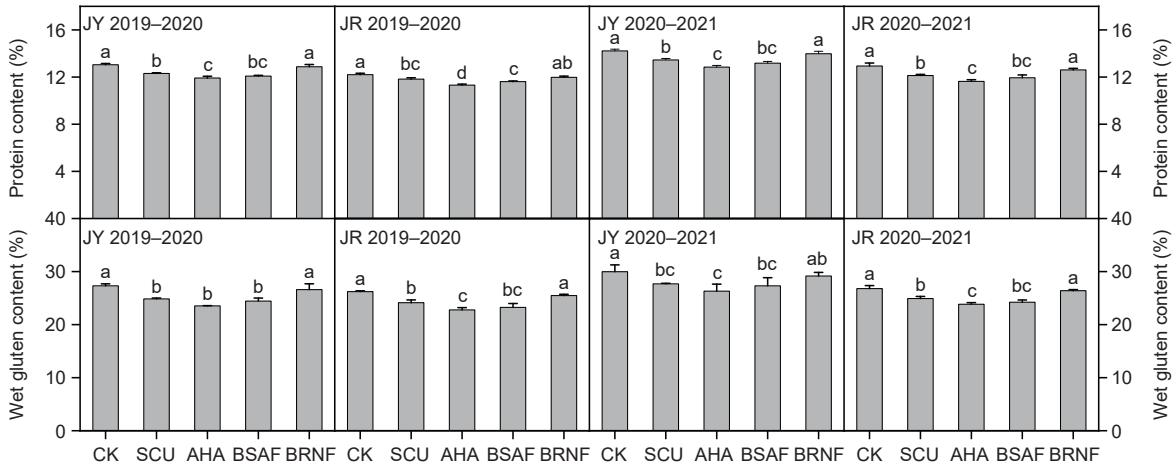


Fig. 7 Effects of different slow-controlled release fertilizers on the protein and wet gluten contents of soft wheat. CK, urea applied at two stages; SCU, sulfur-coated urea; AHA, urease inhibitor urea; BSAF, SCU and AHA blended at 1:1; BRNF, a mixture of common urea, sulfur-coated urea and polymer-coated urea at ratio of 1:1:1. JY and JR represent the Jiangyan and Jurong sites, Jiangsu Province, China, respectively. Bars indicate SD of three replicates. Different lowercase letters indicate significant differences at the 0.05 level.

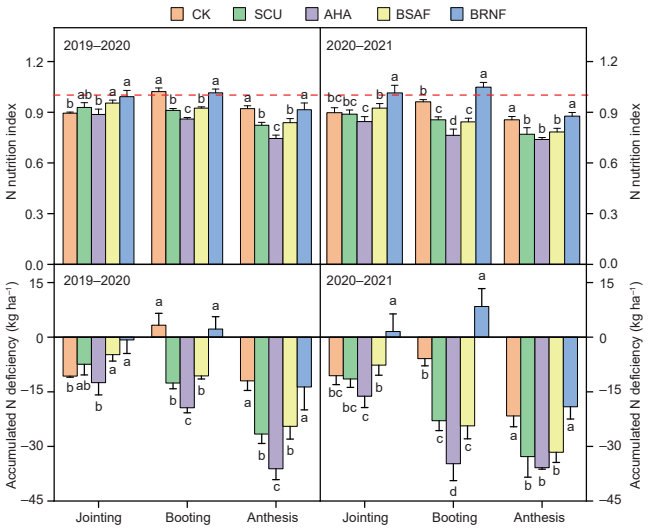


Fig. 8 Effects of different slow-controlled release fertilizers on the N nutrition index and accumulated N deficit of wheat plants at anthesis and maturity. CK, urea applied at two stages; SCU, sulfur-coated urea; AHA, urease inhibitor urea; BSAF, SCU and AHA blended at 1:1; BRNF, a mixture of common urea, sulfur-coated urea and polymer-coated urea at ratio of 1:1:1. Bars indicate SD of three replicates. Different lowercase letters indicate significant differences at the 0.05 level.

N absorption and utilization, dry matter accumulation and increasing yield (Lyu *et al.* 2015; Li *et al.* 2019; Li R C *et al.* 2021). Compared with CK, the average yield of BRNF increased by 6.73% in both years and sites (Table 1). Spike number is the key factor that determines the yield of wheat (Dou *et al.* 2024). Compared with CK, BRNF increased the yield because of an increase in spike number (Table 1). An excessive supply of N fertilizer in the early growth stage of wheat will produce more ineffective tillers, which will affect the establishment of an appropriate wheat population. In this study, compared with CK, tiller numbers for SCU, AHA, BSAF, and BRNF were maintained or increased at the jointing stage. However, SCU, AHA, and BSAF showed reduced tiller numbers at the flowering stage, whereas BRNF showed an increasing trend (Fig. 3). Therefore, the tiller to spike ratios of SCU, AHA, and BSAF significantly decreased, while the ratio in BRNF significantly increased compared with CK. NDVI can indirectly reflect the tiller dynamics of wheat. Previous studies have shown that the canopy reflectance spectrum of wheat is greatly affected by different N fertilizer conditions (Duan *et al.* 2017). NDVI is also one of the important parameters that can accurately reflect crop growth and nutritional conditions (Hassan *et al.* 2019). In this study, NDVI increased from the jointing to booting stages and gradually decreased from the booting to milking stages (Fig. 5). BRNF had greater vegetation coverage in the later growing period of wheat, resulting in a higher NDVI after the jointing period.

The accumulation of dry matter is the basis for the formation of wheat yield, especially the accumulation of dry matter after flowering which contributes more than two-thirds of the grain weight (Yan *et al.* 2022; Zhu *et al.* 2024). In this study, DMAA, DMAM, and PDMA in the BRNF treatment significantly increased compared with CK, while they significantly decreased in AHA (Table 2). In the same growing season, the Jiangyan site had higher dry matter accumulation and yield than the Jurong site, which may have been due to the differences in soil fertility and texture (Li *et al.* 2020; Ma *et al.* 2022b; Zhang *et al.* 2022b).

4.3. Effects of different slow-controlled release fertilizers on the contents of protein and wet gluten, as well as N accumulation and remobilization in soft wheat

In this study, the contents of protein and wet gluten in SCU, AHA and BSAF showed significant decreases compared with CK (Fig. 7). BRNF also showed a decreasing trend, but there were no significant differences. A previous study showed that a one-time basal application of slow-controlled release fertilizers can reduce the protein and wet gluten contents of soft wheat, which is beneficial for the production of biscuit wheat (De Santis *et al.* 2020). However, other studies found that a one-time basal application of controlled-release N fertilizer can increase the wheat grain protein content (Zhang *et al.* 2022b). The difference may be due to the different types of fertilizers used in those studies.

The protein content in the grain mainly depends on the transfer of N accumulated before anthesis and the absorption of N after anthesis. A previous study found that PNA is the key factor determining the grain protein content (Li J P *et al.* 2021), which is consistent with our results. In this study, protein content showed significantly positive relationships with the NAA, NAM, and PNA in both years and sites (Table 3). However, the coefficient of determination for the linear regression equation between PNA and protein content was relatively high, indicating that PNA is more important to protein content (Fig. 9). Therefore, reducing PNA is one way to reduce the grain protein content of soft wheat. In addition, the coefficients of determination for the linear regression equation between grain yield and NAA or NAM were relatively high, this indicated that NAA and NAM are more important for yield formation. A previous study found that N deficiency can reduce the SPAD of the upper three leaves in the later growth stage (Zhu *et al.* 2024). In this study, BRNF showed no significant difference compared with CK at the flowering and milking periods. SCU, AHA, and BSAF all showed significant downward trends. BRNF provides a small amount of N after flowering, which can stabilize the wheat grain yield and improve the quality of soft wheat. However, the N supplies of SCU, AHA, and BSAF were low after flowering, and the yields and protein contents all showed decreasing trends, which is not conducive to the coordination of yield and quality in soft wheat.

In addition, the protein content in the Jiangyan site was higher than that of the Jurong site (Fig. 7), which may be related to the different conditions such as precipitation, temperature, and soil properties (Ma *et al.* 2022b). Previous studies showed that the substitution effect of slow-controlled released N fertilizer for a split application of ordinary urea varied depending on regional climatic factors, soil physicochemical factors, and field management measures

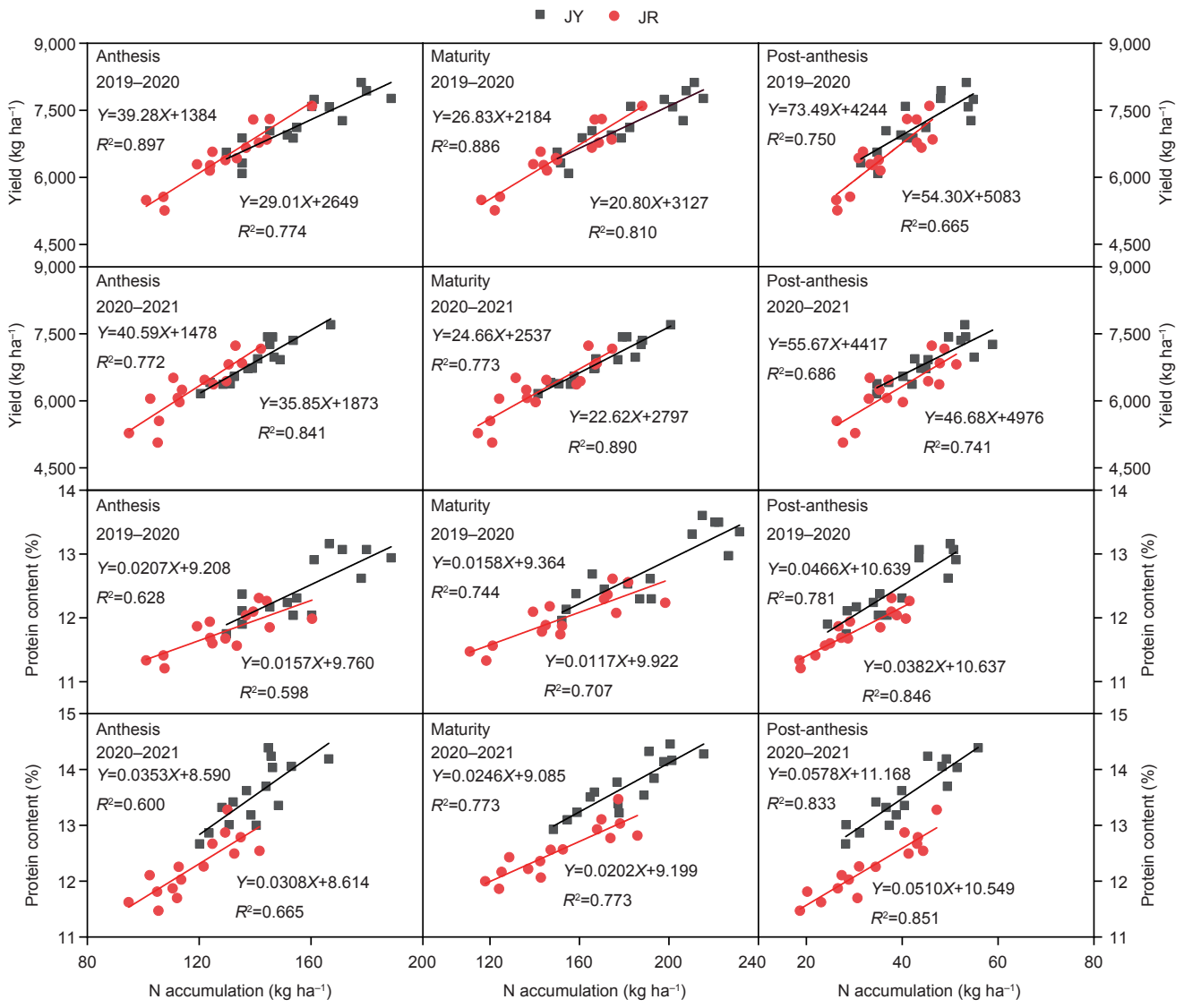


Fig. 9 Correlation analysis between N accumulation and both yield and protein content of soft wheat under different slow-controlled release fertilizers. JY and JR represent the Jiangyan and Jurong sites, Jiangsu Province, China, respectively.

(Zhang *et al.* 2022b). For example, Ma *et al.* (2022b) showed that rainfall and accumulated temperature in different ecological sites could affect the nutrient release patterns of different slow-controlled release N fertilizers and thus affect wheat yield and N use efficiency. Li *et al.* (2020) reported that the combination of slow-controlled release N and urea increased maize yield, and that increase was more significant in sandy soils. Although a recent study showed that split application of slow-controlled release N fertilizer improved the stability of wheat yield and N use efficiency in different sites (Ma *et al.* 2022b), few studies have reported the effects of slow-controlled release N fertilizer on wheat grain protein content in different ecological regions. In this study, slow-controlled release N fertilizer mainly reduced the N absorption of wheat after anthesis to reduce the grain protein content of wheat. Due to the higher soil fertility at the Jiangyan site, it might still maintain a high level after the anthesis of wheat, which increased the relative N absorption and affected the grain protein content. A framework to describe the mechanism by which the application of slow-controlled release fertilizer blends promotes the coordination of yield and quality of soft wheat is shown in Fig. 10.

5. Conclusion

The N release from different slow-controlled release fertilizers was found to be significantly different. AHA presented a fast release mode, SCU and BSAF presented a slow-release mode, and BRNF presented a controlled release mode. Compared with CK, BRNF improved grain yield and reduced the protein content, while SCU, AHA and BSAF all showed decreasing trends. The tiller numbers and NDVI of BRNF all increased from the booting stage to the maturity stage. The NNI of BRNF was closer to 1 at the jointing and booting periods and reduced the N loss. BRNF also promoted N absorption and utilization, and the NUE, NAE, and NRF all showed increasing trends. However, the AHA, SCU and BSAF showed the opposite trends. At the same time, BRNF improved PDMA and CDA to improve grain yield, and

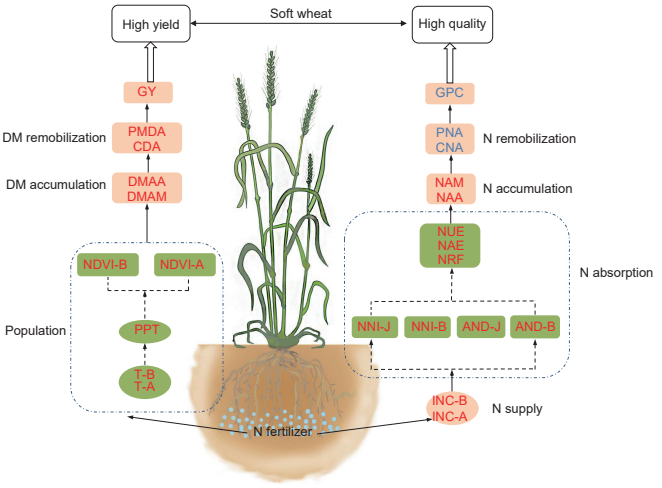


Fig. 10 Mechanism by which the application of slow-controlled release blended fertilizer promotes the coordination of yield and quality of soft wheat. GY, grain yield; GPC, grain protein content; PDMA, post-anthesis dry matter accumulation; CDA, contribution rate of dry matter accumulated post-anthesis to the grain; PNA, post-anthesis N accumulation; CNA, contribution rate of N accumulated post-anthesis to the grain; DMAA, dry matter accumulation at anthesis; DMAM, dry matter accumulation at maturity; NAM, N accumulation at maturity; NAA, N accumulation at anthesis; NUE, N use efficiency; NAE, N agronomic efficiency; NRF, N apparent recovery fraction; NNI, N nutrition index; AND, accumulated N deficit; T, tillers; PPT, percentage of productive tillers; INC, inorganic N content of the soil; DM, dry matter; J, jointing; B, booting; A, anthesis; NDVI, normalized difference vegetation index. Red letters indicate improvement, blue letters indicate reduction.

reduced PNA and CNA to lower the grain protein content. These results suggested that a one-time basal application of slow-controlled release fertilizer blended at a specific ratio could be promising for broad use in soft wheat production.

Acknowledgements

This study was supported by projects of the National Key Research and Development Program of China (2023YFD2300202), the Key Research and Development Program of Jiangsu Province, China (BE2022308), the National Natural Science Foundation of China (32372224, 32021004, 32030076, and 32172116), the China Agriculture Research System (CARS-03), and the Collaborative Innovation Center for Modern Crop Production co-sponsored by Province and Ministry, China (CIC-MCP).

Declaration of competing interest

The authors declare that they have no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that they did not use AI in the preparation and writing of this manuscript.

Appendices associated with this paper are available at https://doi.org/10.1016/j.jia.2025.02.038

References

Ding Y G, Zhang X B, Ma Q, Li F J, Tao R R, Zhu M, Li C Y, Zhu X K, Guo W S, Ding J F. 2023. Tiller fertility is critical for improving grain yield, photosynthesis, and nitrogen efficiency in wheat. *Journal of Integrative Agriculture*, **22**, 2054–2066.

Dou Y X, Zhao H B, Yang H M, Wang T, Liu G F, Wang Z H, Malhi S. 2024. The first factor affecting dryland winter wheat grain yield under various mulching measures: Spike number. *Journal of Integrative Agriculture*, **23**, 836–848.

Duan T, Chapman S, Guo Y, Zheng B. 2017. Dynamic monitoring of NDVI in wheat agronomy and breeding trials using an unmanned aerial vehicle. *Field Crops Research*, **210**, 71–80.

Gao Y X, Shao Y Q, Wang J Q, Hu B, Feng H J, Qu Z M, Liu Z G, Zhang M, Li C L, Liu Y L. 2024. Effects of straw returning combined with blended controlled-release urea fertilizer on crop yields, greenhouse gas emissions, and net ecosystem economic benefits: A nine-year field trial. *Journal of Environmental Management*, **356**, 120633.

Geng J, Chen J, Sun Y, Zheng W, Tian X, Yang Y, Li C, Zhang M. 2016. Controlled release urea improved nitrogen use efficiency and yield of wheat and corn. *Agronomy Journal*, **108**, 1666–1673.

Hassan M A, Yang M J, Rasheed A, Yang G J, Reynolds M, Xia X C, Xiao Y G, He Z H. 2019. A rapid monitoring of NDVI across the wheat growth cycle for grain yield prediction using a multi-spectral UAV platform. *Plant Science*, **282**, 95–103.

Hu S Y, Qiao B W, Yang Y H, Rees R M, Huang W H, Zou J, Zhang L, Zheng H Y, Liu S Y, Shen S J. 2023. Optimizing nitrogen rates for synergistically achieving high yield and high nitrogen use efficiency with low environmental risks in wheat production — Evidences from a long-term experiment in the North China Plain. *European Journal of Agronomy*, **142**, 126681.

Jiang Z R, Chen Q L, Liu D, Tao W K, Gao S, Li J Q, Lin C H, Zhu M C, Ding Y F, Li W W. 2024. Application of slow-controlled release fertilizer coordinates the carbon flow in carbon–nitrogen metabolism to effect rice quality. *BMC Plant Biology*, **24**, 621.

Ke J, Sun J, Chen T T, Tao S B, Zhu T Z, Yin C J, He H B, You C C, Wu L Q, Guo S S. 2023. Effects of mixed fertilizers formed by the compounding of two targeted controlled-release nitrogen fertilizers on yield, nitrogen use efficiency, and ammonia volatilization in double-cropping rice. *The Crop Journal*, **11**, 628–637.

Ke J, Xing X M, Li G H, Ding Y F, Dou F G, Wang S H, Liu Z H, Tang S, Ding C Q, Chen L. 2017. Effects of different controlled-release nitrogen fertilisers on ammonia volatilisation, nitrogen use efficiency and yield of blanket-seedling machine-transplanted rice. *Field Crops Research*, **205**, 147–156.

Kong X F, Hou R X, Yang G. 2024. Effects of climactic warming on the starch and protein content of winter wheat grain under conservation tillage in the North China Plain. *Soil and Tillage Research*, **238**, 105995.

Lawrencia D, Wong S K, Low D Y S, Goh B H, Goh J K, Ruktanonchai U R, Soottitantawat A, Lee L H, Tang S Y. 2021. Controlled release fertilizers: A review on coating materials and mechanism of release. *Plants*, **10**, 238.

Li C L, Wang Y, Li Y X, Zhu L, Cao Y Q, Zhao X H, Feng G Z, Gao Q. 2020. Mixture of controlled-release and normal urea to improve nitrogen management for maize across contrasting soil types. *Agronomy Journal*, **112**, 3101–3113.

Li G H, Zhao B, Dong S T, Zhang J W, Liu P, Ren B Z, Lu D L, Lu W P. 2019. Morphological and physiological characteristics of maize roots in response to controlled-release urea under different soil moisture conditions. *Agronomy Journal*, **111**, 1849–1864.

Li J P, Wang Z M, Yao C S, Zhang Z, Liu Y, Zhang Y H. 2021. Micro-sprinkling irrigation simultaneously improves grain yield and protein concentration of winter wheat in the North China Plain. *The Crop Journal*, **9**, 1397–1407.

Li R C, Gao Y X, Chen Q, Li Z L, Gao F, Meng Q M, Li T G, Liu A R, Wang Q, Wu L, Wang Y, Liu Z G, Zhang M. 2021. Blended controlled-release nitrogen fertilizer with straw returning improved soil nitrogen availability, soil microbial community, and root morphology of wheat. *Soil and Tillage Research*, **212**, 105045.

Lyu X X, Yang Y C, Li Y C, Fan X H, Wan Y S, Geng Y Q, Zhang M. 2015. Polymer-coated tablet urea improved rice yield and nitrogen use efficiency. *Agronomy Journal*, **107**, 1837–1844.

Ma Q, Qian Y S, Yu Q Q, Cao Y F, Tao R R, Zhu M, Ding J F, Li C

Y, Guo W S, Zhu X K. 2023. Controlled-release nitrogen fertilizer application mitigated N losses and modified microbial community while improving wheat yield and N use efficiency. *Agriculture, Ecosystems & Environment*, **349**, doi: 10.1016/j.agee.2023.108445.

Ma Q, Sun Q, Zhang X B, Li F J, Ding Y G, Tao R T, Zhu M, Ding J F, Li C Y, Guo W S, Zhu X K. 2022a. Controlled-release nitrogen fertilizer management influences grain yield in winter wheat by regulating flag leaf senescence post-anthesis and grain filling. *Food and Energy Security*, **11**, e361.

Ma Q, Tao R R, Ding Y G, Zhang X B, Li F J, Zhu M, Ding J F, Li C Y, Guo W S, Zhu X K, Sheng H J. 2022b. Can split application of slow-release fertilizer improve wheat yield, nitrogen efficiency and their stability in different ecological regions? *Agronomy*, **12**, 407.

Ma Q, Wang M Y, Zheng G L, Yao Y, Tao R R, Zhu M, Ding J F, Li C Y, Guo W S, Zhu X K. 2021. Twice-split application of controlled-release nitrogen fertilizer met the nitrogen demand of winter wheat. *Field Crops Research*, **267**, 108163.

Morris C F, Engle D A, Kiszonas A M. 2020. Breeding, selection, and quality characteristics of soft white wheat. *Cereal Foods World*, **65**, 53.

Naz M Y, Sulaiman S A. 2016. Slow release coating remedy for nitrogen loss from conventional urea: A review. *Journal of Controlled Release*, **225**, 109–120.

Rekowski A, Wimmer M A, Hitzmann B, Hermannseder B, Hahn H, Zörb C. 2020. Application of urease inhibitor improves protein composition and bread-baking quality of urea fertilized winter wheat. *Journal of Plant Nutrition and Soil Science*, **183**, 260–270.

De Santis M A, Giuliani M M, Flagella Z, Reyneri A, Blandino M. 2020. Impact of nitrogen fertilisation strategies on the protein content, gluten composition and rheological properties of wheat for biscuit production. *Field Crops Research*, **254**, 107829.

Shakoor A, Xu Y L, Wang Q, Chen N Y, He F, Zuo H F, Yin H X, Yan X Y, Ma Y H, Yang S Y. 2018. Effects of fertilizer application schemes and soil environmental factors on nitrous oxide emission fluxes in a rice-wheat cropping system, east China. *PLoS ONE*, **13**, e0202016.

Shang Q S, Wang Y P, Tang H, Sui N, Zhang X S, Wang F. 2021. Genetic, hormonal, and environmental control of tillering in wheat. *The Crop Journal*, **9**, 986–991.

Sieling K, Kage H. 2021. Apparent fertilizer N recovery and the relationship between grain yield and grain protein concentration of different winter wheat varieties in a long-term field trial. *European Journal of Agronomy*, **124**, 126246.

Wang Q, Wen J, Wen Y J, Zhang Y, Zhang N, Wang Y N, Bai L Y, Su S M, Zeng X B. 2021. Alteration of soil-surface electrochemical properties by organic fertilization to reduce dissolved inorganic nitrogen leaching in paddy fields. *Soil and Tillage Research*, **209**, 104956.

Wang Y Q, Peng Y, Lin J Q, Wang L X, Jia Z K, Zhang R. 2023. Optimal nitrogen management to achieve high wheat grain yield, grain protein content, and water productivity: A meta-analysis. *Agricultural Water Management*, **290**, 108587.

Yan S C, Wu Y, Fan J L, Zhang F C, Guo J J, Zheng J, Wu L F. 2022. Optimization of drip irrigation and fertilization regimes to enhance winter wheat grain yield by improving post-anthesis dry matter accumulation and translocation in Northwest China. *Agricultural Water Management*, **271**, 107782.

Yang X Y, Li C L, Zhang Q, Liu Z G, Geng J B, Zhang M. 2017. Effects of polymer-coated potassium chloride on cotton yield, leaf senescence and soil potassium. *Field Crops Research*, **212**, 145–152.

Yang Y C, Zhang M, Zheng L, Cheng D D, Liu M, Geng Y Q. 2011. Controlled release urea improved nitrogen use efficiency, yield, and quality of wheat. *Agronomy Journal*, **103**, 479–485.

Yin L J, Dai X L, He M R. 2018. Delayed sowing improves nitrogen utilization efficiency in winter wheat without impacting yield. *Field Crops Research*, **221**, 90–97.

Yu X, Keitel C, Zhang Y, Wangeci A N, Dijkstra F A. 2022. Global meta-analysis of nitrogen fertilizer use efficiency in rice, wheat and maize. *Agriculture, Ecosystems & Environment*, **338**, 108089.

Yu X R, Chen X Y, Wang L L, Yang Y, Zhu X W, Shao S S, Cui W X, Xiong F. 2017. Novel insights into the effect of nitrogen on storage protein biosynthesis and protein body development in wheat caryopsis. *Journal of Experimental Botany*, **68**, 2259–2274.

Zhang G X, Liu S J, Dong Y J, Liao Y C, Han J. 2022a. A nitrogen fertilizer strategy for simultaneously increasing wheat grain yield and protein content: Mixed application of controlled-release urea and normal urea. *Field Crops Research*, **277**, 108405.

Zhang G X, Zhao D H, Liu S J, Liao Y C, Han J. 2022b. Can controlled-release urea replace the split application of normal urea in China? A meta-analysis based on crop grain yield and nitrogen use efficiency. *Field Crops Research*, **275**, 108343.

Zhang S H, Qi X H, Gao M Y, Dai C J, Yin G H, Ma D Y, Feng W, Guo T C, He L. 2024. Estimation of wheat protein content and wet gluten content based on fusion of hyperspectral and RGB sensors using machine learning algorithms. *Food Chemistry*, **448**, 139103.

Zheng B Q, Fang Q, Zhang C X, Mahmood H, Zhou Q, Li W Y, Li X N, Cai J, Wang X, Zhong Y X, Huang M, Cao W X, Dai T B, Jiang D. 2020. Reducing nitrogen rate and increasing plant density benefit processing quality by modifying the spatial distribution of protein bodies and gluten proteins in endosperm of a soft wheat cultivar. *Field Crops Research*, **253**, 107831.

Zheng B Q, Zhang X Q, Wang Q, Li W Y, Huang M, Zhou Q, Cai J, Wang X, Cao W X, Dai T B, Jiang D. 2021. Increasing plant density improves grain yield, protein quality and nitrogen agronomic efficiency of soft wheat cultivars with reduced nitrogen rate. *Field Crops Research*, **267**, 108145.

Zheng W K, Zhang M, Liu Z G, Zhou H Y, Lu H, Zhang W T, Yang Y C, Li C L, Chen B C. 2016. Combining controlled-release urea and normal urea to improve the nitrogen use efficiency and yield under wheat–maize double cropping system. *Field Crops Research*, **197**, 52–62.

Zhu T Z, Yin C J, Zhu T C, Zhou P F, Wu L Q, Wang G J, He H B, You C C, Zhang Q W, Ke J. 2024. Delaying panicle nitrogen application to emergence of 3rd leaf from flag leaf increases the grain-filling ability and yield of large-panicle rice by increasing stem nonstructural carbohydrates at heading. *Field Crops Research*, **312**, 109405.

Executive Editor-in-Chief Shaokun Li
Managing Editor Ning Wang