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Differences in Dry Matter Accumulation and Distribution Patterns between Pre-Elite Seed and Certified Seed of Virus-Free Potato

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Abstract: Virus-free seed potatoes are generally divided into pre-elite seeds and certified seeds. To study the differences in dry matter accumulation and distribution between pre-elite seeds and certified seeds through a field randomized block two-factor experiment, pre-elite seeds and certified seeds of four varieties were selected to explore the differences in growth characteristics between the two levels of virus-free potatoes and to find a way to improve potato seed expansion efficiency. The results showed that the growth process of pre-elite seeds was slower and the growth period was longer than certified seeds. The dry matter accumulation of pre-elite seeds in various organs was lower than in certified seeds, and the distribution ratio in the roots and stems of each variety was also lower than the certified seed, while there was no significant difference in the leaf and tuber distribution ratio. The average dry matter accumulation rate in both pre-elite and certified seeds was sorted by size of tubers > leaves > stems > roots; however, it was significantly lower in pre-elite seeds than in certified seeds. Tuber fresh weight, tuber volume, tuber number, and the theoretical yield of certified seeds were higher than those of pre-elite seeds. Experiments have shown that appropriately prolonging the harvest time of virus-free potatoes, especially pre-elite seeds, and increasing the proportion of dry matter allocated to roots and stems by pre-elite seeds in the early growth stages can effectively increase yield.

Keywords: virus-free potato; pre-elite seed; certified seed; dry matter accumulation; dry matter distribution

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1. Introduction

Potato (*Solanum tuberosum* L.) is one of the world's most important staple food crops, with an annual production of more than 323 million tons [1,2]. Dry matter accumulation is the material basis for potato yield formation [3], and the direction of dry matter distribution is an important factor in determining the yield of tubers [4]. Dry matter distribution centers must change as different organs perform different tasks at different times [5]. Potato plants derive 90–95% of their dry matter from photosynthesis-assimilated products, and the distribution of assimilated products in the organs varies with the growth and development process of potatoes [6]. The accumulation, distribution, and transfer of assimilation products during reproduction directly affect the formation of tuber yield, and the more dry matter is accumulated to a certain extent, the higher the tuber distribution, the higher the economic coefficient, and the higher the yield [7]. Compared to cereal crops, potatoes need to accumulate more dry matter to ensure yield [8].

Potato is a tuber reproduction crop. Seed potato quality is the most important factor affecting potato production. Good seed potato is the material basis for potato quality. High yield is the key to improving production levels [9]. Therefore, seed potato production is the source of the potato industry and is also the most important link in this industrial chain; the development of the entire potato industry has a close relationship with the development of seed potatoes [10]. The tuber is the main growth and harvesting organ of potatoes, but it tends to accumulate viruses and degrade during production, causing a reduction in yield [11,12]. The use of virus-free seed potatoes is an important measure to solve this critical problem and improve yields, and virus-free seed potatoes are generally divided into two levels: pre-elite seed and certified seed. With the promotion of potato detoxification technology and the gradual increase in the area of virus-free potatoes, research on virus-free potatoes is increasing but mainly focuses on tissue culture technology of virus-free seedlings and the production of miniature potatoes (pre-elite seeds) [13–15]. However, there is less research on further field expansion technology for pre-elite seeds, resulting in low yields and high costs, which largely limit the application of virus-free seed potatoes. Studying the differences in growth and development characteristics between pre-elite seeds and certified seeds could enable the development of field expansion techniques for different levels of seed potatoes. Furthermore, it is of great significance to improve the growth and yield of virus-free seed potatoes, reduce production costs, and expand the promotion and application area and proportion of virus-free seed potatoes [16].

A few studies have been reported on differences in agronomic traits, physiological characteristics, mineral absorption and distribution, and accumulation and distribution of assimilation products in different levels of seed potatoes [17,18]. However, these studies still have the problem of studying a single variety and single seed potato level. Potato plant dry matter accumulation and distribution patterns are important for optimizing nutrient uptake efficiency and tuber production management [19]. Therefore, we studied the differences in dry matter accumulation and distribution patterns between pre-elite and certified potato seeds, which is a key aspect of optimizing seed potato expansion technology. In this study, based on previous studies, the pre-elite and certified seeds of four different maturity types were used as materials to study more systematically the differences in total plant dry matter accumulation, dynamic changes in the distribution of dry matter in various organs, and yield differences of different levels of virus-free potatoes during the whole growth period to provide a theoretical basis for improving the efficiency of potato seed expansion and reducing production costs.

2. Materials and Methods

2.1. Site Description and Materials

The test materials were the pre-elite and certified seeds of four potato varieties within two maturities (Chuanyu 117—medium maturity, Shepody—medium maturity, Favorita—early maturity, and Zhongshu No. 3—early maturity, Table 1). The average size of the pre-elite seed potatoes was 3.5 g, and the average size of the certified seed potatoes was 41 g. The trial was conducted in late December 2019 in Huihe Village, Wenjiang District, Sichuan Province (30°42′57.80″ N, 103°52′25.65″ E), in a subtropical humid climate; the annual precipitation was 918.3 mm, and the area was previously used to cultivate rice. The land at the trial site was relatively flat, with regular plots and uniform ground strength. The soil texture here was silt loam, with sand accounting for 29% of the topsoil, silt accounting for 50%, and clay accounting for 21%. The organic matter content of the soil was 28.47 g kg^{-1} in the 0–20 cm tillage layer, total nitrogen was 1.24 g kg^{-1}, total phosphorus was 0.64 g kg^{-1}, total potassium was 13.62 g kg^{-1}, alkaline dissolved N was 99.47 mg kg^{-1}, fast-acting P was 41.86 mg kg^{-1}, fast-acting K was 46.84 mg kg^{-1}, and pH was 5.04. Before planting, we tilled and rototilled the soil to a depth of 15 to 20 cm.

Table 1. Basic information on test materials.

Variety	Pre-Elite Seed				Certified Seed			
	Chuanyu 117	**Favorita**	**Shepody**	**Zhongshu No. 3**	**Chuanyu 117**	**Favorita**	**Shepody**	**Zhongshu No. 3**
Maturity	Medium	Early	Medium	Early	Medium	Early	Medium	Early
Growth period (d)	-	-	-	-	83	65	90	67

Note: d represents days. Since the pre-elite seed has not yet reached production standards, there is no growth period present.

2.2. Experimental Design and Management

The experiment used a randomized two-factor group design with treatment factors of variety and seed potato level, namely, Chuanyu 117 pre-elite seed (CP), Chuanyu 117 certified seed (CC), Favorita pre-elite seed (FP), Favorita certified seed (FC), Shepody pre-elite seed (XP), Shepody certified seed (XC), Zhongshu No. 3 pre-elite seed (ZP), and Zhongshu No. 3 certified seed (ZC), with a total of 8 treatments, 3 replications, 24 plots, 4 rows per plot, and 38 plants per row. Fertilizer was applied by strip application at the time of sowing, with a one-time application of 50 kg of compound fertilizer (containing nitrate nitrogen type, total nutrients $\geq$ 40%, N:P:K = 20:5:15) per acre. Cultivation was carried out with a large monolithic and double-row film cover, with a monolithic width of 80 cm, a monolithic height of 20 cm, a wide row of 70 cm, a narrow row of 40 cm, and a plant spacing of 20 cm; field management measures were the same as the actual local production level and attention was paid to pest and disease control.

2.3. Plant Sampling and Measurements

2.3.1. Proportion of Dry Matter Accumulation and Distribution

Four plants were randomly selected in each plot at the seedling stage for each sampling, and samples were taken every 7 days starting from 20 days after seedling emergence. The whole plants were dug out, cleaned, and divided into four parts: stem, leaf, root, and tuber. The four plants were combined and treated in separate organs (root, tuber, stem, and leaf), killed at 105 °C for 30 min, and dried at 80 °C. Then, the dried dry matter was weighed, the weight was recorded, and the dry matter accumulation of a single plant was calculated, as well as the dry matter distribution ratio. The dry matter accumulation process was simulated using the logistic equation [20].

2.3.2. Yield and Its Composition

During the harvest period, all potato tubers harvested from each plot of the experiment were observed, the soil was removed from the tubers, all tubers were weighed using an electronic scale in kg to the nearest 0.01 kg, the yield per hectare was converted to kg ha^{-1}, and the number of individual tubers and tuber volume were examined.

2.4. Calculation Formula

The logistic growth function model and its properties [21]: $W = \frac{W_m}{1+e^{a+bt}}$, where t is the number of days after potato emergence (d); W is the amount of dry matter accumulated (g); and a, b, and W_m are three coefficients to be determined, all of which have some biological significance. W_m indicates the maximum accumulation of dry matter (g); when $t = \frac{a}{b}$, the rate of accumulation of dry matter or nutrients reaches its maximum at this time: $V_m \frac{-b \times Wm}{4}$ (g d^{-1}); $t0$ indicates the moment when the accumulation rate of dry matter or nutrients is maximum, and the accumulation rate at this time (V_m) is also called the "velocity characteristic value"; when $t = \frac{\ln\left(2+\sqrt{3}\right)-a}{b}$, this is the starting time of the rapid accumulation of dry matter (t_1); when $t = \frac{\ln\left(2-\sqrt{3}\right)-a}{b}$, this is the end time of the period of rapid accumulation of substances (t_2); t_1 and t_2 divide the logistic growth function "S" curve into three stages: in the $0 - t_1$ time, the dry matter accumulation is slowly increasing; in the $t_1 - t_2$ time, the dry matter accumulation rate is accelerated, almost a straight-line increasing trend; after the t_2 time, the dry matter accumulation rate is slowed down again, so that W eventually tends to W_m. $\Delta t = t_2 - t_1$, which is called the "time characteristic value", indicates the duration of the vigorous growth period (the period of the rapid increase in dry matter accumulation).

2.5. Data Analysis

For data processing and calculations, we used Microsoft Excel 2021. Dynamic simulations and regression analyses of dry matter and nutrient accumulation were performed using Origin 2022. SPSS statistical software (Version 27.0 for Windows) was used to perform significant differentiation analyses. A least significant test (LSD) at a probability level of $p < 0.05$ was used to determine the significance of differences.

3. Results

3.1. Comparison of the Growth Process of Pre-Elite and Certified Seeds

The dry matter accumulation balance period is the period when the total amount of dry matter accumulation in the roots, stems, and leaves of the plant are consistent with the amount of dry matter accumulation in the tubers, marking the shift of the plant growth center from above ground to below ground and the beginning of tuber yield formation. The dry matter accumulation of certified seeds was higher than pre-elite seeds, and the dry matter balance period of the certified seeds was 3–7 days later than pre-elite seeds (Figure 1). After the dry matter accumulation balance period, a "Scissors Gap" was formed between the dry matter accumulation of tubers and the sum of roots, stems, and leaves; the larger the Scissors Gap, the higher the tuber yield. The Scissors Gap of each certified seed variety was greater than the pre-elite seed, with values of 71.14%, 56.19%, 52.39%, and 40.32% for Chuanyu 117, Favorita, Shepody, and Zhongshu No. 3, respectively, in descending order.

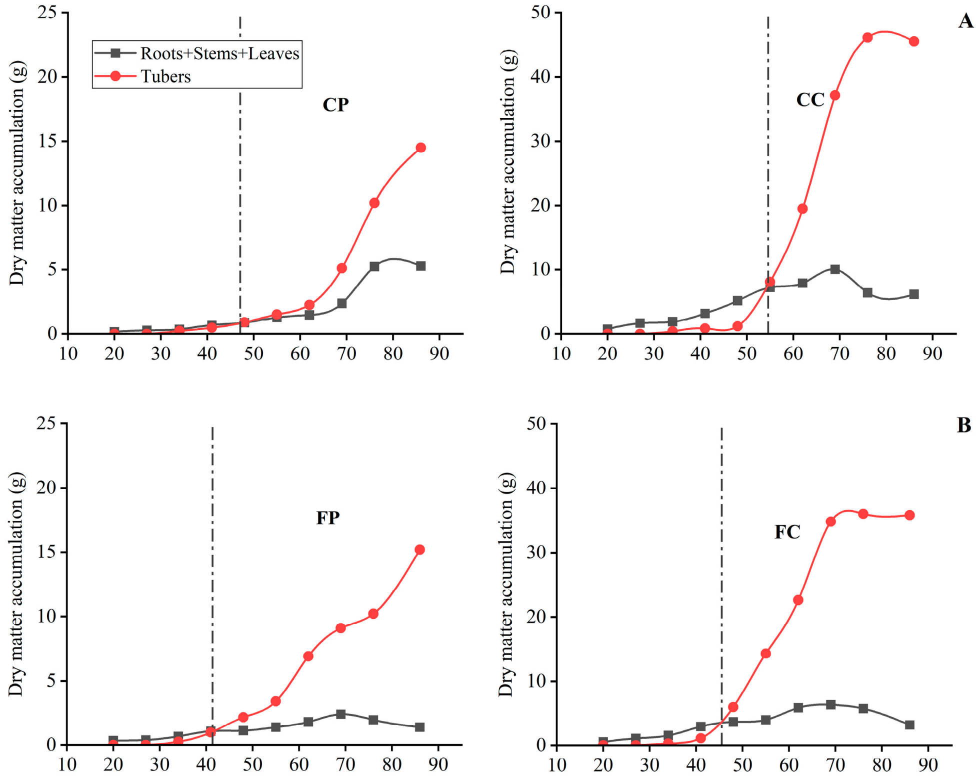

Figure 1. *Cont.*

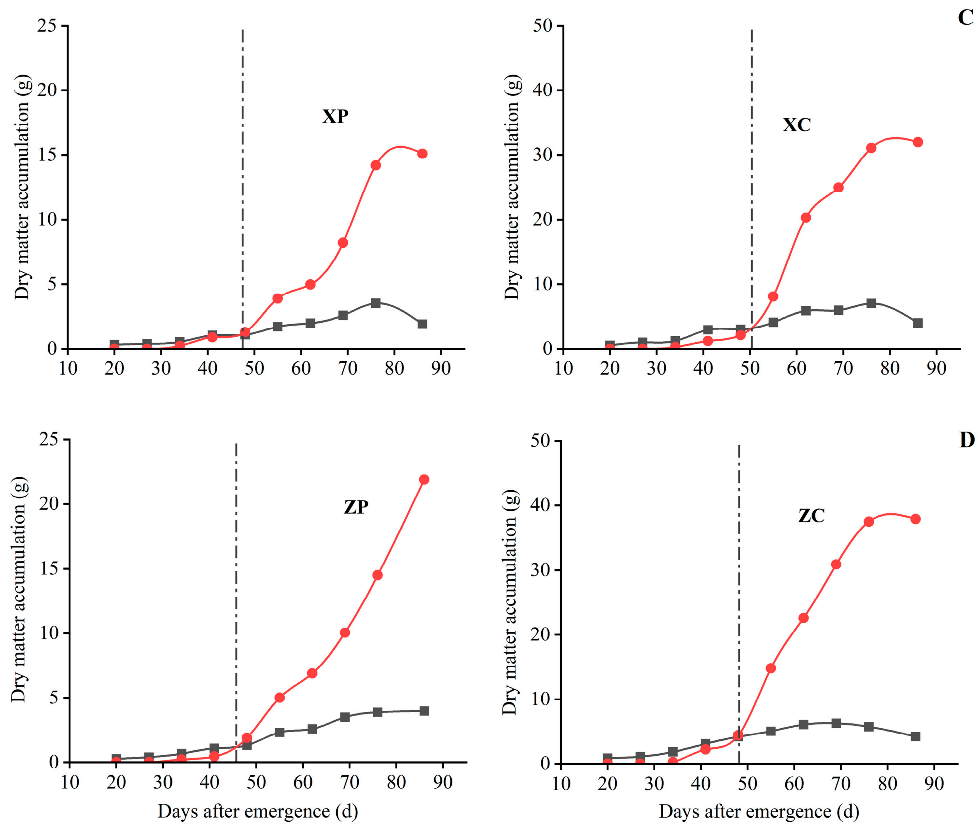

Figure 1. Comparison of dry matter accumulation balance period of Chuanyu 117 (**A**), Favorita (**B**), Shepody (**C**), and Zhongshu No. 3 (**D**) between pre-elite and certified seeds. The graph on the left represents pre-elite seeds, and the graph on the right represents certified seeds. The dashed line represents the beginning of tuber yield formation. CC, FC, XC, and ZC represent the certified seeds of Chuanyu 117, Favorita, Shepody, and Zhongshu No. 3, respectively. CP, FP, XP, and ZP represent the pre-elite seeds of these four varieties, respectively.

3.2. Comparison of the Changing Pattern of Dry Matter Accumulation between the Pre-Elite and Certified Seeds

3.2.1. Comparison of the Changing Pattern of Dry Matter Accumulation in Roots, Stems, and Leaves

The dry matter accumulation of the roots, stems, and leaves of both the pre-elite and certified seeds showed a single-peaked curve for the growth process, and the dry matter accumulation of all organs of the certified seeds was higher than that of the pre-elite seeds (Figure 2). The roots dry matter accumulation of each pre-elite seed reached its maximum value later than that of the certified seed, averaging 15.75 d (Figure 2A). The stem dry matter accumulation of the pre-elite seeds of Chuanyu 117 and Zhongshu No. 3 increased until harvest, while Favorita and Shepody reached a maximum at 69 and 76 d, respectively; in addition, the certified seeds of all four varieties showed a complete single-peaked curve change (Figure 2B). It can be seen that the leaf dry matter accumulation of each pre-elite seed reached a maximum at a later period than its certified seed, with an average of 5.25 d later (Figure 2C).

3.2.2. Comparison of the Changing Pattern of Dry Matter Accumulation in Tubers

It can be seen that the tuber dry matter accumulation of Zhongshu No. 3, Shepody, Chuanyu 117, and Favorita showed an increasing trend between the pre-elite and certified seeds during the entire growth period, except for in Chuanyu 117 certified seeds, in which it was lower than that of the pre-elite seed at 34 days after seedling emergence (Figure 3), and the tuber dry matter accumulation of the certified seed was greater than that of the pre-elite seed. The tuber dry matter accumulation of different varieties in both the pre-elite seeds (Figure 3A) and certified seeds (Figure 3B) showed an "S"-type change curve with the growth process. The maximum accumulation of tuber dry matter (W_m) and the maximum rate of dry matter accumulation (V_m) in the pre-elite seeds were lower than those of the certified seeds, and the period when the rate of tuber dry matter accumulation reached its maximum (t_0) and the start of rapid dry matter accumulation (t_1) were later than those of the certified seeds; the duration of rapid dry matter accumulation (Δt) was also longer than that of the certified seeds (Table 2). The pre-elite seeds t_0 of Zhongshu No. 3, Shepody, Chuanyu 117, and Favorita were 8 d, 6 d, 15 d, and 8 d later, t_1 were 4 d, 5 d, 11 d, and 4 d later, and Δt were 7 d, 3 d, 8 d, and 9 d longer than those of the certified seeds, respectively.

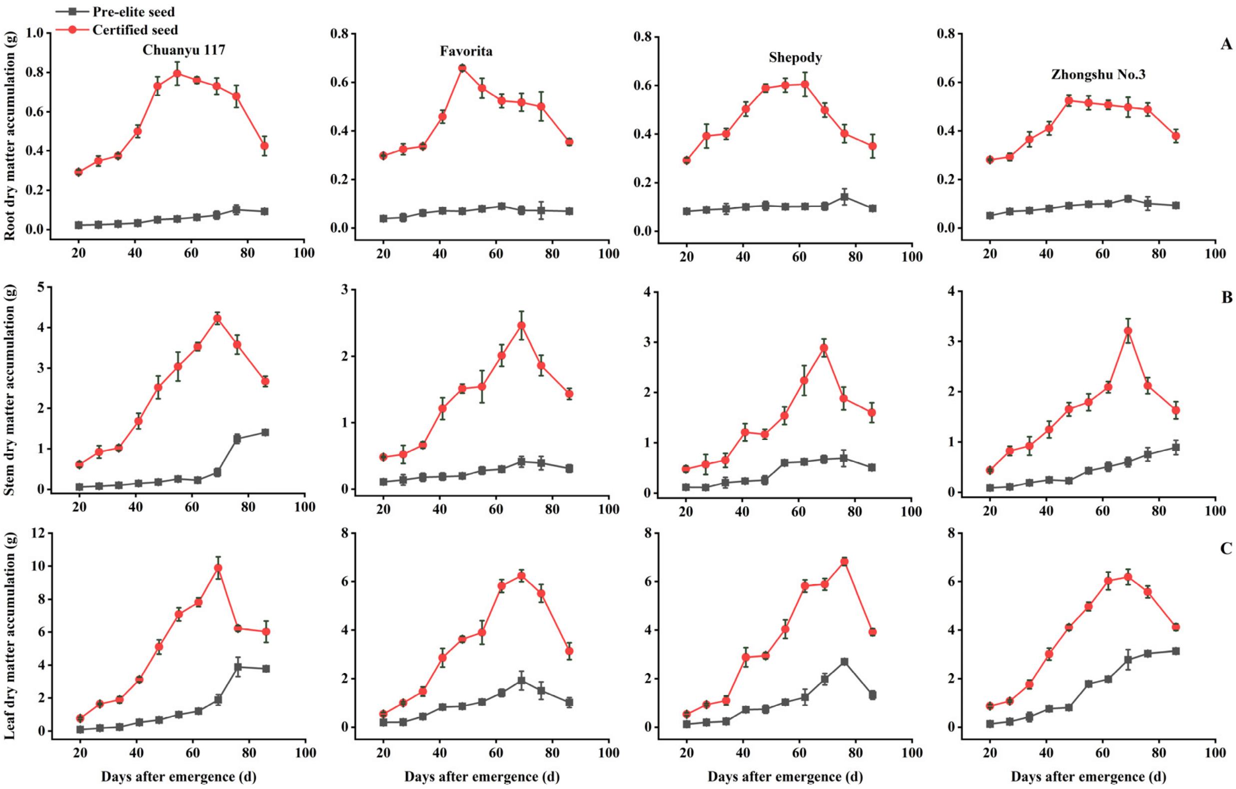

Figure 2. Comparison of dry matter accumulation in roots (**A**), stems (**B**), and leaves (**C**) of different potato varieties between pre-elite and certified seeds. In the graph, the varieties from left to right are Chuanyu 117, Favorita, Shepody, and Zhongshu No. 3. The error bars represent the standard errors.

Table 2. Parameters and secondary parameters of the logistic equation for the dry matter of tubers in the pre-elite seed and certified seed.

Seed Level	Variety	W_m (g)	a	b	R^2	t_0 (d)	t_1 (d)	t_2 (d)	Δt (d)	V_m (g d^{-1})
Pre-elite seed	Zhongshu No. 3	19.2224	7.4124	−0.1103	0.9918	67	55	79	24	0.5303
	Shepody	15.8358	9.6694	−0.1458	0.9875	66	57	75	18	0.5774
	Chuanyu 117	21.9536	9.1719	−0.1177	0.9927	78	67	89	22	0.6461
	Favorita	16.8341	6.9710	−0.1050	0.9975	66	54	79	25	0.4417
Certified seed	Zhongshu No. 3	38.2606	8.9549	−0.1512	0.9978	59	51	68	17	1.4463
	Shepody	32.0101	10.1848	−0.1701	0.9958	60	52	68	15	1.3615
	Chuanyu 117	48.0480	11.4907	−0.1824	0.9949	63	56	70	14	2.1913
	Favorita	37.8004	9.5113	−0.1631	0.9922	58	50	66	16	1.5408

Note: t is the number of days after potato emergence and $0 \leq t \leq 86$; Wm is the maximum dry matter accumulation of potato; t_0 is the time when the maximum rate of dry matter accumulation occurs during the potato growth period; t_1 and t_2 are the two inflection points of the logistic growth curve, which is the starting and ending time of the rapid dry matter accumulation period; V_m is the maximum rate of dry matter growth during the potato growth period; and Δt is the duration of the rapid dry matter accumulation period.

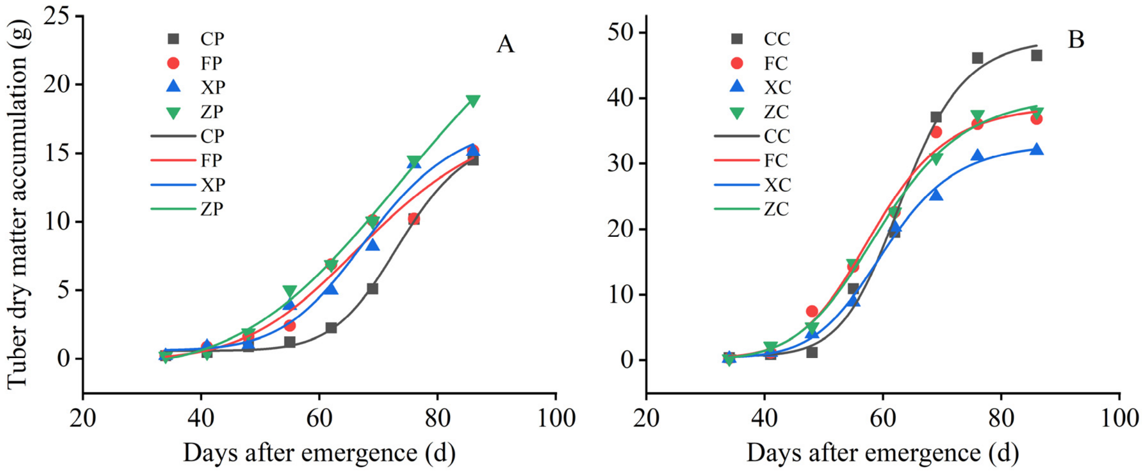

Figure 3. Comparison of tuber dry matter accumulation of different varieties of potato between pre-elite seeds (**A**) and certified seeds (**B**). The dots represent numerical values, while lines are a "logistic" fit of these values. CC, FC, XC, and ZC represent the certified seeds of Chuanyu 117, Favorita, Shepody, and Zhongshu No. 3, respectively. CP, FP, XP, and ZP represent the pre-elite seeds of these four varieties, respectively.

3.2.3. Comparison of the Changing Pattern of Dry Matter Accumulation in the Whole Plants

The whole-plant dry matter accumulation of Zhongshu No. 3, Shepody, Chuanyu 117, and Favorita varieties during the entire growth period according to the logistic curve is shown in Figure 4, and the fit equation parameters and secondary parameters are shown in Table 3. The whole-plant dry matter accumulation of different varieties in the pre-elite seeds showed a gradual increase with the growth process (Figure 4A), while the certified seeds showed a complete "S"-shaped change curve (Figure 4B). Overall, the dry matter accumulation rate of certified seeds slowed down to around 75 d, while the dry matter of the pre-elite seeds still accumulated rapidly until the harvest period. As can be seen from Table 3, the maximum accumulation of whole-plant dry matter (W_m) and the maximum rate of dry matter accumulation (V_m) in the pre-elite seeds were lower than in the certified seeds, the period when the rate of whole-plant dry matter accumulation reached its maximum (t_0) and the start of rapid dry matter accumulation (t_1) were later than in certified seeds, and the duration of rapid dry matter accumulation (Δt) was also longer than in the certified seeds. The pre-elite seeds t_0 of Zhongshu No. 3, Shepody, Chuanyu 117, and Favorita were 10 d, 7 d, 17 d, and 8 d later, t_1 were 7 d, 6 d, 15 d, and 4 d later, and Δt were 7 d, 2 d, 2 d, and 7 d longer than their certified seeds, respectively.

Table 3. Parameters and secondary parameters of the logistic equation for whole-plant dry matter of the pre-elite seed and certified seed.

Seed Level	Variety	W_m (g)	a	b	R^2	t_0 (d)	t_1 (d)	t_2 (d)	Δt (d)	V_m (g d^{-1})
Pre-elite seed	Zhongshu No. 3	24.8373	6.5261	−0.0983	0.9959	66	53	80	27	0.6104
	Shepody	18.6422	8.5085	−0.1326	0.9795	64	54	74	20	0.6178
	Chuanyu 117	27.6825	8.7059	−0.1150	0.9886	76	64	86	22	0.7957
	Favorita	18.0456	6.4574	−0.1025	0.9989	63	50	76	26	0.4624
Certified seed	Zhongshu No. 3	46.1289	7.2442	−0.1302	0.9953	56	46	66	20	1.5012
	Shepody	40.1361	8.0937	−0.1427	0.9893	57	48	66	18	1.4314
	Chuanyu 117	59.5946	7.9193	−0.1343	0.9887	59	49	69	20	2.0009
	Favorita	45.0720	7.7984	−0.1411	0.9854	55	46	65	19	1.5896

Note: t is the number of days after potato emergence and $0 \leq t \leq 86$; W_m is the maximum dry matter accumulation of potato; t_0 is the time when the maximum rate of dry matter accumulation occurs during the potato growth period; t_1 and t_2 are the two inflection points of the Logistic growth curve, which is the starting and ending time of the rapid dry matter accumulation period; V_m is the maximum rate of dry matter growth during the potato growth period; and Δt is the duration of the rapid dry matter accumulation period.

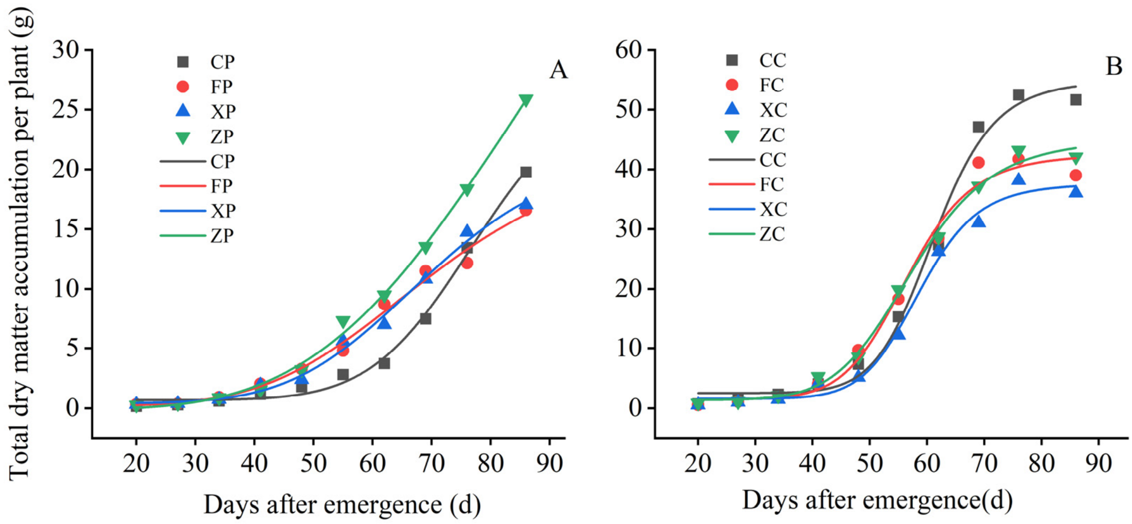

Figure 4. Comparison of whole-plant dry matter accumulation of different varieties of potato between pre-elite seeds (**A**) and certified seeds (**B**). The dots represent numerical values, while lines are a "logistic" fit of these values. CC, FC, XC, and ZC represent the certified seeds of Chuanyu 117, Favorita, Shepody, and Zhongshu No. 3, respectively. CP, FP, XP, and ZP represent the pre-elite seeds of these four varieties, respectively.

3.3. Comparison of Dry Matter Distribution Patterns among Different Organs

The distribution pattern of dry matter to each organ was the same between the pre-elite seeds and certified seeds (Figure 5), the distribution ratio of roots, stems, and leaves gradually decreased with the extension of the growth period, the distribution ratio of tubers gradually increased with the extension of the growth period, and the distribution ratio of dry matter to each organ was sorted by size of leaves > stems > roots > tubers in the early distribution period and tubers > leaves > stems > roots in the late distribution period. The dry matter of each variety within pre-elite seeds was almost not distributed to the roots after 65 d, while the certified seeds did not distribute dry matter to the roots until 80 d; the pre-elite seeds stopped distributing dry matter to the roots 15 days earlier than the certified seeds (Figure 5A). The percentage of dry matter distribution to the stems in the certified seeds was higher than in the pre-elite seeds, and the percentage of dry matter distribution to the stem of the pre-elite seeds was lower than 5% at 62 d, while that of the certified seeds was lower than this level only at 76 d (Figure 5B). There was no significant difference in the proportion of leaf dry matter distribution between the pre-elite and certified seeds of each variety, and the proportion of leaf dry matter distribution increased from 20 d to 41 d for the certified seeds of each variety, but gradually decreased after that, while the proportion of leaf dry matter distribution for the pre-elite seeds gradually decreased (Figure 5C). Both the pre-elite and certified seeds of each variety did not allocate dry matter to tubers from 20 d to 27 d, but the percentage of tuber dry matter allocation gradually increased in the late stages of growth for both the pre-elite and certified seeds of each variety (Figure 5D). Overall, the root and stem distribution ratios of the pre-elite seeds were lower than those of the certified seeds, while the leaf and tuber distribution ratios did not differ significantly.

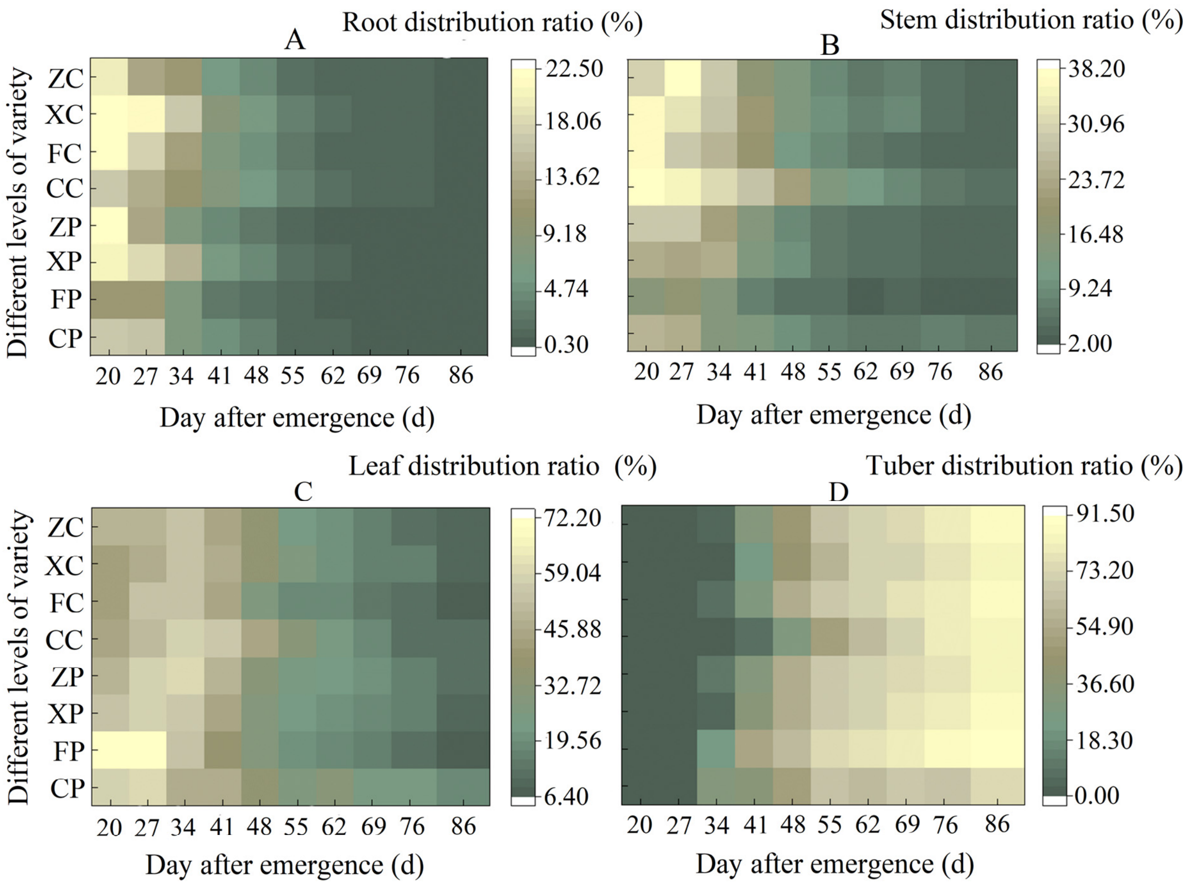

Figure 5. Comparison of dry matter distribution ratios within roots (**A**), stems (**B**), leaves (**C**), and tubers (**D**) of different varieties of potato between pre-elite and certified seeds. The darker the color, the lower the distribution ratio. CC, FC, XC, and ZC represent the certified seeds of Chuanyu 117, Favorita, Shepody, and Zhongshu No. 3, respectively. CP, FP, XP, and ZP represent the pre-elite seeds of these four varieties, respectively.

3.4. Comparison of the Dry Matter Accumulation Rate of Different Organs between the Pre-Elite and Certified Seeds

The rate of dry matter accumulation varied among different varieties and organs (Figure 6), and the average rate of dry matter accumulation in each organ was sorted by size of tubers > leaves > stems > roots. The average dry matter accumulation rate of pre-elite seeds was lower than that of certified seeds, and all reached a significant level ($p < 0.05$), with the average dry matter accumulation rate of certified seeds being significantly higher than that of pre-elite seeds by 382.61% for roots (Figure 6A), 219.81% for stems (Figure 6B), 184.65% for leaves (Figure 6C), and 241.94% for tubers (Figure 6D). However, between the pre-elite and certified seeds, there was no significant difference in the percentage of dry matter accumulation rate in each organ to the whole plant. In the pre-elite seeds, roots, stems, leaves, and tubers accounted for 0.31%, 3.97%, 12.60%, and 83.12% of whole-plant dry matter accumulation, respectively; in the certified seeds, roots, stems, leaves, and tubers accounted for 0.53%, 3.76%, 10.17%, and 85.54% of whole-plant dry matter accumulation, respectively.

3.5. Differences in Theoretical Yield and Its Constituent Factors between the Pre-Elite and Certified Seeds of Different Varieties

The tuber fresh weight, tuber volume, tuber number, and theoretical yield of certified seeds were all greater than those of the pre-elite seeds, except for the pre-elite seed of Chuanyu 117, which had a greater number of potatoes per plant than its certified seed. Analysis of variance (Table 4) and Duncan's multiple comparisons showed that tuber fresh weight, tuber volume, tuber number, and theoretical yield of the certified seeds of Zhongshu No. 3, Shepody, Chuanyu No. 117, and Favorita were all highly significantly different from their pre-elite seeds ($p < 0.01$), except for tuber number of the certified seed of Chuanyu 117, which was significantly different from its pre-elite seed ($p < 0.05$). Overall, the tuber fresh weight, tuber volume, tuber number, and theoretical yield of the certified seeds were 114.71%, 113.58%, 54.26%, and 214.70% higher than those of the pre-elite seeds on average, respectively.

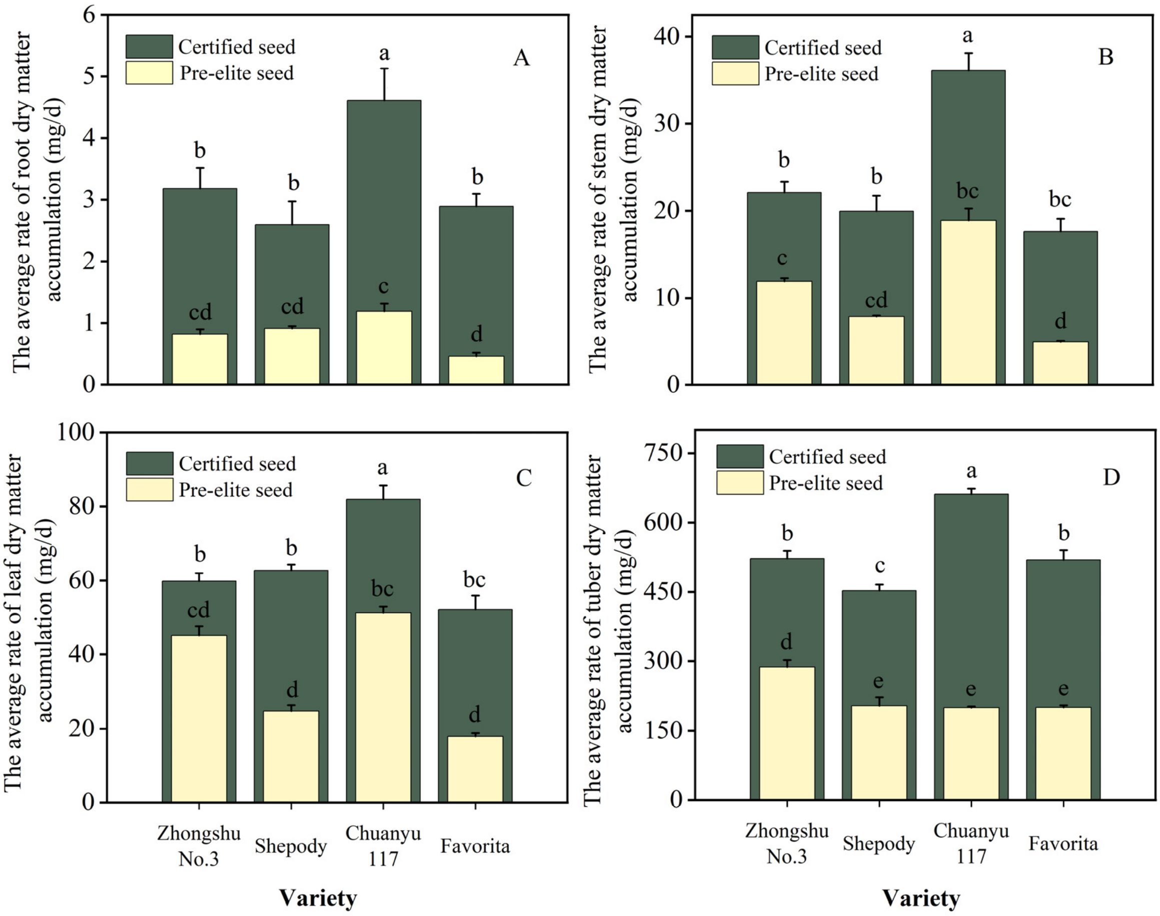

Figure 6. Comparison of dry matter accumulation rates within roots (**A**), stems (**B**), leaves (**C**), and tubers (**D**) of different varieties of potato between the pre-elite and certified seeds. Different lowercase letters indicate significant differences between treatments ($p < 0.05$). The dark green pillars represent the certified seeds, while the yellow pillars represent pre-elite seeds.

Table 4. Tuber fresh weight, tuber volume, tuber number and theoretical yield of the pre-elite and certified seeds.

Seed Level	Variety	Tuber Fresh Weight (g)	Tuber Volume (cm^3)	Tuber Number (pcs)	Theoretical Yield (kg ha^{-1})
Pre-elite seed	Zhongshu No. 3	121.79 ± 23.13 cC	112.73 ± 20.54 cC	4.53 ± 0.42 dDE	11,070.49 ± 2102.3 cC
	Shepody	76.54 ± 8.39 dD	71.20 ± 7.79 dD	3.27 ± 0.64 eDE	6957.16 ± 762.58 dD
	Chuanyu 117	86.56 ± 14.72 dD	81.20 ± 14.91 dCD	9.73 ± 0.31 aA	7868.66 ± 1337.77 dD
	Favorita	85.39 ± 24.31 dD	79.67 ± 22.85 dCD	3.00 ± 0.35 eE	7762.04 ± 2209.70 dD
Certified seed	Zhongshu No. 3	183.27 ± 12.82 bB	170.33 ± 11.55 bB	6.40 ± 0.72 cC	16,658.81 ± 1165.36 bB
	Shepody	164.80 ± 12.28 bB	153.07 ± 11.50 bB	4.80 ± 0.60 dD	14,980.46 ± 1116.07 bB
	Chuanyu 117	250.74 ± 23.49 aA	231.87 ± 29.27 aA	8.27 ± 0.95 bAB	22,792.51 ± 2135.14 aA
	Favorita	173.65 ± 21.28 bB	161.47 ± 27.37 bB	7.40 ± 0.72 bcBC	15,784.77 ± 1934.11 bB

Note: Data in the table are means ± standard errors, different lowercase letters within the same column indicate significant differences between treatments ($p < 0.05$), and capital letters indicate highly significant differences between treatments ($p < 0.01$).

4. Discussion

4.1. Differences in Dry Matter Accumulation Patterns between the Pre-Elite and Certified Seeds

Dry matter accumulation is the basis for crop yield formation [22,23], and the dry matter accumulation balance period is a critical period when the potato growth center shifts from above ground to below ground [24]. The root system of potatoes is relatively small, and the root to crown ratio is relatively low [25]. Therefore, most of the dry matter for plant growth depends on the photosynthesis of leaves. In the early stage of dry matter accumulation balance, the stronger the above-ground part, the larger the source, and in the later stage of dry matter accumulation balance, more dry matter can be distributed to the underground part [26]. Establishing a larger "source" of photosynthetic organs prior to rapid potato tuber growth is extremely important for rapid tuber growth in the middle and late stages [27]. Potato is a source-limited crop [28,29]; increasing source availability can increase dry matter accumulation in tubers. In this study, we found that the dry matter accumulation balance period in pre-elite seeds was 3–7 days earlier than in certified seeds, indicating that the above-ground portions of pre-elite seeds did not build sufficient sources before the dry matter accumulation balance period, resulting in less dry matter delivered to tubers than in certified seeds. Therefore, if the time to reach the balance period of dry matter accumulation can be extended, the yield of pre-elite seeds can be improved.

In terms of dynamic changes in potato dry matter accumulation, a large number of studies have shown that whole-plant and tuber dry matter accumulation during the entire potato growth period showed similar "S" curve changes. The dry matter accumulation of roots, stems, and leaves shows a single-peak curve change, and the dry matter accumulation rate of each organ and the whole plant shows a single-peak curve change, but the peak appears at different times [30–33]. The results of this experiment showed that all organ and whole-plant dry matter accumulations of certified seeds were higher than those of pre-elite seeds during the entire growth period, and the trend of change was consistent, with roots, stems, and leaves showing a single-peaked curve, and tuber and whole-plant dry matter accumulations showed an "S" shaped trend, which was consistent with previous research results. However, the whole-plant dry matter accumulation differed significantly between the pre-elite and certified seeds, with the whole-plant dry matter accumulation of the pre-elite reaching a maximum until harvest and still showing a rapid growth trend, while the certified seed formed a complete "S" pattern, indicating a significant delay in the growth of the pre-elite seed. In this study, we also compared the differences in dry matter accumulation rates between pre-elite and certified seeds and found that dry matter accumulation rates in various organs of pre-elite seeds were lower than those of certified seeds. This indicated that at the same time, dry matter accumulation in various organs of pre-elite seeds was lower than in certified seeds. If the harvest period of the pre-elite seeds was delayed, their yield would also increase correspondingly.

4.2. Differences in Dry Matter Distribution Patterns between the Pre-Elite and Certified Seeds

The direction of dry matter distribution is an important factor in determining the yield level [34]. The amount of dry matter allocated in different plant organs varies among potato varieties [35]. Some studies have shown that the distribution of dry matter in potatoes changed as growth progressed and growth centers shifted, and at different stages of growth and development, the percentage of the dry matter distribution in each organ was different [36–38]. In this study, we found that the distribution ratio of roots, stems, and leaves were higher for both the pre-elite and certified seeds in the early stage of growth and decreased in the late stage, while the distribution ratio of tubers was lower in the early stage of growth and increased in the late stage of the growth process, finally reaching a maximum.

The proportion of dry matter allocated to different organs was different, with roots, stems, and leaves having a high proportion of dry matter allocation in the early stage for their morphological establishment and a lower proportion in the late stage, with the content only able to maintain their growth and the rest supplied to the tubers [39]. The results of this experiment indicated that the proportion of dry matter allocated to roots and stems is significantly higher in the certified seeds than in pre-elite seeds, while there was no significant difference in the proportion of allocation to leaves and tubers, indicating that the pre-elite seeds' roots and stems need to accumulate more dry matter to ensure that the plant can absorb and transport more nutrients. Therefore, promoting the allocation of dry matter to roots and stems in the early growth stages of pre-elite seeds was conducive to improving the allocation of dry matter to tubers in the late growth stages, which would ultimately improve the yield of pre-elite seeds.

4.3. Differences in Yields between the Pre-Elite and Certified Seeds

Yield depends not only on the total amount of dry matter produced by the plant, but also on how much is allocated to economically useful parts [40]. For potatoes, the more dry matter accumulated in the tuber, the higher the yield. Wubante [41] and Abbasian [42] showed that potatoes accumulated more dry matter in leaves and stems in the early growth stages, which would promote the accumulation of tuber dry matter in the late growth stage and ultimately increase yield. The results of our experiment showed that the pre-elite seeds had a slower growth rate, lower dry matter accumulation in various organs and whole plants, and a lower percentage of root and stem dry matter distribution compared to the certified seeds, resulting in lower tuber fresh weight, tuber volume, tuber number, and theoretical yield of the pre-elite seeds compared to the certified seeds. Therefore, the differences in dry matter accumulation and distribution between the pre-elite seeds and certified seeds are ultimately manifested in the yield. In the actual production of seed potatoes, it is necessary to extend the harvest time of seed potatoes, especially pre-elite seed, which will increase the amount of dry matter transported by tubers and increase the yield of seed potatoes.

5. Conclusions

There was a significant difference in the growth characteristics between the pre-elite seeds and certified seeds. The pre-elite seeds had a slower growth process, a longer growth period, and lower dry matter accumulation in various organs and whole plants than certified seeds. In addition, the root and stem distribution ratios of pre-elite seeds were significantly lower than those of certified seeds, while there was no significant difference in leaf and tuber distributions, and dry matter distribution in pre-elite seeds to tubers started 3–7 days earlier than in certified seeds. In terms of yield and its constituent factors, tuber fresh weight, tuber volume, tuber number, and theoretical yield of certified seeds were all higher than those of pre-elite seeds. In actual potato production, the harvest time of potatoes, especially the pre-elite seeds, should be extended, and the proportion of dry matter allocated to roots and stems should be increased in the early growth stages, which would promote the distribution of dry matter to tubers in the late growth stages and, ultimately, improve the yield of virus-free potato seeds.

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