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EDITED BY
Zhiguang Liu,
Shandong Agricultural University, China

REVIEWED BY
Dianjun Lu,
Chinese Academy of Sciences (CAS), China
Guodong Liu,
University of Florida, United States

*CORRESPONDENCE
Ziyi Zhang,
zzybiology@126.com

†These authors have contributed equally to this work

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Benefits of controlled-release fertilizers for potato sustainable nitrogen management

Huiling Xue[1†], Xiaofan Zheng[1†], Hong Wei[2], Jing Yang[1], Ashok Alva[3], Mingshou Fan[4] and Ziyi Zhang[1*]

[1]Key Laboratory of Plants Adversity Adaptation and Genetic Improvement in Cold and Arid Regions of Inner Mongolia, College of Life Sciences, Inner Mongolia Agricultural University, Hohhot, China, [2]Agricultural and Animal Husbandry Technology Extension Center, Hohhot, China, [3]USDA-ARS, Prosser, WA, United States, [4]College of Agronomy, Inner Mongolia Agricultural University, Hohhot, China

The evaluation of potato response to controlled-release fertilizers (CRFs), as a sole source of nitrogen (N) or as a blend with a soluble N source, is essential to 1) develop the best management recommendations for using CRFs in potato production and 2) provide guidelines to CRF manufacturers for developing an optimal product. This study aimed to evaluate the potato yield and quality responses to N CRFs (polymer-coated urea [PCU]) vs soluble N sources. The experiments were conducted in major potato-growing regions in the United States and China. The current industry-recommended practice of 112 kg N/ha pre-plant soil broadcast of urea plus five in-season fertigations of 224 kg N/ha as urea ammonium nitrate (UAN-32) was compared to a single pre-plant application of 224 kg N/ha as a CRF as the sole source of N or as multiple blends of CRFs and soluble N sources (i.e., urea) at various ratios. The results demonstrated that petiole nitrate_N (NO_3_N) levels and tuber yield with single pre-plant broadcast applications of 224 kg N/ha as CRF/urea blends (ratio of 25/75 or 50/50) were similar to those obtained with industry-standard N management practice. N uptake and yield were significantly greater with 220 kg/ha N as the CRF than those with the same N rate as urea. Unlike the current potato industry N practice, using CRFs as either a sole source of N or blended with urea reduces the total N rate and application frequency.

KEYWORDS

best management practice, environmental impacts, fertigation, nitrogen leaching, N_2O emissions, sustainable nutrient management

1 Introduction

Potato, an annual herbaceous tuber plant of the Solanaceae family, is the fourth major food crop in the world after rice, wheat, and maize (Alva et al., 2011; Waqas et al., 2021). In potato plants, tubers constitute the part with economic significance (Alva et al., 2012). Potato is a high-return cash crop in the United States (Stefaniak et al., 2021). The US Pacific Northwest (PNW) States, i.e., Oregon (OR), Washington (WA), and Idaho (ID), represent an important region in the country for potato production, with 61 million metric tons (61% of the US total) on 208,000 ha (56% of the US total) (Bull, 2023; United States Department of AgricultureNational Agricultural Statistics Service, 2023).

Potato plays a significant role in developing countries to cater to the rapidly increasing demand for a food source with the accelerated rate of population growth (Raymundo et al., 2016). Potato is an important crop in China, with a total production of 78 million metric tons, ranking first in the world (Brandon, 2024), as a staple food and a significant economic base, especially for farmers in mountainous areas with low-fertile soils (Jing et al., 2018). Seven provinces, including the Inner Mongolia Autonomous Region (IMAR) in northern China, contribute to 54% of China's total potato production. Potato is an important crop in the IMAR with a production of 5.6 million tons on 227,000 ha, which account to 7% and 9% of the total production and acreage in China, respectively (Xu et al., 2021; IMARBS, 2023; Li M. et al., 2023).

Adequate nutrient management is the key for maximizing the yield and quality of potato (Petropoulos et al., 2020). The management of nitrogen (N) fertilization, in terms of rate, source, timing, and method of application, influences the yield and quality of potatoes (Alva, 2004). Nitrogen is the most important nutrient for potato plant growth and tuber yield and quality (Rember et al., 2020). Accordingly, potato plant growth and tuber yield can be improved substantially with optimal N fertilizer practice, especially in low-fertile soils (Alva et al., 2002; Makani et al., 2020). However, excessive application of N that does not contribute to enhanced yield or quality returns is an economic loss and has negative environmental impacts (Wang et al., 2019; Stefaniak et al., 2021).

The current recommended N management practice for irrigated high yield and quality potato production in the US PNW region is a total N rate of 340–390 kg/ha as a combination of pre-plant (1/3 of the total N rate) broadcast of soluble granular N sources and multiple in-season fertigations (5–10 applications) using liquid N sources with irrigation water (Lang et al., 1999; Alva et al., 2009). In China, the recommended N management practice for drip irrigation of potato in the IMAR is for a total N rate of 98–220 kg/ha as a combination of the pre-plant (1/4–1/2 of the total N rate) broadcast of soluble granular N forms and multiple in-season fertigations of liquid N sources (Li et al., 2019; Wang et al., 2019).

Potato is a shallow root crop; therefore, excessive N application, particularly in sandy soils with irrigation, can be subject to nitrate N leaching losses below the root zone and can contaminate groundwater in concentrations exceeding acceptable standards for drinking water (Woli et al., 2016; Chen et al., 2017; Ierna and Mauromicale, 2019).

Controlled-release fertilizer (CRF) technology provides an option to regulate the nutrient release duration and rate to match the nutrient requirement of the crop in question (Wang et al., 2011; Zhang et al., 2019); therefore, the frequency and rate of nutrient application can be reduced considerably for various crops (Yang et al., 2016). The use of controlled-release fertilizers as an N source, for several crops except potato, unlike in the soluble urea, has been shown to enhance N use efficiency, minimize N losses below the root zone, reduce labor and fuel need for the application of fertilizers, and mitigate negative environmental impacts (Qu et al., 2020). Over the recent years, numerous types of CRFs have been evaluated for various crops (Eerd et al., 2018). However, CRFs for potato N management are not evaluated in major potato production regions in the US and China.

In China, the CRF has been widely used on corn and rice but not as much on potato (Liu et al., 2020). This is in part due to the lack of research-based information to develop recommendations on the rate, timing, and frequency of the application of the CRF to potato as a sole source of N and/or in an optimal ratio of CRF and urea to achieve high yields of high-quality tubers for maximum net returns.

The hypothesis of this study was that the N rate and frequency of applications can be reduced for irrigated high-productive potato production by using a CRF/urea blend without a negative impact on the yield and quality compared to those with the use of soluble N fertilizers as a combination of pre-plant broadcast and multiple in-season fertigations. The studies reported in this paper were conducted in Paterson, Washington State, United States, and Wuchuan, IMAR, China.

2 Materials and methods

2.1 Overview of the experiments

2.1.1 Paterson, United States

Three years of field experiments were conducted in Paterson, Benton County, WA, United States (2010, 2012, and 2014; 121°07′ west longitude and 37°28′ north latitude; annual mean precipitation of 200 mm predominantly during winter months; mean temperature of 12°C). The soil organic matter and total N content were 4.7 and 0.44 g/kg, respectively. Available P and K were 34 and 214 mg/kg, respectively. Nitrogen sources used were soluble urea (46% N) and a controlled-release fertilizer (polymer-coated urea [PCU], with a designated release duration of 90 days, 46% N). The "Umatilla Russet" cultivar was used in the study conducted in Quincy fine sand (92% sand) soil. Overhead irrigation was practiced using a center pivot, scheduled to replenish daily crop evapotranspiration (ET).

The experiment was conducted over 3 years using a randomized complete block design (RCBD) with four replications. During the first 2 years of the study (2010 and 2012), 10 treatments were carried out, with details given in Table 1. In the third year of the study (2014), the treatments were slightly modified (Table 1) based on the yield response of the first 2 years. The plot area (six rows, each 12-m long) was 64.8 m^2, row spacing was 0.9 m, plant spacing was 0.2 m, and planting density was 55,555 plants/ha.

Recommended crop and irrigation (using a center pivot irrigation system) management practices were followed in each year's experiment (Lang et al., 1999). Phosphorus and potassium fertilizers, as a single super phosphate and muriate of potash, were broadcast-applied based on pre-plant soil test results using the guidelines from Washington State University, Cooperative Extension Service (Lang et al., 1999).

2.1.2 Wuchuan, China

A parallel study was conducted in Wuchuan, Hohhot City, Inner Mongolia, China (2019) (41°23′ north latitude and 111°53′ east longitude; annual mean temperature of 3.0°C; and mean precipitation of 350 mm). The soil organic matter and total N content were 16.2 and 1.5 g/kg, respectively. Available P and K were 16 and 140 mg/kg, respectively. Wuchuan County is the main potato-producing area in the northwest region of China, with soil and climatic conditions well-suited for the optimal growth and high yields of good-quality potatoes. Plants were irrigated using a drip system; the drip tube had an inner diameter of 16 mm, with drippers with a flow rate of 1.75 L/h/emitter at 300-mm spacing. Irrigation scheduling was practiced to replenish water deficiency when the available soil water content was depleted to 65%, 70%, 75%, and 60% at seedling, tuber initiation, tuber bulking, and maturation stages,

TABLE 1 Nitrogen management treatments evaluated in 4 years of field experiments conducted in Paterson, WA, United States, and in Wuchuan County, Inner Mongolia Province, China.

Year/ location	TRT no.	Pre-plant			In-season			
		N rate (kg/ha)	N source CRF/urea	Method of application	N rate (kg/ha)	N source	Method of application	Frequency
2010/Paterson	1	0	N/A	N/A	224	UAN-32	FT	5
	2	112	0/100	BC	224	UAN-32	FT	5
	3	224	100/0	BC	N/A	N/A	N/A	N/A
	4	224	75/25	BC	N/A	N/A	N/A	N/A
	5	224	50/50	BC	N/A	N/A	N/A	N/A
	6	336	75/25	BC	N/A	N/A	N/A	N/A
	7	336	50/50	BC	N/A	N/A	N/A	N/A
	8	224	100/0	BD	N/A	N/A	N/A	N/A
	9	224	75/25	BD	N/A	N/A	N/A	N/A
	10	224	50/50	BD	N/A	N/A	N/A	N/A
2012/Paterson	1	0	0	N/A	0	N/A	N/A	N/A
	2	112	0/100	BC	224	UAN-32	FT	5
	3	224	100/0	BC	N/A	N/A	N/A	N/A
	4	244	50/50	BC	N/A	N/A	N/A	N/A
	5	244	25/75	BC	N/A	N/A	N/A	N/A
	6	336	50/50	BC	N/A	N/A	N/A	N/A
	7	336	25/75	BC	N/A	N/A	N/A	N/A
	8	224	100/0	BD	N/A	N/A	N/A	N/A
	9	224	50/50	BD	N/A	N/A	N/A	N/A
	10	224	25/75	BD	N/A	N/A	N/A	N/A
2014/Paterson	1	0	N/A	N/A	0	0	FT	0
	2	0	N/A	N/A	336	UAN-32	FT	5
	3	112	0/100	BC	224	UAN-32	FT	5
	4	224	100/0	BC	N/A	N/A	N/A	N/A
	5	336	100/0	BC	N/A	N/A	N/A	N/A
	6	224	50/50	BC	N/A	N/A	N/A	N/A
	7	336	50/50	BC	N/A	N/A	N/A	N/A
	8	224	25/75	BC	N/A	N/A	N/A	N/A
	9	336	25/75	BC	N/A	N/A	N/A	N/A
2019/Wuchuan	1	0	N/A	N/A	N/A	N/A	N/A	N/A
	2	220	Urea	BD	N/A	N/A	N/A	N/A
	3	220	CRF	BD	N/A	N/A	N/A	N/A

Note: TRT, treatment; frequency, number of in-season fertigations; N/A, not applicable; UAN-32, urea ammonium nitrate; FT, in-season fertigation; CRF, controlled-release fertilizer; BC, broadcast application of granular fertilizer, pre-plant; BD, band application of granular fertilizer next to seed, pre-plant. In column 4, under a pre-plant N source, some treatments show two values separated by "/," which represents the percent of N source derived from CRF/urea.

respectively (Shi et al., 2021). The N sources evaluated were soluble urea (46% N) and CRF with a designated release duration of 90 days (46% N). The experiment was conducted in sandy loamy soil using the potato variety "Zhongshu No. 18" (planted on 4 May 2019). The irrigation time and rate (m^3/ha) were 6 July (225), 17 July (300), 31 July (300), 12 August (300), and 1 September (225) for the growing season of 1,350 m^3/ha. The effective precipitation during the growing season was 235 mm.

The experiment was conducted using a completely randomized design with four replications of the following treatments (Table 1): 1) control, i.e., no N; 2) standard practice, i.e., a single pre-plant application of 220 kg N/ha as urea; and 3) a similar N rate as in 2) but using CRF. The pre-plant soil application of the N source, as per the treatment, also included P and K, at the rates based on the soil test levels, using single super phosphate and potassium sulfate, respectively. No other nutrient sources or soil amendments were applied.

2.2 Data collection

In the Paterson study, the total tuber yield was calculated using the tuber weight from the harvest area from each plot (two rows, rows 3 and 4, of 6.1 m each) and converting the tuber weight from the harvest area into Mg per hectare. A sub-sample of the tuber was used for tuber grading using an electronic tuber size grader to separate the tubers into the following size grades: i.e., >340 g, 227–340 g, 113–227 g, <113 g, and US No. 2 plus culls. Tuber-specific gravity was measured on a sub-sample of 10 tubers from the harvest area for each plot.

Petioles were sampled from rows 2 and 5 from each plot, i.e., bordering yield estimation rows, at various times during the growing season. These samples were dried at 72°C, ground, and extracted in 4% acetic acid (0.2 g petiole tissue in 50 mL acetic acid). Concentrations of NO_3^-_N in the petiole extract were determined using a flow injection auto-analyzer, while those of P and K were analyzed by inductively coupled plasma emission spectroscopy (ICPAES; PerkinElmer, Optima 3000, PerkinElmer Analytical Services, Boston, MA).

In the Wuchuan experiment, the tuber yield was measured by harvesting tubers (two rows of 3.6 m each) and then converted to Mg per hectare. Whole plants were sampled on days 50 (seedling stage), 70 (tuber initiation stage), 90 (tuber bulking stage), and 110 (tuber maturation stage) after planting. Each plant was separated into leaf, shoot, root, stolon, and tuber; the samples were dried at 105°C for 0.5 h and then 72°C for 24 h and ground, and the concentration of N was measured using an automatic nitrogen analyzer (K06, SSK0621009, Hohhot, IMAR, China).

The significances of the response data were evaluated by the analysis of variance (ANOVA) test. Differences among the treatments were examined by Fisher's least significant difference (LSD) test. Significance between the treatments was accepted at $p < 0.05$. Excel 2013 (Microsoft, Redmond, WA, United States), SPSS 20.0 (IBM, Armonk, NY, United States), and SigmaPlot 12.0 (SYSTAT, San Jose, CA, United States) were used for data processing, statistical analyses, and drawing graphs, respectively.

3 Results

3.1 Potato yield and quality influenced by different fertilization practices

The Paterson experiment results over 3 years showed that the total tuber yield and yields of tubers across different size grades were similar across the single pre-plant broadcast application of 224 kg/ha N as CRF or CRF/urea blend at 50/50 or 75/25 blends (25/75 blend in 2012 and 2014) (Figures 1A–C). These yields were also similar to those of the US PNW potato-recommended fertilizer practice of a pre-plant broadcast of 112 kg/ha N (as urea) plus 224 kg/ha N (as UAN-32) in five fertigations at 2-week intervals starting 4 weeks after seedling emergence. Therefore, the 3-year study consistently demonstrated that by using the CRF, the 1) total annual N rate can be reduced from the recommended 336 to 224 kg/ha with no negative impact on the tuber yield or quality; 2) a single pre-plant application of a full rate of 224 kg/ha N as only CRF or CRF/urea blends was more effective than the current N management recommendation of a single pre-plant application plus five in-season fertigations. Therefore, the use of CRFs, as the sole source N or blend with urea, is economically more advantageous than the current recommended N practice of a combination of pre-plant plus multiple fertigations by reducing the labor and fuel costs for application.

Furthermore, our results demonstrated that the tuber yield and quality were similar when using CRF/urea blends at 25/75 or 50/50 compared to that using a full rate of N as the CRF. Using soluble urea blended with the CRF is beneficial for supplying readily available N in abundance during the early growing season to meet the high N requirement for the rapid vegetative growth period, while the CRF provided the continued release of soluble N in small doses over the rest of the growing season. This successful strategy of blending urea with the CRF lowers the total cost of the N fertilizer unlike when using only the CRF as the sole source of N to attain the same target N rate for the season.

Some previous investigations of other high-value cash crops have shown that since the total N rate is reduced with the use of CRF compared to that of the soluble N source, the former needs to be target-applied as a band application rather than broadcast-applied. In contrast, our results have shown that the band application of the CRF did not demonstrate any yield increase compared to that with the broadcast application at a given total N rate. This provides another economic advantage of reducing the cost of application since labor requirement is lower for broadcasting, as compared to that for banding. The later method of application needs additional cost since it requires equipment modifications.

3.2 Petiole NO_3^--N response

The petiole is the main plant part to accumulate NO_3^-_N, and the content of petiole NO_3^-_N is generally used as a diagnostic index for the evaluation of N management to attain high yields. The amount of N fertilizers applied is closely related to petiole NO_3^-_N in potato (Petropoulos et al., 2020). As shown in Figure 2 (Paterson), in the 2010 experiment, increasing the total N rate to 336 kg/ha (at both 50/50 and 75/25 ratios of CRF/urea) had no significant advantage in terms of petiole NO_3^-_N concentrations compared to that at 224 kg/ha N. Petiole NO_3^-_N concentrations in the CRF as the sole source of N were lower than those in the currently recommended N management

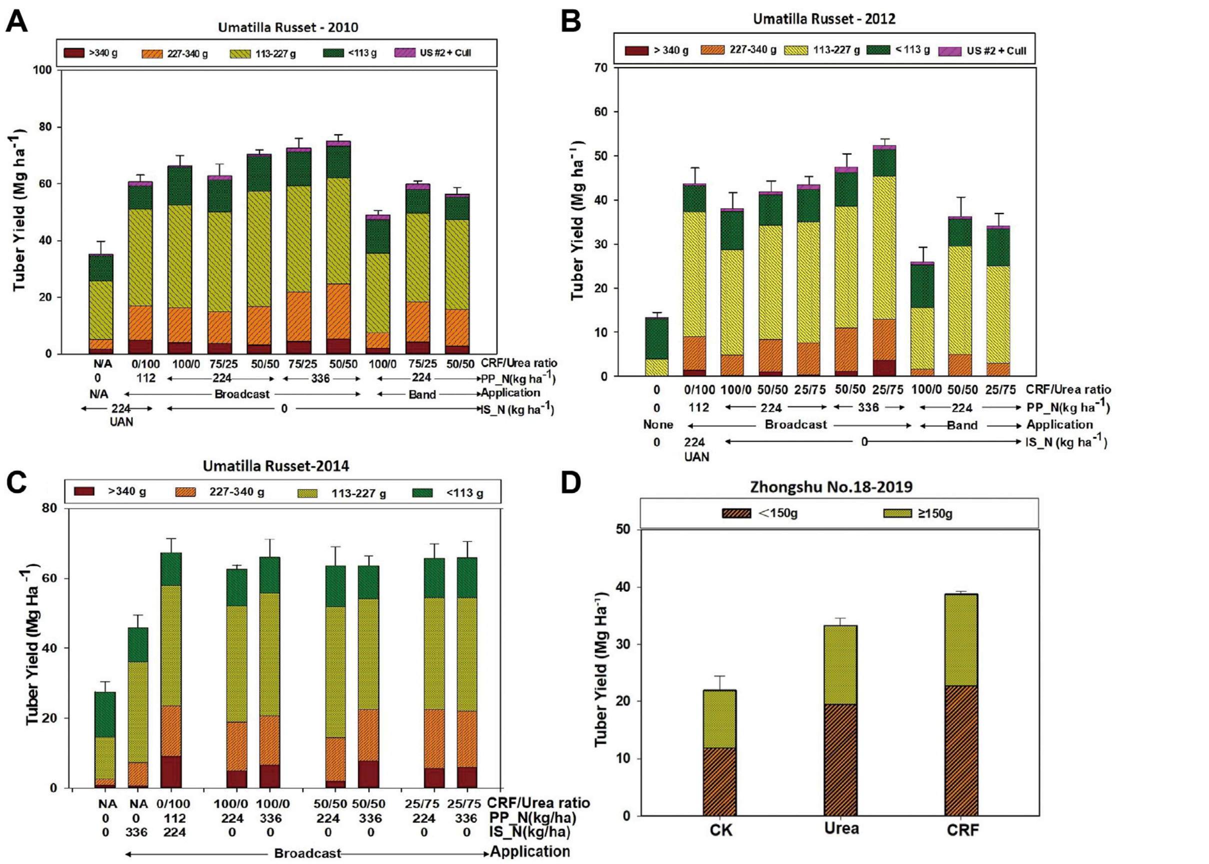

FIGURE 1
Effects of different N fertilization treatments on the total potato yield and yield of different sized grade potato. **(A–C)** are for the Paterson experiment, United States, for 2010, 2012, and 2014, respectively. The potato variety used was "Umatilla Russet." The N rate, source, timing, and method of application for each treatment are shown at the bottom of each figure, with full details in Table 1. **(D)** is for the Wuchuan County experiment, China, 2019. The N rate for urea or CRF treatment was 220 kg/ha. The potato variety used was "Zhongshu No. 18." CRF, controlled-release fertilizer; PP-N, pre-plant N rate; IS-N, in-season N rate as fertigation; UAN, urea ammonium nitrate-32; CK, control in 2010; 2012 experiments: broadcast = pre-plant N was broadcasted over the entire plot area and incorporated in the topsoil during soil preparation tillage and band = pre-plant N was banded along the planting row, 10 cm beside the seed piece and 10 cm below the top of the planting ridge. The vertical line on top of each histogram in each figure represents the standard error of the mean total yield.

practice, i.e., the pre-plant broadcast of urea and in-season fertigations with UAN-32. Petiole NO_3^-_N concentrations at a total N rate of 224 kg/ha (at 50/50 ratio of CRF/urea) as the broadcast application were greater than those with the band application of the similar N blend. However, petiole NO_3^-_N concentrations were lower at a 75/25 ratio of CRF/urea blends at a total N rate of 224 kg/ha than those with CRF/urea blend with a lower proportion of CRF.

The 2014 experiment showed that petiole NO_3^-_N concentrations decreased during the growing period for CRF treatments both as the sole source of N or CRF/urea blends at 50/50 or 25/75 ratios, unlike those in the industry-standard N management treatment (data not presented). However, tuber yields were similar across all the above treatments (Figure 1C). Increasing the total N rate to 336 kg/ha (at a 50/50 or 25/75 ratio of CRF/urea) had no significant advantage in terms of petiole NO_3^-_N concentrations and/or total tuber yields compared to that at 224 kg/ha N.

In summary, results of the 3-year potato N management field experiments in a high-production growing region in Paterson, United States, demonstrated benefits of using the CRF compared to the use of a soluble N source by the reduction in the total N requirement and reduction in the cost of application by reducing the frequency of application, thereby requiring lower labor and fuel costs. Detailed economic analyses are recommended for a given production and market conditions to estimate the net returns across different treatments evaluated in this study. Likewise, it is highly recommended for the evaluation of environmental quality responses, with the use of CRF as a sole source of N or CRF/urea blends vs the use of only soluble urea. These investigations must include the evaluation of nitrate leaching and emission of ammonia and/or nitrous oxide, which will provide a measure of the potential mitigation of adverse effects on water and air quality by using the CRF.

3.3 Wuchuan experiment

The tuber yield was approximately 22 Mg/ha in the control treatment (Figure 1D). The yield increased by 48 or 73% with the

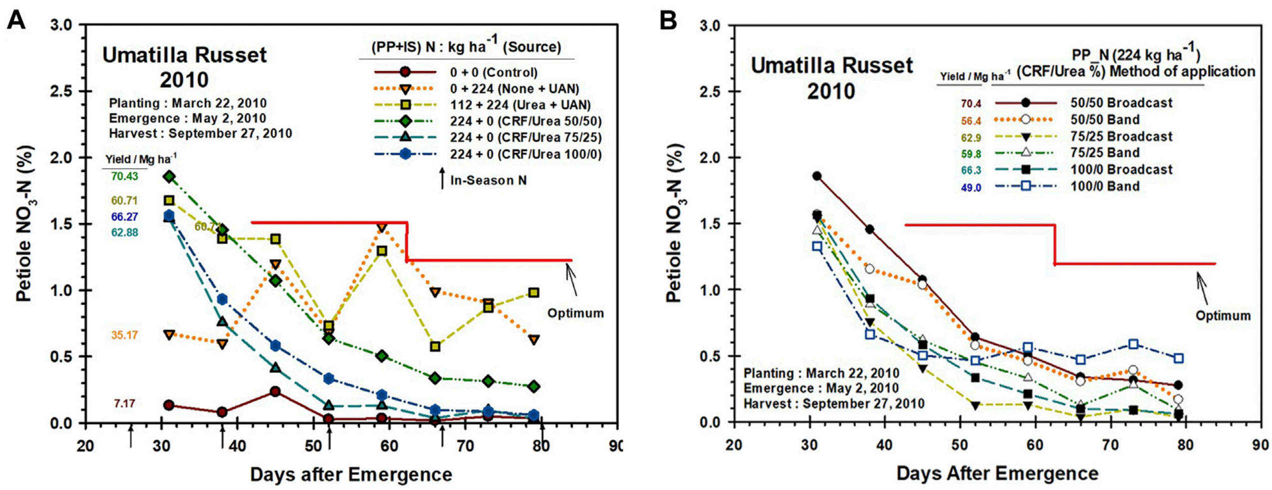

FIGURE 2
Effects of different N fertilization treatments on petiole NO_3^--N levels of "Umatilla Russet" potato plants. Notes: 2010, Paterson experiment, United States. Data for a 1-year experiment are only presented as an example. The trend was similar for the remaining 2 years of the study. PP, pre-plant N application; IS, in-season N application; CRF, controlled-release fertilizer; UAN, urea ammonium nitrate-32 used as the N source for fertigation; broadcast, pre-plant N was broadcasted over the entire plot area and incorporated in the topsoil during soil preparation tillage; band, pre-plant N was banded along the planting row, 10 cm beside the seed piece and 10 cm below the top of the planting ridge. Total tuber yields for each treatment are shown in both figures. The red line across the growth stage shows optimal petiole NO_3^--N concentrations to be maintained over the growing season for high-yielding potato production as per Washington State University cooperative extension recommendations. Arrows pointing to the x-axis only in **(A)** show the timing of in-season fertigations for some treatments. No IS-N for the treatments in **(B)**.

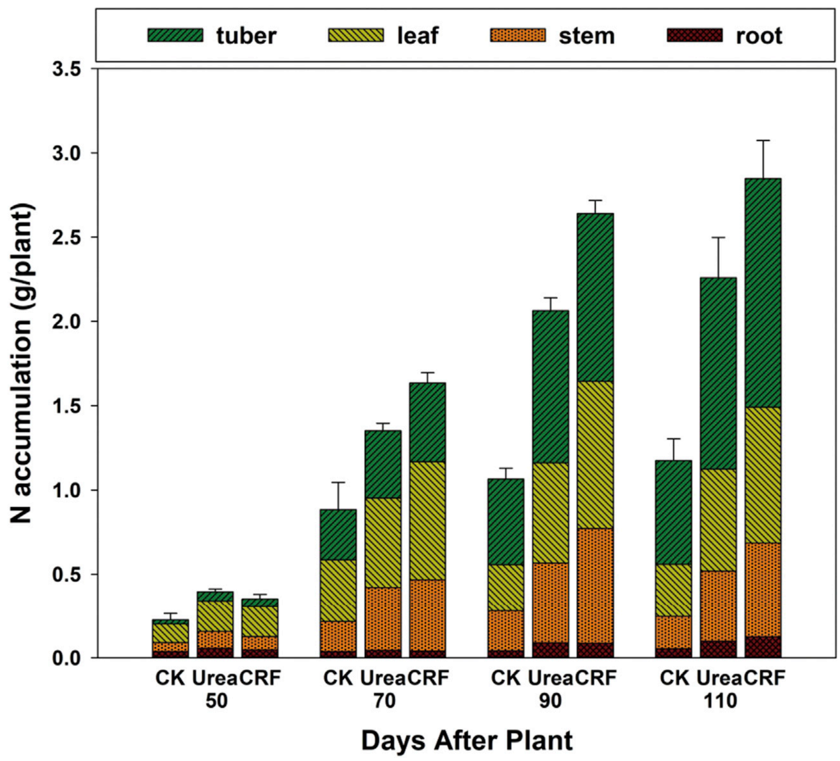

FIGURE 3
Total N in tuber, roots, stem, and leaves per plant sampled 50, 70, 90, and 110 days after emergence (DAE) in the control treatment (CK) or in the plants that received 220 kg/ha N as urea or CRF. Wuchuan County, China experiment, 2019.

application of 220 kg/ha N as urea or CRF, respectively. Therefore, there was a distinctive advantage of using CRF for substantial yield increase compared to using soluble urea at the same N rate. The proportion of large-sized potato tubers was also much greater with the CRF treatment than that in the urea treatment at a similar N rate.

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The total N content in the plant increased from 50 to 90 days after emergence (DAE) and then remained steady until 110 DAE (Figure 3). The N content in the leaves was the highest, while it was the lowest in the roots. On 50 DAE, N contents in different plant parts were significantly greater in the plants under urea or CRF treatment than those in the control treatment. On 70 DAE, N contents in the roots and stems were not significantly different in the urea and CRF treatments. On 90 DAE, N contents in all plant parts attained peak values. Root N contents were influenced significantly by N treatments and followed the order CRF = urea > CK. N contents in the stems and leaves followed the order CRF > urea > CK. Therefore, N uptake was significantly greater in the plants that received CRF than that of the plants that received urea at the same N rate. A similar trend was maintained on 110 DAE.

4 Discussion

The results of the 4-year field experiments on potato N management have shown that the use of CRF at a reduced N rate and frequency of application improved the potato yield, petiole NO_3^-_N level, and plant N content compared to those obtained with the use of only soluble urea. These results agree with those reported by Li Y. et al. (2023), i.e., unlike the soluble N sources, the CRF improved the nutrient uptake efficiency and reduced the nutrient losses, thereby enhancing the crop yield and quality. Studies have shown that the combination of CRF and soluble urea maximized tomato yield in different planting systems (Qu et al., 2020). Early maturing rape yield increased with the use of CRF compared to that with soluble fertilizers (Tian et al., 2016). Furthermore, the use of CRF enhanced the stability of soil bacterial ecology; improved soil-available potassium, ammonium, and nitrate; and increased corn yield (Li Z. et al., 2023).

The tuber yield and quality obtained with the use of CRF/urea blend at a 50/50 or 25/75 ratio were similar to those obtained with using only CRF at a similar N rate for the growing season. The former N product provides an opportunity to lower the cost of N fertilizers per unit N basis. The band application of CRF or CRF/urea blend resulted in a lower yield than that obtained with the broadcast application of the same product at the same N rate. The application of CRF/urea blend, at either a 50/50 or 25/75 ratio, increased the NO_3^-_N concentrations in potato petioles compared to those in the plants that received the current US PNW potato N management recommendation treatment, i.e., pre-plant urea broadcast plus five in-season fertigations using UAN-32.

In Wuchuan County, China, the experimental application of total N entirely as CRF significantly increased the total N in plants and the tuber yield compared to those of the plants with the application of the same N rate as urea.

5 Conclusion

Four years of replicated field studies demonstrated that potato yields and petiole NO_3^-_N levels of the plants with the application of CRF/urea blends, at either a 25/75 or 50/50, were very similar to those obtained using a similar N rate only as CRF. Blending CRF with urea helps reduce the cost of N fertilizers per unit N compared to that of using only CRF. Tuber yields and quality were similar with a single pre-plant broadcast application of 224 kg N/ha CRF or CRF/urea blends compared to those with the industry-standard practice of 112 kg N/ha as urea with a pre-plant broadcast application plus five in-season fertigations of 224 kg N/ha using UAN-32. Therefore, using CRF enables the reduction in the total N rate and frequency of application, which, in turn, offsets the increased cost of CRF compared to soluble N sources per unit N.

Controlled-release fertilizer significantly increased the N content and N accumulation in potato roots, stems, and leaves at the later stage of plant growth and tuber yield. Further studies are required to evaluate the leaching of NO_3^--N, N_2O emissions, and NH_3 volatilization using CRF compared to soluble urea at the same N rate. Demonstration of the potential reduced risk of N losses when using CRF will increase the N use efficiency and reduce negative impacts on the environment.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

HX: conceptualization, data curation, software, supervision, writing–review and editing, and writing–original draft. XZ: data curation, formal analysis, and writing–original draft. HW: methodology and writing–original draft. JY: investigation and writing–review and editing. AA: supervision and writing–review and editing. MF: investigation and writing–review and editing. ZZ: methodology, writing–original draft, and writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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