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Slow-Release Fertilizer Improves the Growth, Quality, and Nutrient Utilization of Wintering Chinese Chives (*Allium tuberosum* Rottler ex Spreng.)

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Abstract: Excessive application of fertilizers leads to the loss of a high amount of nutrients and low fertilizer utilization, which severely restricts crop productivity. Establishing better fertilizer usage practices can mitigate the adverse effects of excessive fertilizer use in agricultural practices. This study determined the effects of slow-release fertilizers on the growth; quality; root and nitrate reductase activity; accumulation; distribution of nitrogen (N), phosphorus (P), and potassium (K) in roots, stems, and leaves; and NPK utilization of winter Chinese chives (*Allium tuberosum* Rottler ex Spreng.) in multi-layer covered plastic greenhouses. Treatments were conventional fertilization (CF, NPK: 1369.5 kg ha^{-1}), conventional fertilization with slow-release fertilizer (SRF, NPK: 1369.5 kg ha^{-1}), reduced fertilization with slow-release fertilizers (SRFR, NPK: 942.0 kg ha^{-1}), and no fertilizer arranged in a completely randomized design with three replicates. The SRFR treatment increased Chinese chives yield and economic profitability by 37% and 47%, respectively, compared to the CF treatment. Similarly, nitrate reductase activity, root activity, soluble sugar, soluble protein, and flavonoid contents in the Chinese chives were increased by 40%, 12%, 16%, 6%, and 18%, respectively, in SRFR than CF. In addition to these, we observed a significant reduction in the surplus of N (42%) and P (58%) in soil under SRFR compared to CF. Nutrient uptake and nutrient use efficiency were also greater in SRFR than in CF. The results indicate that the adoption of SRFR can be an efficient approach to enhance quality and productivity of Chinese chives compared to CF under a multi-layer covered plastic greenhouse system.

Keywords: Chinese chives; slow-release fertilizer; yield; dry matter production; quality; nutrient use efficiency

1. Introduction

Chinese chives (*Allium tuberosum* Rottler ex Spreng.) belong to the genus Allium and are a cold-tolerant perennial herbaceous ratoon plant. Most of the species in this genus are used around the world as food, spices, and medicinal materials [1]. Chemical investigations of the different parts of Chinese chives have shown that they contain vitamins, crude fibers, mineral compounds, and sulfur compounds, and have antibacterial properties when consumed by humans [2–4]. Chinese chives are becoming more economically valuable because of their nutritional and functional components [5,6].

Growers in Wushan, China (hometown of Chinese Chives), have increased the production capacity of Chinese chives by adopting multi-layer (four-layer) covered plastic greenhouses during winter [7]. However, cropping year after year with high use of chemical fertilizers and unreasonable levels of irrigation in plastic greenhouses has caused triggered heavy metal pollution in the soil, nutrient loss, eutrophication of groundwater, and reductions in soil fertility and production efficiency [8–10]. Under the premise of ensuring that a given crop yield can be obtained, optimizing the management of fertilizers and avoiding excessive use of fertilizers are important factors in reducing agricultural production costs, maintaining sustainable agricultural development, and achieving environmentally friendly agriculture [11]. Nitrogen (N) from conventional fertilizer, such as urea, is only partially absorbed and utilized by plants. Accumulation of a large amount of NO_3-N in the soil reduces the N usage efficiency of crops, leads to environmental pollution, increases the cost of crop production, and reduces crop yield and quality [12–15]. In recent years, a new type of fertilizer has been developed: slow-release fertilizer (SRF). Slow-release fertilizer releases nutrients slowly over a long release time. Its release of nutrients is consistent with a crop's physiological nutrient requirements. It can reduce the number of fertilization times and total amount of fertilizer applied, while increasing fertilizer use efficiency [16–19]. Slow-release fertilizer may be a good alternative to the conventional chemical fertilizer and can be used to increase N uptake efficiency and crop yield, because the N release rate of SRF corresponds more closely to a plant's N requirements for physiological functions [20,21]. Although the costs of SRFs are usually higher than conventional fertilizers, their application can reduce the amount of residual nutrients in the soil, and improve crop yield and economic efficiency [22,23]. The establishment of methods for SRF use is important in avoiding the excessive application of fertilizers and improving the production capacity of agriculture. To our best knowledge, there are currently no published research data on the effect of fertilizer rate of SRF on nutrient utilization of Chinese chives in multi-layer covered plastic greenhouses in cold regions.

We hypothesized that the application of SRF would (i) promote growth and enhance the productivity and quality of Chinese chives and (ii) increase the accumulation of N, phosphorus (P), and potassium (K) in Chinese chives and nutrient use efficiency. The objectives of this study were to investigate the effects of SRF on the growth, quality, nutrient accumulation, and distribution in different organs, and nutrient use efficiency of wintering Chinese chives under multi-layer (four-layer) covered plastic greenhouses system.

2. Materials and Methods

2.1. Experimental Sites, Greenhouse Management and Environment, and Test Materials

The experiment was conducted from June 2017 to February 2019 at the core demonstration area for Qingchi Chinese chives located in Wushan County, China (N 34°25′–34°57′, E 104°34′–105°08′). Figure 1 shows the experiment on the production of Chinese chives during winter in multi-layer covered plastic greenhouses. Wushan has a typical temperate continental semi-humid monsoon climate. The average annual air temperature was 9.6 °C, and the average annual precipitation was 500 mm. The soil type was sandy loam, the terrain was flat, and the soil fertility was moderate and uniform. Soil was collected from the plow layer (0–20 cm) in the field, and its nutrient content was determined by the conventional chemical analysis methods (alkali-hydrolyzable N, 54.8 mg kg^{-1}; available P, 70.2 mg kg^{-1}; available K, 121.7 mg kg^{-1}; organic matter, 15.6 g kg^{-1}; EC, 2.4 ms cm^{-1}; and (water extracted) pH, 6.8) [24].

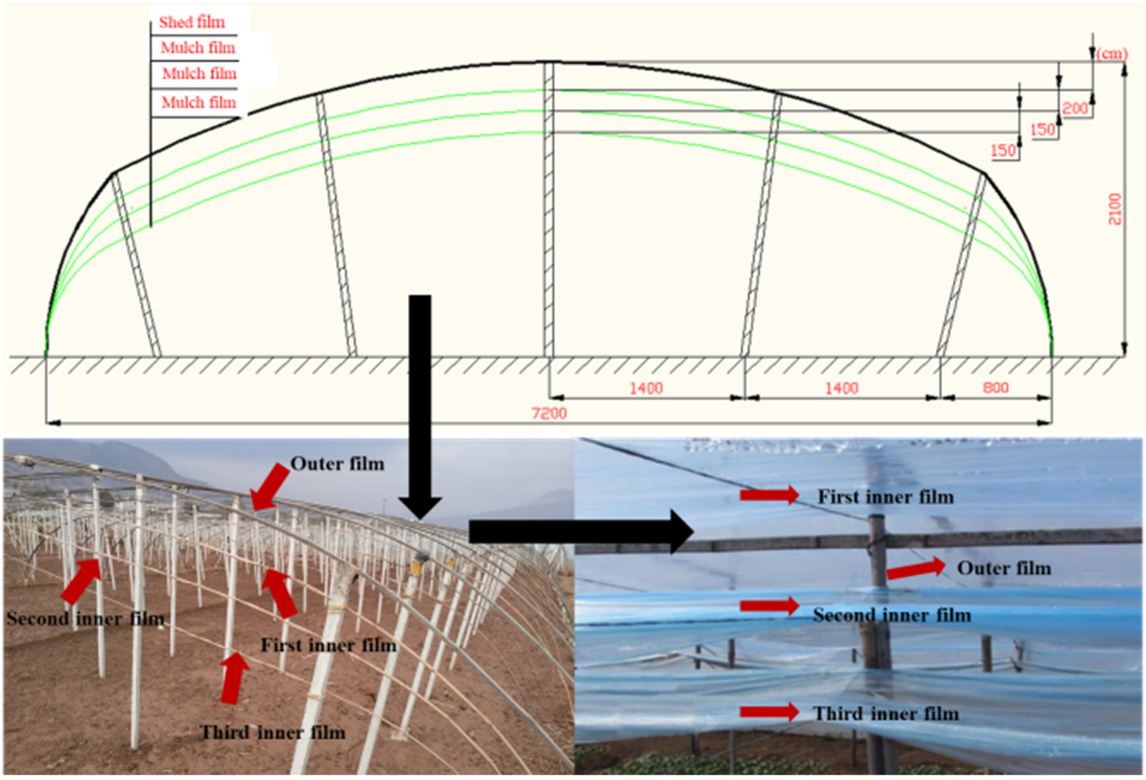

Figure 1. A schematic diagram of the pattern of a multi-layer covered plastic greenhouse.

Data on the microclimate in the multi-layer covered plastic greenhouses were collected by using environmental monitoring devices, including an EL-USB-2 air temperature and humidity recorder, an EL-USB-1-PRO soil temperature recorder (LASCAR Co., Ltd., Salisbury, UK), a GM70 handheld carbon dioxide detector (VAISALA Co., Ltd., Helsinki, Finland), and a YGSC-1 automatic light recorder (Jinzhou Sunshine Weather Technology Co., Ltd., Jinzhou, China) (Figure 2). The average air temperature in the multi-layer covered plastic greenhouses was 12.3 °C (Figure 2A). In the case of extremely low air temperatures, the average air temperature in the multi-layer covered plastic greenhouses was 9.8 °C, and the average temperature of the 0–20 cm plowed soil layer was 10.3 °C (Figure 2B). The average CO_2 concentration was 16,017.7 mg L^{-1} (Figure 2C). The daily average light intensity was 6945.9 Lux, and the average daytime light intensity was above 10,000 Lux for 4 h (Figure 2D).

Chinese chive (cv. 'Chive God F1') seeds obtained from the Fugou County Seedling Research Institute in Henan, China. Slow-release fertilizer, in the form of a resin-coated compound fertilizer used in the experiment, was provided by Hubei Ezhong Ecological Engineering Co., Ltd., Hubei Province, China. The SRF had release longevity of 120 d and an NPK ratio of 26:11:11. Conventional fertilizers used in this experiment included urea containing 46% N, calcium superphosphate containing 12% P, and potassium sulfate containing 50% K.

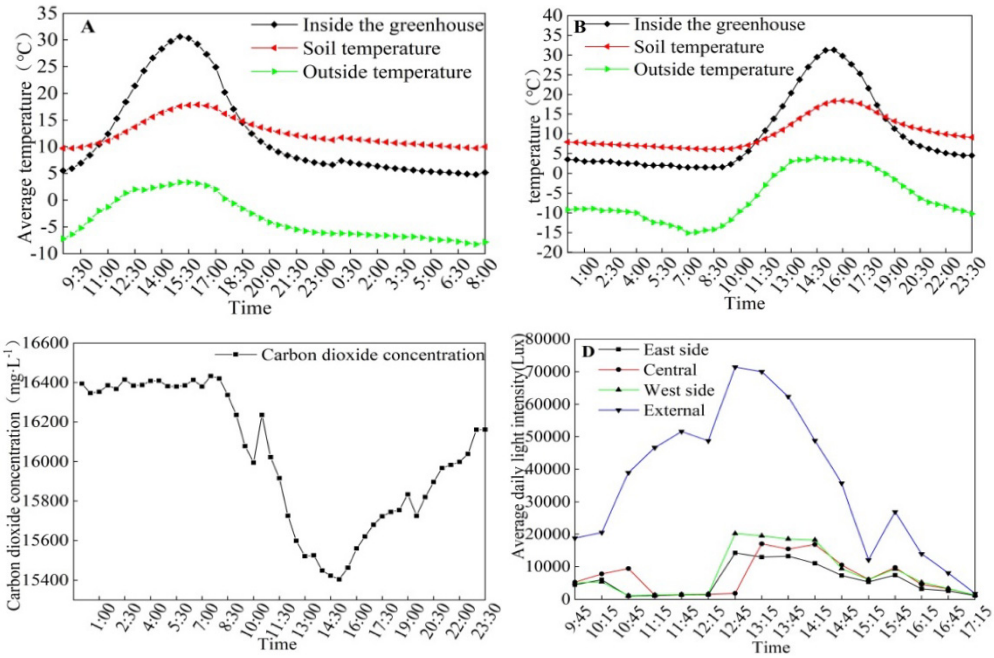

Figure 2. Daily average temperature (**A**), extreme weather shed temperature (**B**), daily average CO_2 concentration (**C**), and daily average light intensity (**D**) in multi-layer (four-layer) covered plastic greenhouses (December 2017 to February 2018 and December 2018 to February 2019).

2.2. Methods and Treatments

The experiment was arranged in a completely randomized design with three replications of four treatments:

(i) No fertilizer (CK).

(ii) Conventional fertilization (CF, NPK dosage: 1369.5 kg ha^{-1}: 655.5 kg N ha^{-1}, 559.5 kg P ha^{-1}, and 154.5 kg K ha^{-1}) applied in accordance with the traditional, customary amount of fertilizer used by local farmers.

(iii) Conventional fertilization with slow-release fertilizer (SRF, NPK dosage: 1369.5 kg ha^{-1}: 655.5 kg N ha^{-1}, 559.5 kg P ha^{-1}, and 154.5 kg K ha^{-1}), in which SRF replaced CF, and the nutrient dosage was the same as that of CF).

(iv) Reduced fertilization with slow-release fertilizer (SRFR, NPK dosage: 942.0 kg ha^{-1}: 438.0 kg N ha^{-1}, 180.0 kg P ha^{-1}, 324.0 kg K ha^{-1}). The nutrient dosages were decreased by 31% in this treatment compared to CF, N was decreased by 33%, P was decreased by 68%, and K was increased by 110%.

The plot size was 10 m × 30 m.

Chinese chive seedlings were planted on 20 June 2017. The seedlings were cut from the root apex, with 2–3 cm left to promote the development of new roots. The row spacing was 20 cm, the distance between holes was 10 cm, and three seedlings were planted in each hole. Each treatment received 9750 kg ha^{-1} of dried chicken manure that was uniformly distributed over the soil (on 15 June 2017 and 5 April 2018). During the 2017 rooting period, the CF treatment was top-dressed four times on 5 July, 22 July, 9 August, and 28 August with 25% of the total amount of fertilizer applied at each top-dressing. The SRF and SRFR treatments were top-dressed once during the rooting period in 2017 on July 5. During the 2018 rooting period, the CF treatment was top-dressed three times (on 18 April, 26 July, and 25 September) with one-third of the total amount of fertilizer applied at each top-dressing. The SRF and SRFR treatments were top-dressed twice during the 2018 rooting period on 18 April and 26 July, with 50% the total amount of fertilizer applied at each top-dressing. All treatments were evenly spread with 2475 kg ha^{-1} of oil dregs on 15 August 2017 and 11 August 2018. The slow-release fertilizer required for each production period was applied all at once on 15 November 2017 and 6 November 2018 (Table 1). The greenhouse was covered with plastic shed film up to the production period on 20 November 2017 and 13 November 2018, and then removed up to the rooting period on 15 March 2018 and 20 March 2019. The Chinese chive crop was harvested three times per year for a total of two years and all field management practices other than fertilization were strictly consistent across treatments.

Table 1. The fertilizer ratio and amount for the different treatments in 2017–2019.

Treatment	N (kg ha^{-1})		P (kg ha^{-1})		K (kg ha^{-1})		Total Fertilizer (kg ha^{-1})
	Rooting Period	Production Period	Rooting Period	Production Period	Rooting Period	Production Period	
CK	0	0	0	0	0	0	—
CF	298.5	357.0	394.5	165.0	46.5	108.0	1369.5
SRF	298.5	357.0	394.5	165.0	46.5	108.0	1369.5
SRFR	219.0	219.0	90.0	90.0	162.0	162.0	942.0

Note: In the first year, the rooting period of Chinese chives was from 20 June 2017 to 20 November 2017, the shed was buckled on 20 November 2017, and the production period was from 20 November 2017 to 24 February 2018. In the second year, the rooting period of Chinese chives was from 24 February 2018 to 15 November 2018, the shed was buckled on 15 November 2018, and the production period was from 15 November 2018 to 16 February 2019. In the first year and the second year, the amount of fertilizer applied was the same.

The fertilizer dosage for the SRFR treatment was calculated for the rooting and production periods according to the target yield using the nutrient balance method of absorbing 1.7 kg N, 0.5 kg P, and 1.8 kg K per 1000 kg Chinese chives. The utilization rate of N, P, and K was determined to be 35%, 25%, and 50%, respectively. The target yield of Chinese chives was 45,000 kg ha^{-1}, and the amounts of N, P, and K were determined to be 219 kg ha^{-1}, 90 kg ha^{-1}, and 162 kg ha^{-1}, respectively. Thus, the total nutrient content in the SRFR treatment was 31% lower than that in the CF treatment (in which N was decreased by 33%, P was decreased by 68%, and K was increased by 110%). When the P and K contents were insufficient in the SRF and SRFR treatments, we used superphosphate and potassium sulfate, respectively, to make up the difference. The amount of fertilizer that was used in each treatment is shown in Table 1.

2.3. *Yield and Dry Matter Determination*

After the Chinese chive crop reached the commercial standard, it was harvested and the yield of all plots was determined. Nine holes of Chinese chives were randomly selected from each plot. The plants were divided into roots, stems, and leaves, and their fresh weight was weighed. The dry matter content of the plants (including roots, stems, and leaves) was determined. The plant material was dried at 105 °C for 30 min, and then dried at 75 °C until the weight was constant. Afterward, the dry biomass was weighed [25].

2.4. *Determination of Vitamin C, Soluble Sugar, Soluble Protein, Nitrate, Total Phenol and Flavonoid Contents, Root Activity, and Nitrate Reductase Activity*

Each year, after the Chinese chives crop was harvested for the second time, nine holes of Chinese chives were randomly selected from each plot to determine the quality and physiological parameters. The vitamin C content was measured using the 2,6-dichloroindophenol stain method [26]. The anthrone–sulfuric acid assay method was used to estimate the soluble sugar content [27]. The coomassie brilliant blue method was used to estimate the soluble protein content [28]. Nitrate content was measured using the salicylic acid–sulfuric acid method [29]. Total phenol and flavonoid contents were determined with methanol containing 0.01% HCl [30]. The root activity was determined by the red tetrazolium method (TTC method) [31]. Nitrate reductase (NR) activity was determined by sulfamate colorimetry [32].

2.5. Determination of N, P, and K Contents

The roots, stems, and leaves that had been used to determine the dry matter content (as described above) were ground and sieved through a 2.0 mm screen, and then used to determine plant nutrient content. Nitrogen content was measured using the Kjeldahl method with a fully automatic Kjeldahl K1100F apparatus (Jinan Hanon Instruments Company, Jinan, China) [33]. Phosphorus content was measured using the molybdenum blue colorimetric method and analyzed using a UV-1780 spectrophotometer (Shimadzu Instruments (Suzhou) Co., Ltd. Suzhou, China) [34]. Potassium content was measured using the flame spectrophotometer method and an AP1302 flame photometer (Shanghai Aopu Analytical Instruments Company, Shanghai, China) [35].

2.6. Determination of Accumulation of N, P and K in Organs Apparent Utilization, Partial Factor Productivity, and Agronomic Efficiency

The accumulation and distribution rates of NPK in organs (root, stem, and leaf) were calculated by the following formulas [36],

$$\text{The accumulation of N in an organ (kg ha}^{-1}\text{)} = \text{C} \times \text{W} \tag{1}$$

$$\text{The distribution of N in an organ } (\%) = \frac{\text{C} \times \text{W}}{\text{A}} \tag{2}$$

where C is the content of N in a given organ (g kg^{-1}), W is the dry weight of a given organ (kg ha^{-1}), and A is the total content of N in the plant (kg ha^{-1}). Phosphorus and K accumulation and distribution were also derived from the above equation using P or K instead of N.

Use efficiency, partial factor productivity, and agronomic efficiency of the NPK fertilizer was calculated according to the formulas of Devkota et al. [37], Cassman et al. [38], and Fageria et al. [39], respectively:

$$\text{N use efficiency } (\text{NUE}, \%) = \frac{\text{U}_1 - \text{U}_0}{\text{F}} \tag{3}$$

$$\text{N partial factor productivity } (\text{N PFP}, \text{ kg kg}^{-1}) = \frac{\text{Y}}{\text{F}} \tag{4}$$

$$\text{N agronomic efficiency } (\text{N AE}, \text{ kg kg}^{-1}) = \frac{\text{Y}_1 - \text{Y}_0}{\text{F}} \tag{5}$$

where U_1 and U_0 represent the plant N content with N fertilizer and plant N content without N fertilizer, respectively; Y represents the crop yield with N fertilizer; Y_1 and Y_0 represent the crop yield with N fertilizer and crop yield without N fertilizer, respectively; and F represents the N fertilizer rate. The use efficiency, partial factor productivity, and agronomic efficiency of P and K were also derived from the above equations using P or K instead of N.

2.7. Statistical Analysis

The parameters were analyzed using IBM SPSS 20.0, Origin Pro 9.0. Data collected are expressed as the mean ± standard error of three replicates for each treatment. Line graphs, bar charts, and tables were constructed using Origin Pro 9.0. Means were compared using Duncan's multiple range test at $p < 0.05$.

3. Results

3.1. Dry Matter Accumulation

During the cultivation of Chinese chives in the multi-layer covered plastic greenhouses, the application of SRF was found to significantly promote the growth of Chinese chives during winter by increasing the fresh weight and dry weight of leaves by 57% and 31%, respectively, and both the fresh weight and dry weight of the roots by 13%, as compared to CF, but there was no significant effect on the dry weight of stems (Figure 3). The fresh weight and dry weight of leaves of the SRFR treatment were significantly increased by 27% and 44%, and the fresh weight and dry weight of roots increased by 26% and 23%, respectively, as compared to CF.

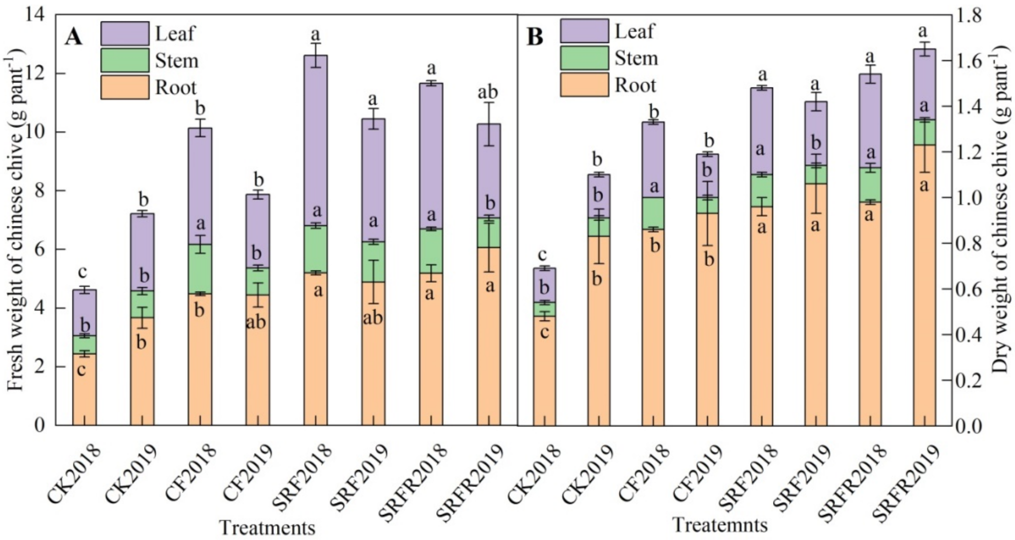

Figure 3. The effect of slow-release fertilizer on the fresh weight of shoots and roots (**A**) and the dry weight of shoots and roots (**B**) of wintering Chinese chives in multi-layer covered plastic greenhouses. Vertical bars represent the mean ± standard error (n = 3 replicates with nine plants per replicate). Different letters denote significant differences ($p < 0.05$). CF: NPK 1369.5 kg ha^{-1}; SRF: NPK 1369.5 kg ha^{-1}; SRFR: NPK 942.0 kg ha^{-1}; CK: no fertilizer.

3.2. *Yield and Economic Benefits*

The application of SRF significantly improved the yield of Chinese chives during winter (Table 2). The SRF and SRFR treatments produced a significant yield increase during the first through third harvests as compared to CF. Total yield of SRF and SRFR was increased by 39% and 37%, respectively, compared to CF. In terms of economic benefits, SRF recorded the highest revenue, which was 41% greater than that of CF, whereas SRFR had the highest net return, which was 47% greater than that of CF (Table 3).

Table 2. The effect of slow-release fertilizer on the yield of wintering Chinese chives in multi-layer covered plastic greenhouses.

Year	Treatment	Yield (kg ha^{-1})			Total Yield (kg ha^{-1})	Increase in Total Yield Compared to CF(kg ha^{-1})	Increase in Total Yield Compare to CF(%)
		First Harvest	Second Harvest	Third Harvest			
2018	CK	11,540.0 ± 253.1c	9340.1 ± 69.8c	6758.4 ± 60.6d	27,638.4 ± 235.8c	-	-
	CF	14,699.9 ± 102.4b	11,892.0 ± 83.1b	9483.5 ± 129.2c	36,075.3 ± 142.7b	-	-
	SRF	22,700.0 ± 303.6a	16,160.1 ± 160.7a	13,805.0 ± 142.3a	52,665.0 ± 584.5a	16,589.7	46.0
	SRFR	22,560.0 ± 158.6a	15,900.0 ± 176.3a	13,203.5 ± 106.0b	51,663.5 ± 385.4a	15,588.2	43.2
2019	CK	10,446.5 ± 192.3c	8692.5 ± 120.0c	5460.6 ± 248.0c	24,599.6 ± 530.2c	-	-
	CF	16,443.7 ± 115.7b	13,302.8 ± 117.5b	9108.5 ± 90.9b	38,855.0 ± 291.7b	-	-
	SRF	23,204.9 ± 105.5a	16,354.6 ± 975.0a	11,864.4 ± 116.6a	51,423.9 ± 1002.91a	12,568.9	32.3
	SRFR	22,975.6 ± 181.5a	16,144.4 ± 179.0a	11,680.9 ± 177.3a	50,800.9 ± 331.1a	11,945.9	30.7
Year (Y)		*	ns	***	ns	***	***
Treatment (T)		***	***	***	***	ns	ns
T × Y		***	.	***	***	ns	ns

Note: CF: NPK 1369.5 kg ha^{-1}; SRF: NPK 1369.5 kg ha^{-1}; SRFR: NPK 942.0 kg ha^{-1}; CK: no fertilizer. Values are expressed as means ± standard error (n = 3 replicates). Significant differences among treatments for a particular year based on Duncan's multiple range test ($p < 0.05$) are shown with different letters. The significance of the effect of a particular factor as well as the interactions between factors are described by following symbols, "ns", $p > 0.1$; ".", $p < 0.1$; "*", $p < 0.05$; "**", $p < 0.01$; and "***", $p < 0.001$.

Table 3. The effect of slow-release fertilizer on economic benefits.

Year	Treatment	Revenue (CNY ha^{-1})	Increase in Revenue Compared to CF (%)	Fertilizer Cost (CNY ha^{-1})	Fertilization Labor Cost (CNY.time^{-1})	Net Return (CNY ha^{-1})	Increase Revenue Compare to CF (%)
2018	CK	89,258.7 ± 1279.6c	-	-	-	-	-
	CCF	114,383.6 ± 374.8b	-	15,025.5	350.0	99,008.1 ± 374.8b	-
	SRF	16,9792.2 ± 2033.3a	48.4	16,909.5	200.0	152,622.7 ± 2033.3a	54.2
	SRFR	167,882.7 ± 1319.4a	46.8	14,039.9	200.0	153,642.8 ± 1319.4a	55.2
2019	CK	74,416.2 ± 1336.4c	-	-		-	-
	CCF	116,613.4 ± 837.7b	-	20,864.9	300.0	101,287.9 ± 837.7b	-
	SRF	156,120.7 ± 2834a	33.9	6825.0	250.0	138,961.2 ± 2834a	37.2
	SRFR	154,352.7 ± 1191a	32.4	21,850.5	250.0	140,062.8 ± 1191a	38.3

Note: Net income (CNY ha^{-1}) = revenue (CNY ha^{-1}) − fertilizer cost (CNY ha^{-1}) − fertilization labor cost (CNY time^{-1}). The price of Chinese chives for the first, second, and third harvests was 5.0 CNY kg^{-1}, 2.8 CNY kg^{-1}, and 0.8 CNY kg^{-1} in 2018, respectively, and 4.0 CNY.kg^{-1}, 3.0 CNY.kg^{-1}, and 1.2 CNY.kg^{-1} in 2019, respectively. Slow-release fertilizer was 3.3 CNY kg^{-1}, urea was 2.0 CNY kg^{-1}, calcium superphosphate was 0.75 CNY kg^{-1}, potassium sulfate was 6 CNY kg^{-1}, and dried chicken manure was 0.7 CNY kg^{-1}. Fertilization labor cost was 50.0 CNY time^{-1}. Values are expressed as means ± standard error (n = 3 replicates). Significant differences among treatments for a particular year based on Duncan's multiple range test ($p < 0.05$) are shown with different letters. CF: NPK 1369.5 kg ha^{-1}; SRF: NPK 1369.5 kg ha^{-1}; SRFR: NPK 942.0 kg ha^{-1}; CK: no fertilizer.

3.3. Root Activity and Nitrate Reductase Activity

The continuous application of SRF was found to significantly promote root activity and leaf nitrate reductase activity in wintering Chinese chives (Figure 4). The root activity of the SRF and SRFR treatments was significantly increased by 13% and 12%, respectively, as compared to CF. The leaf nitrate reductase activity of the SRF and SRFR treatments was significantly increased by 24% and 40%, respectively, as compared to CF. However, there was no significant difference in root activity between SRF and SRFR. Moreover, nitrate reductase activity with SRFR was significantly 20% higher than that with SRF.

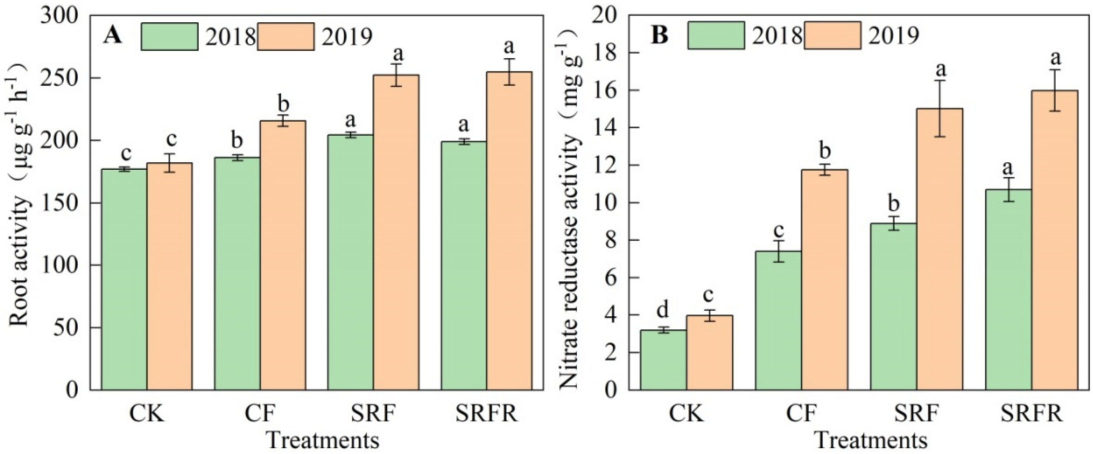

Figure 4. The effect of slow-release fertilizer on root activity (**A**) and nitrate reductase activity (**B**) of wintering Chinese chives cultivated in multi-layer covered plastic greenhouses. Vertical bars represent the mean ± standard error (n = 3 replicates with nine plants per replicate). Significant differences among treatments for a particular year based on Duncan's multiple range test ($p < 0.05$) are shown with different letters. CF: NPK 1369.5 kg ha^{-1}; SRF: NPK 1369.5 kg ha^{-1}; SRFR: NPK 942.0 kg ha^{-1}; CK: no fertilizer.

3.4. Nutritional Quality

The application of SRF significantly improved vitamin C content of Chinese chives cultivated in multi-layer covered plastic greenhouses during winter by 6.1% compared to CF (Figure 5). However, vitamin C content in the SRFR treatment was not significantly increased compared to CF (Figure 5A). Soluble sugar content of the SRF and SRFR treatments was significantly increased by 12% and 16%, respectively, compared to CF (Figure 5B). The SRF and SRFR treatments also significantly increased flavonoid content of chives by 13% and 18%, respectively; however, there was no significant effect on total phenol content (Figure 5D,E). Additionally, SRF had no significant effect on the soluble protein content, whereas the SRFR treatment had a significantly higher soluble protein content compared to CF (Figure 5C). Nitrate content of the SRF and SRFR treatments decreased significantly by 21% and 29%, respectively, compared to CF (Figure 5F).

3.5. Soil Nutrient Balance

The application of SRF significantly reduced soil N, P, and K surplus compared to CF fertilizer (Table 4). Compared to the CF treatment, the amounts of N, P, and K removed through harvest of Chinese chives was increased by 45%, 45%, and 49% for SRF, respectively, and by 31%, 12%, and 39% for SRFR, respectively; however, SRFR did not significantly increase P absorption. The surpluses of the soil N, P, and K of SRF treatment were decreased significantly by 11%, 2.0%, and 21%, respectively, compared to CF. Soil N and P surpluses of SRFR were significantly lower than those of CF (decreases of 42% and 58%, respectively), and soil K surplus of SRFR was significantly 91% higher than that of CF.

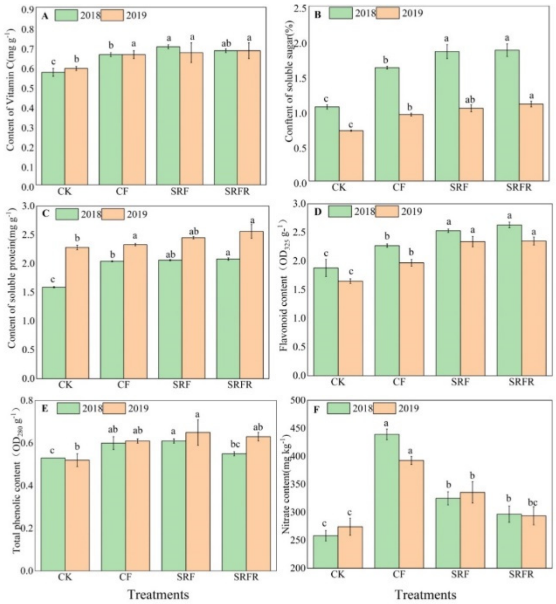

Figure 5. The effect of slow-release fertilizer on vitamin C (**A**), soluble sugar (**B**), soluble protein (**C**), flavonoid (**D**), total phenol (**E**), and nitrate contents (**F**) of wintering Chinese chives cultivated in multi-layer covered plastic greenhouses. Vertical bars represent the mean ± standard error (n = 3 replicates with nine plants per replicate). Significant differences among treatments for a particular year based on Duncan's multiple range test (p < 0.05) are shown with different letters. CF: NPK 1369.5 kg ha^{-1}; SRF: NPK 1369.5 kg ha^{-1}; SRFR: NPK 942.0 kg ha^{-1}; CK: no fertilizer.

Table 4. The effect of slow-release fertilizer on the soil nutrient balance in multi-layer covered plastic greenhouses.

Years	Treatments	N		P		K	
		Crop Harvest (kg ha^{-1})	**Soil N Surplus**	**Crop Harvest (kg ha^{-1})**	**Soil P Surplus**	**Crop Harvest (kg ha^{-1})**	**Soil K Surplus**
2018	CK	90.5 ± 1.5d	-14.8 ± 1.5d	10.9 ± 0.4e	117.8 ± 0.4d	36.3 ± 0.3c	25.1 ± 0.3d
	CF	168.4 ± 0.7c	592.4 ± 0.7a	37.8 ± 0.5c	650.4 ± 0.5a	82.6 ± 0.1b	133.3 ± 0.1b
	SRF	260.1 ± 0.6a	500.7 ± 0.6b	55.6 ± 0.5a	632.6 ± 0.5b	126.0 ± 2.4a	89.9 ± 2.4c
	SRFR	230.7 ± 0.8b	312.6 ± 0.8c	42.5 ± 0.5b	266.2 ± 0.5c	130.1 ± 0.9a	255.3 ± 0.9a
2019	CK	29.7 ± 0.7d	75.6 ± 0.7d	7.2 ± 0.1c	121.5 ± 0.1d	9.6 ± 0.5d	51.8 ± 0.5d
	CF	103.6 ± 1.6c	657.2 ± 1.6a	21.0 ± 1.1b	667.2 ± 1.1a	38.8 ± 1.7c	177.1 ± 1.7b
	SRF	140.6 ± 2.3a	620.7 ± 2.3b	29.9 ± 0.5a	658.3 ± 0.5b	56.2 ± 1.7a	159.7 ± 1.7c
	SRFR	129.7 ± 2.0b	413.6 ± 2.0c	23.3 ± 1.8b	285.4 ± 1.8c	47.0 ± 1.5b	338.4 ± 1.5a
Year (Y)		***	***	***	***	***	***
Treatment (T)		***	***	**	***	***	***
Y × T		***	***	.	***	***	***

Note: nitrogen (N); phosphorus (P); potassium (K). Soil N (P, K) surplus = nutrient input – crop nutrient harvest. Nutrient inputs included fertilizer and dried chicken manure (105.3 kg N ha^{-1}, 128.7 kg P ha^{-1}, and 61.4 kg K ha^{-1}). CF: NPK 1369.5 kg ha^{-1}; SRF: NPK 1369.5 kg ha^{-1}; SRFR: NPK 942.0 kg ha^{-1}; CK: no fertilizer. Values are expressed as means ± standard error (n = 3 replicates). Significant differences among treatments for a particular year based on Duncan's multiple range test (p < 0.05) are shown with different letters. The significance of the effect of a particular factor as well as the interactions between factors are described by following symbols: "ns", p > 0.1; ".", p < 0.1; "*", p < 0.05; "**", p < 0.01; and "***", p < 0.001.

3.6. N, P, and K Accumulation and Distribution in the Root, Stem, and Leaf of Chinese Chives

There was a significant interaction between year and fertilizer treatment of on N, P, and K uptake in the root, stem, and leaf of Chinese chives (Tables 5–7). The accumulation of N in the leaves of Chinese chives of the SRF and SRFR treatments was 71% and 44% greater, respectively, than that in the leaves of the CF treatment. Meanwhile, the N uptake of roots of Chinese chives of the SRFR treatment decreased by 7.1%, and the N uptake of stems of Chinese chives of the SRFR treatment increased by

11%, compared to CF. The uptake of P in the leaves of Chinese chives of the SRF and SRFR treatments was increased by 73% and 22%, respectively, compared to the CF treatment (Table 6). Potassium uptake in leaves of Chinese chives of the SRF and SRFR treatments was significantly increased by 53% and 48%, respectively, compared to the CF treatment (Table 7).

Table 5. The effect of slow-release fertilizer on nitrogen (N) accumulation and distribution in wintering Chinese chives in multi-layer covered plastic greenhouses.

Year	Treatment	Leaf		Stem		Root	
		N Uptake (kg ha^{-1})	Distribution Rate (%)	N Uptake (kg ha^{-1})	Distribution Rate (%)	N Uptake (kg ha^{-1})	Distribution Rate (%)
2018	CK	68.9 ± 1.5d	30.4 ± 0.5a	21.6 ± 0.0d	9.5 ± 0.1d	136.2 ± 0.3c	60.1 ± 0.4c
	CF	92.8 ± 0.6c	16.1 ± 0.1c	75.6 ± 0.2b	13.1 ± 0.1b	409.5 ± 6.9a	70.9 ± 0.3a
	SRF	186.2 ± 0.5a	29.4 ± 0.3a	74.0 ± 0.3c	11.7 ± 0.1c	373.8 ± 6.0b	59.0 ± 0.4c
	SRFR	145.8 ± 0.5b	23.2 ± 0.2b	84.9 ± 0.6a	13.5 ± 0.1a	396.8 ± 6.2a	63.2 ± 0.3b
2019	CK	22.4 ± 0.9d	33.4 ± 1.7a	7.3 ± 0.2c	10.9 ± 0.9a	38.8 ± 5c	55.7 ± 2.3b
	CF	77.6 ± 1.2c	27.9 ± 1.8b	26.0 ± 1.5b	9.3 ± 0.7a	178.3 ± 14.5ab	62.8 ± 2.2a
	SRF	109.1 ± 3.4a	31.5 ± 0.2ab	31.6 ± 1.1a	9.2 ± 0.5a	206.1 ± 5.3a	59.3 ± 0.4ab
	SRFR	101.4 ± 1.8b	35.5 ± 1.2a	28.3 ± 0.3b	10.0 ± 0.4a	158.7 ± 8.5b	54.5 ± 1.5b
Year (Y)		***	***	***	***	***	***
Treatment (T)		***	***	***	*	***	***
Y × T		***	***	***	***	***	***

Note: nitrogen (N). CF: NPK 1369.5 kg ha^{-1}; SRF: NPK 1369.5 kg ha^{-1}; SRFR: NPK 942.0 kg a^{-1}; CK: no fertilizer. Values are expressed as means ± standard error (n = 3 replicates with nine plants per replicate). Significant differences among treatments for a particular year based on Duncan's multiple range test ($p < 0.05$) are shown with different letters. The significance of the effect of a particular factor as well as the interactions between factors is described by following symbols, "ns", $p > 0.1$; "*", $p < 0.05$; "**", $p < 0.01$; and "***", $p < 0.001$.

Table 6. The effect of slow-release fertilizer on phosphorus (P) accumulation and distribution in wintering Chinese chives in multi-layer covered plastic greenhouses.

Year	Treatment	Leaf		Stem		Root	
		P Uptake (kg ha^{-1})	Distribution Rate (%)	P uptake (kg ha^{-1})	Distribution Rate (%)	P Uptake (kg ha^{-1})	Distribution Rate (%)
2018	CK	7.5 ± 0.30d	15.7 ± 0.8b	3.5 ± 0.0c	7.2 ± 0.1c	36.8 ± 0.8c	77.0 ± 0.8ab
	CF	19.4 ± 0.30c	11.0 ± 0.2c	18.5 ± 0.0a	10.5 ± 0.1a	137.9 ± 1.8a	78.5 ± 0.4a
	SRF	39.6 ± 0.45a	21.5 ± 0.2a	16.1 ± 0.2b	8.7 ± 0.1b	128.7 ± 0.5b	69.8 ± 0.2c
	SRFR	26.6 ± 0.15b	15.0 ± 0.0b	15.9 ± 0.6b	9.0 ± 0.4b	134.4 ± 1.2a	76.0 ± 0.4b
2019	CK	5.2 ± 0.1c	20.6 ± 1.5a	2.1 ± 0.1c	8.3 ± 0.5a	19.1 ± 2.3b	71.18 ± 1.9a
	CF	14.8 ± 1.1b	19.6 ± 2.7a	6.2 ± 0.6b	8.1 ± 0.6a	57.5 ± 7.6a	72.3 ± 3a
	SRF	20.9 ± 0.6a	20.8 ± 1.7a	9.0 ± 1.0a	9.4 ± 1.3a	69.1 ± 4.1a	69.8 ± 1.3a
	SRFR	15.9 ± 1.8b	18.9 ± 1.4a	7.4 ± 0.4ab	8.9 ± 0.5a	61.3 ± 4.3a	72.2 ± 1.0a
Year (Y)		***	***	***	ns	***	***
Treatment (T)		***	**	***	.	***	**
Y × T		***	*	***	*	***	ns

Note: phosphorus (P). CF: NPK 1369.5 kg ha^{-1}; SRF: NPK 1369.5 kg ha^{-1}; SRFR: NPK 942.0 kg ha^{-1}; CK: no fertilizer. Values are expressed as means ± standard error (n = 3 replicates with nine plants per replicate). Significant differences among treatments for a particular year based on Duncan's multiple range test ($p < 0.05$) are shown with different letters. The significance of the effect of a particular factor as well as the interactions between factors are described by following symbols: "ns", $p > 0.1$; ".", $p < 0.1$; "*", $p < 0.05$; "**", $p < 0.01$; and "***", $p < 0.001$.

The rate of N distribution in the leaves of the SRF and SRFR treatments at the end of the experiment was 48% and 36% greater, respectively, than that of the CF treatment (Table 5). Additionally, the rate of N distribution in the roots of Chinese chives of the SRF and SRFR treatments was significantly lower than that of the CF treatment. The rate of P distribution in the leaves of Chinese chives of the SRF and SRFR treatments was significantly 51% and 36% greater, respectively, than that of the CF treatment; however, the P distribution rate in the roots of Chinese chives of the CF treatment were high (Table 6).

The rate of K distribution in the leaves of Chinese chives of the SRF and SRFR treatments at the end of the experiment was 25% and 23% greater, respectively, than that of the leaves of the CF treatment (Table 7); although, the K distribution rate of roots of Chinese chives of the treatment CF was high. The roots had the highest N, P, and K distribution rates among all treatments, followed by the leaves and stems with the lowest N, P, and K distribution rates.

Table 7. The effect of slow-release fertilizer on potassium (K) accumulation and distribution in wintering Chinese chives in multi-layer covered plastic greenhouses.

Year	Treatment	Leaf		Stem		Root	
		K Uptake (kg ha^{-1})	Distribution Rate (%)	K Uptake (kg ha^{-1})	Distribution Rate (%)	K Uptake (kg ha^{-1})	Distribution Rate (%)
2018	CK	21.2 ± 0.4d	26.1 ± 0.5b	15.2 ± 0.6d	18.7 ± 0.8a	44.9 ± 0.3c	55.3 ± 0.3c
	CF	63.0 ± 0.3c	26.6 ± 0.2b	19.7 ± 0.2c	8.3 ± 0.1c	154.1 ± 1.1b	65.1 ± 0.2a
	SRF	93.5 ± 2.4b	33.1 ± 0.6a	32.6 ± 0.2a	11.5 ± 0.2b	156.2 ± 1.1b	55.3 ± 0.5c
	SRFR	104.6 ± 1.1a	34.0 ± 0.2a	25.5 ± 0.3b	8.3 ± 0.2c	177.2 ± 2.3a	57.7 ± 0.2b
2019	CK	5.5 ± 0.3d	22.2 ± 1.2b	4.2 ± 0.2c	16.9 ± 1.0a	15.4 ± 0.8b	60.9 ± 2.2a
	CF	24.3 ± 0.1c	21.5 ± 1.9b	14.5 ± 1.7b	12.6 ± 0.4b	76.7 ± 7.8a	65.9 ± 1.5a
	SRF	38.3 ± 2.5a	26.8 ± 1.1a	17.9 ± 0.8a	12.8 ± 1.4b	87.0 ± 7.9a	60.4 ± 1.9a
	SRFR	31.7 ± 1.5b	25.5 ± 1.2ab	15.3 ± 0.5ab	12.3 ± 0.2b	78.5 ± 2.3a	62.2 ± 0.9a
Year (Y)		***	***	***	***	***	***
Treatment (T)		***	**	***	***	***	*
Y × T		***	***	***	**	***	***

Note: potassium (K). CF: NPK 1369.5 kg ha^{-1}; SRF: NPK 1369.5 kg ha^{-1}; SRFR: NPK 942.0 kg ha^{-1}; CK: no fertilizer. Values are expressed as means ± standard error (n = 3 replicates with nine plants per replicate). Significant differences among treatments for a particular year based on Duncan's multiple range test ($p < 0.05$) are shown with different letters. The significance of the effect of a particular factor as well as the interactions between factors is described by following symbols, "ns", $p > 0.1$; "*", $p < 0.05$; "**", $p < 0.01$; and "***", $p < 0.001$.

3.7. Nutrient Utilization

The application of SRF had affected the fertilizer use efficiency of wintering Chinese chives (Table 8). The N and P use efficiencies of treatments SRF and SRFR were significantly increased by 9.8% and 15.8% and 4.8% and 9.6%, respectively, compared to the CF treatment. Moreover, K use efficiency of SRF treatment was increased by 19.7%, whereas that of the SRFR treatment was decreased by 4.3% compared to the CF treatment. Nitrogen and P use efficiencies of the SRFR treatment were 6.0% and 7.2% greater, respectively, than those with the SRF treatment. Nitrogen and P agronomic efficiencies were increased by 135% and 642% for the SRF treatment, and by 257% and 641% for the SRFR treatment, respectively, compared to the CF treatment. Nitrogen and P partial factor productivities of the SRFR treatment were significantly increased by 58% and 329%, respectively, compared to those of the CF treatment. However, K partial factor productivity of the SRFR treatment was significantly decreased by 34% compared to the CF treatment. Nitrogen agronomic efficiency and partial factor productivity of the SRFR treatment were 55% and 52% higher, respectively, than those of the SRF treatment.

Table 8. The effect of slow-release fertilizer on the nutrient utilization rate of wintering Chinese chives in multi-layer covered plastic greenhouses.

Year	Treatment	UE (%)			AE (kg kg^{-1})			PEP (kg kg^{-1})		
		N	P	K	N	P	K	N	P	K
2018	CF	11.9 ± 0.3c	4.8 ± 0.07c	30.0 ± 0.1b	12.9 ± 0.4c	15.1 ± 0.5c	54.6 ± 1.7c	55 ± 0.2c	64.5 ± 0.2c	233.5 ± 0.9b
	SRF	25.9 ± 0.1b	8.0 ± 0.03b	58.1 ± 1.1a	38.2 ± 0.6b	143.5 ± 1.4a	162 ± 2.8a	80.4 ± 0.9b	94.1 ± 1 b	340.9 ± 3.8a
	SRFR	32.0 ± 0.5a	17.5 ± 0.5a	28.9 ± 0.2b	54.9 ± 0.5a	133.5 ± 1.3b	74.1 ± 0.7b	118 ± 0.9a	287 ± 2.1a	159.5 ± 1.2c
2019	CF	11.3 ± 0.2c	2.5 ± 0.2b	18.9 ± 1.4b	16.2 ± 0.2b	19.0 ± 0.2b	68.7 ± 0.6b	45.4 ± 0.3b	53.2 ± 0.4b	192.5 ± 1.4b
	SRF	16.9 ± 0.3b	4.1 ± 0.1b	30.1 ± 1.2a	28.2 ± 3.1b	101.4 ± 2.8a	119.6 ± 13.3a	57.4 ± 2.8b	67.3 ± 3.2b	243.5 ± 12.0a
	SRFR	22.8 ± 0.6a	8.9 ± 1.0a	11.5 ± 0.4c	46.6 ± 4.5a	113.4 ± 10.9a	63.0 ± 6.1b	90.3 ± 5.1a	219.8 ± 12.4a	122.1 ± 6.9c
Year (Y)		***	***	***	*	***	*	***	***	***
Treatment (T)		***	***	***	***	***	***	***	***	***
Y × T		***	***	***	*	*	*	**	*	***

Note: nitrogen (N); phosphorus (P); potassium (K); use efficiency (UE); agronomic efficiency (AE); partial factor productivity (PFP). CF: NPK 1369.5 kg ha^{-1}; SRF: NPK 1369.5 kg ha^{-1}; SRFR: NPK 942.0 kg ha^{-1}; CK: no fertilizer. Values are expressed as means ± standard error (n = 3 replicates with nine plants per replicate). Significant differences among treatments for a particular year based on Duncan's multiple range test ($p < 0.05$) are shown with different letters. The significance of the effect of a particular factor as well as the interactions between factors are described by following symbols, "ns", $p > 0.1$; "*", $p < 0.05$; "**", $p < 0.01$; and "***", $p < 0.001$.

4. Discussion

4.1. Effect of Slow-Release Fertilizer on Dry Matter Accumulation and Yield

Due to traditional fertilization, the phenomenon of excessive fertilization is widespread in vegetable cultivation systems. The root system of vegetables is shallower in the soil compared with deep-rooted crops; therefore, vegetable roots have weaker ability to absorb water and nutrients. Slow-release fertilizer has slow nutrient release rate and provides a low level of nutrient loss, which is beneficial to vegetable crops. One application of SRF can meet a crop's nutrient requirement for an entire growth period [40]. Li et al. [41] found that the application of SRF could increase the dry weight of root, stem, and leaf of cabbage compared to ordinary compound fertilizer (*Brassica rapa* ssp. pekinensis). In the present study, the application of SRF was found to increase the accumulation of root biomass, provide a stable nutrient supply to strengthen the roots and seedlings of perennial Chinese chives, and increase the production capacity for this crop during winter. In addition, the continuous application of SRFR was found to significantly increase the fresh weight (27%) and dry weight (44%) of leaves. A 31% reduction in fertilizer application with SRF not only reduced the amount of fertilizer input and the number fertilization times, but also increased yield and economic benefits by 37% and 47%, respectively, compared to CF. This is similar to the research results of Timilsena et al. [17] on the application effect of SRFs on vegetables. This is mainly due to the frequent irrigation in vegetable production leading to N leaching and volatilization and loss of common chemical fertilizers, resulting in a shortage of N in the later stages of plant growth as well as N deficit around the root system, which in turn leads to a decrease in the ability of plants to synthesize dry matter. In contrast, SRF can sustain a stable rate of nutrient release, with a slow rate of release in the early stage of growth. Slow-release fertilizers released their nutrient contents gradually to coincide with the nutrient requirement of plants [42], thereby improving the capacity of the soil to supply nutrients; preventing nutrient loss due to frequent irrigation, allowing plants to absorb large amounts of nutrients through roots; and providing sufficient amounts of nutrients for winter production of Chinese chives. Upon entering the winter production period, SRF accelerated its nutrient release rate, which provided a sustained and stable nutrient supply for above-ground growth of Chinese chives, improved the ability of plants to synthesize dry matter, and increased plant dry matter accumulation, thus promoting an increase in yield of Chinese chives [41].

4.2. Effect of Slow-Release Fertilizer on Root Activity, Nitrate Reductase Activity, and Nutritional Quality

Root activity is an important physiological index that promotes the formation of photosynthetic matter. Root activity directly affects the ability of a plant to absorb and utilize nutrients [43]. In the present study, a 31% reduction in fertilizer with SRF was found to significantly increase root activity and nitrate reductase activity in leaves of Chinese chives by 12% and 40%, respectively, compared to the CF treatment. The release of nutrients in the early stage of application of conventional fertilizers and their accumulation in the soil around the roots may result in salt stress in the root environment, inhibition of root growth, and a reduction in root activity. In the later stages, high loss of nutrients and nutrient deficiencies in roots might result in decrease root activity. However, SRF could provide nutrients according to the demand at different growth and development stages of Chinese chives. Thus, it may not cause an excessive amount of nutrients to accumulate or lead to inadequate nutrient supply due to the loss of high amounts of nutrients in the later stages, thus satisfying the root system's demand for nutrients and enhancing root activity. Nitrate reductase activity in leaves of Chinese chives of the SRF treatment was the highest among treatments. This result may be due to the release of N after the application of the conventional chemical fertilizer, which may break the balance of the carbon and N metabolism in Chinese chives and inhibited nitrate reductase activity.

Excessive fertilizer application can have many negative effects on the quality of vegetables and reduce the nutritional value and safety of vegetables. In the present study, the application of SRF improved the nutritional quality of Chinese chives and increased the contents of vitamin C, soluble protein, and total phenol in leaves. Research has shown that K improves crop quality and fertilization with K increases the accumulation of sugar in soybean (*Glycine max* (Linn.) Merr.) seed [44,45]. In the present study, SRF was found to significantly increase the content of soluble sugar under a 31% reduction in fertilizer application. This result may have been due to the increased absorption of K. Zhang et al. [46] showed that appropriate ammonium-to-nitrate ratio improved soluble protein in pepper (*Capsicum annuum* L.). We found that the application of SRF may significantly increase the soluble protein content of Chinese chives. This may be due to SRF with a urease inhibitor and a nitrification inhibitor being able to regulate nitrification of ammonium-N, and thus regulate the ammonium-to-nitrate ratio and increase soluble protein content. In addition, the application of SRF was found to significantly decrease the accumulation of nitrate in the leaves of Chinese chives. This was likely due to the slow release of N from the SRF, which reduced the amount of N that may be converted to nitrate, and thus decreased nitrate content in the leaves of Chinese chives. This result is consistent with the findings of Zhao et al. [47].

4.3. Effect of Slow-Release Fertilizer on Nutrient Utilization

Fertilizer use efficiency is closely related to the rational release of nutrients, which is reflected not only in an increase in yield, but also in the amount of nutrients left in the soil [48]. Nitrogen inputs and residues in the soil are high in greenhouse vegetable cultivation ecosystems [49]. Slow-release fertilizer can increase soil availability of N, the development of the root system, and nutrient absorption capacity of rapeseed (*Brassica napus* L.) [50]. In the present study, for two consecutive years, the amounts of N, P, and K that were removed through the harvest of Chinese chives of the SRF treatment were significantly higher than those with CF treatment. Furthermore, we found that the absorption of N and K in the SRFR treatment was significantly increased by 31% and 17%, respectively, and that the absorption of P was also increased, compared to CF. The results showed that SRF can reduce the amount of required fertilizer and promote the absorption of nutrients. This may be due to the traditional high amount of irrigation applied in multi-layer covered plastic greenhouses, rapid release of nutrients from ordinary chemical fertilizers in the early growth stage [48], and rapid hydrolysis of urea, causing high N losses [51]. However, SRF provides a more continuous and slower supply of N than urea, contains nutrients in a form that delays their availability for plant uptake after application, and is controlled to match the nutrient requirements of plants [52,53]. In addition, the application of SRF promotes the absorption of N and increases the distribution rate of N, P, and K in the leaves of Chinese chives, and decreases the distribution rate of N, P, and K in roots, compared to the CF treatment. The results showed that the application of SRF was beneficial, as nutrients accumulated in the roots of Chinese chives were transported to the leaves during the production period, which increased the accumulation of N, P and K in leaves.

Local irrigation and fertilization methods as well as climatic conditions determine the leaching, loss, and surplus of fertilizer nutrients to a certain extent. Ammonium N in fertilizer can be nitrated after being applied to the soil. When applied on the surface, more than half of the urea can be lost through ammonia volatilization [54]. In the present study, a 31% reduction in fertilizer application with SRF significantly decreased N and P surplus in the soil by 42% and 58%, respectively, compared to CF, while also enhancing N and P uptake. The reduction in N and P surplus in the soil with SRF may help reduce the loss of nutrients and pollution of the environment. In contrast to N, the application of K has been neglected in many developing countries, leading to K deficiencies in soils in many regions [55]. In the present study, in the case of the same amount of nutrients applied, SRF was found to significantly decrease the surplus of K in the soil compared to the CF treatment. However, a 31% reduction in fertilizer application with SRFR increased the input of K, and the surplus of K in the soil was significantly higher than that with CF and SRF. A large surplus of K in the soil may cause a large loss of K nutrients. Therefore, the determination of a chemical fertilizer reduction target must be combined with the actual yield, the nutrient demand, and the soil's capacity to supply nutrients to maintain the soil's nutrient balance and fertility and effectively reduce nutrient loss.

Fertilizer use efficiency has become a critical measure of sustainable agriculture and environmental friendliness. Nutrients in conventional fertilizers are not only easy to volatilize, but can also be easily absorbed and fixed by the soil or lost by other means [56]. In the present study, under the condition of the same amount of nutrients applied, SRF was found to significantly increase the use efficiencies of fertilizer N, P, and K compared to CF, and the use efficiencies of fertilizer N and P under a 31% reduction in fertilizer application (i.e., SRFR) increased significantly by 15.8% and 9.6%, respectively, whereas the use efficiency of fertilizer K decreased by 4.3%. The reason for this may be due to the SRF treatment slowly releasing nutrients into the soil according to the needs of Chinese chives, so as to reduce the loss of nutrients and ensure that Chinese chives receive an adequate supply of nutrients in the later stages of growth. The decrease in the use efficiency and partial factor productivity of K in the SRFR treatment may have been due to increase in the K input in the 31% decrease in fertilizer application with the SRFR treatment, and sulfate fertilizer used to replace some of the K. Studies have shown that adding larger amounts of K fertilizers is a practical way to synergistically improve the agronomic efficiency of N [57]. Our study showed that a 31% reduction in fertilizer application with SRF significantly improved the agronomic efficiency of fertilizer N and P by 256% and 320%, respectively, and the partial factor productivity of fertilizer N and P by 107% and 329%, respectively. Urease inhibitors and nitrification inhibitors, when added to a SRF, can regulate the hydrolysis and transformation of N, inhibit the nitrification of ammonium-N by nitrite bacteria in the soil [58], control the nutrient release rate, reduce the leaching of N in the soil caused by irrigation, increase the content of inorganic N in the soil, retard the fertilizer's efficiency, maintain the release of nutrients in a sustained and stable state, and maximize the fertilizer's efficiency and the utilization rate [59,60]. Under a reduction in the amount of fertilizer applied, the replacement of conventional fertilizers with SRFs with a urease inhibitor and a nitrification inhibitor has greatly improved the use of nutrients and crop yield. The results of this study show that Wushan's Chinese chives cultivation system still has great potential for reducing the use of fertilizer in production, which may further improve the utilization of nutrients, ensure that industrial cultivation systems are utilized sustainably, and help reduce environmental pollution.

5. Conclusions

The results of this study indicate that a 31% reduction in SRF (SRFR, NPK: 942.0 kg ha^{-1}, a 33% decrease in N, a 68% decrease in P, and a 110% increase in K) can significantly decrease nutrient surplus in the soil, maintain the soil's nutrient balance, and improve the soil's fertility, thus creating a suitable nutritional environment for vigorous growth of Chinese chives. By applying SRF and reducing the amount of fertilizer, the number of applications of fertilizer can be decreased and the yield and economic benefits of Chinese chives can be significantly increased. Simultaneously, the vitamin C, soluble sugar, soluble protein, and flavonoid contents, and the root activity and nitrate reductase activity in leaves, can be increased, and the nitrate content in leaves can be significantly decreased. A 31% reduction in SRF was also found to increase the uptake of N, P, and K in leaves and the fertilizer N and P use efficiencies, thus increasing the production of Chinese chives and the expected environmental and economic benefits.

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