agriculture

MDPI

Article

Effects of Fertilization Mode on the Growth of *Lactuca sativa* L. and Soil Nutrients in Facilitated Cultivation

Wei Li [1], Yanpeng Wei [2], Jiale Zhao [2], Weiye Han [1], Ding Li [1], Jianzhong Wang [1], Mengfei Zhao [1], Lin Chen [1], Limei Chen [1,*] and Lina Zhou [1,*]

[1] College of Engineering and Technology, Jilin Agricultural University, Changchun 130022, China; foxy_v@163.com (W.L.); yezi9zzz@163.com (W.H.); lid990629@163.com (D.L.); wjz12123@2980.com (J.W.)

[2] Key Laboratory of Bionics Engineering, Jilin University, Ministry of Education, Changchun 130025, China; china_dp@163.com (Y.W.); zhaojl@jlu.edu.cn (J.Z.)

* Correspondence: chenlimei@jlau.edu.cn (L.C.); zhoulina976430@163.com (L.Z.); Tel.: +86-13039010328 (L.C.); +86-15144195131 (L.Z.)

Abstract: This paper aims to find a fertilization method that better matches the growth characteristics of vegetables and reduces the soil and environmental problems caused by unreasonable fertilization methods, in view of the strong buffering of the clayey black soil in the north and the mismatch between the amount of chemical fertilizer applied and the growth characteristics of vegetables during cultivation. In this experiment, *Lactuca sativa* L. (*Lactuca sativa*) was studied in a randomized complete block design in greenhouse and five different fertilizer application methods were arranged: exponential fertilization (EF), linear fertilization (LF), average fertilization (AF), one-time fertilization (OF), and no fertilization as a control group (CG). The effects of different fertilization methods on soil nutrients, agronomic traits of *Lactuca sativa* growth, and related quality were investigated, and the pattern of effects of different fertilization methods on growth and soil nutrients was obtained. The results of the experiment showed that the exponential fertilization method gradually took advantage as the growth time extended. The plant height (PLH), leaf length (LL), leaf width (LW), yield, soluble protein (SP), soluble sugar (SS), vitamin C (VC), and elemental nitrogen (EN) and potassium (EK) of *Lactuca sativa* were significantly improved under the exponential fertilization method compared with other fertilization methods, by 29.9 cm, 51.5 cm, 5.96 cm, 22, 2.32 kg/m^2, 0.23%, 0.44%, 3.93%, 94.66 mg/kg, 1.58 g/kg, and 1.94 g/kg, respectively. The alkali-hydrolyzed nitrogen (SAN), available phosphorus (SAP), and available potassium (SAK) in the soil after fertilization were 139.69 mg/kg, 50.23 mg/kg, and 180.30 mg/kg, respectively. The above results showed that the exponential fertilization method not only improved the quality of *Lactuca sativa* and thus the quality of the crop growth traits, but also changed the soil nutrients favorably after fertilization, which is of some importance for the protection of black soils.

Keywords: *Lactuca sativa* L.; exponential fertilization; agronomic trait; soil nutrient

Citation: Li, W.; Wei, Y.; Zhao, J.; Han, W.; Li, D.; Wang, J.; Zhao, M.; Chen, L.; Chen, L.; Zhou, L. Effects of Fertilization Mode on the Growth of *Lactuca sativa* L. and Soil Nutrients in Facilitated Cultivation. *Agriculture* **2023**, *13*, 1630. https://doi.org/10.3390/agriculture13081630

Received: 18 June 2023
Revised: 13 August 2023
Accepted: 17 August 2023
Published: 18 August 2023

1. Introduction

In order to maximize the profitability of planting leafy vegetables, farmers use mineral fertilizers extensively in the cultivation process, which has made excessive application of chemical fertilizers on leafy vegetables very common in recent years [1]. According to statistics, for the same area planted with vegetables and food crops, vegetable planting fertilizer application has far exceeded the amount of fertilizer application for food crops by as much as ten times [2]. The mismatch between vegetable yields and the increased amount of fertilizer application due to the blind pursuit of vegetable yields has led to increasingly serious environmental problems such as soil consolidation, destruction of soil bulking structure, water pollution, and eutrophication caused by excessive application of chemical fertilizers [3]. The quality and yield of vegetables and fruits have dropped dramatically, which is a serious threat to people's health as well as the safety of the country's agricultural products [4].

In response to the current mismatch between fertilizer application and crop growth, scholars from various countries have conducted a series of studies on optimizing fertilizer application patterns and proper fertilization methods. Zhuang et al. [5] investigated the impact and potential of optimal fertilizer application practices on rice production. The results of the study indicate that optimal fertilization practices are a promising management strategy for sustainable rice production, leading to improved nitrogen use efficiency, increased yields, and reduced nitrogen losses. Wang jun et al. [6] aimed to optimize the effectiveness of fertilizer application in reducing nitrogen and phosphorus run-off losses. The results showed that conservation tillage and optimal fertilizer application could reduce nitrogen and phosphorus losses during the growing season of winter crops in the Chaohu Lake area while increasing crop yields. In northern China, the summer is hot and dry, and during autumn and winter the temperature differences between day and night is large, humidity is low, and the season is often accompanied by severe weather such as rain, snow, and wind; therefore, vegetable-growing in the north is often conducted in vegetable greenhouses. At present, research on vegetable greenhouses in the north has focused on organic agricultural amendments [7], reducing pollution from fertilizer application [8], and replacing chemical fertilizers with municipal waste [9]. To our knowledge, no research has been conducted thus far on the rational fertilization program proposed for vegetable greenhouse cultivation in northern China.

For northern vegetable greenhouse cultivation, the use of exponential fertilization may provide a new solution to the above problems. Exponential fertilization increases the amount of fertilizer applied reasonably according to the needs of different crop indices of growth, which can improve nutrient utilization and enhance crop yields while avoiding damage to the soil, water bodies, and the environment from excess fertilizer [10]. Exponential fertilization is a fertilization method based on the theory of the nutrient steady state, which combines the exponential growth of seedlings with the exponential supply of fertilizer to meet the nutrient requirements of seedlings during periods of rapid growth while preventing environmental pollution caused by over-fertilization [11]. Exponential fertilization has been widely used in forestry as an optimized fertilization method but is less used in greenhouse vegetable growing [12]. Ni et al. [13] studied the effects of average and exponential fertilization on seedling height, root collar diameter, total biomass, and N/P/K accumulation in *Quercus nuttallii* seedlings. The study showed that the exponential fertilization not only met the nutritional requirements of *Quercus nuttallii* seedlings, but also promoted the growth of seedlings and their root systems, and indirectly accelerated the accumulation of N/P/K, thus improving the quality of the plantation. Wang et al. [14] investigated the nitrogen requirements of Hanatemari grown with exponential fertilization to enhance robust seedlings, nutrient dynamics, biomass, and growth. The study showed that exponential fertilization with reasonable regulation of fertilizer applied improves the quality of seedlings. Schulz D.G. et al. [15] studied the effect of different fertilization methods on *L. divaricata* seedlings during growth, and the results showed that exponential fertilization is a valid option to reduce initial nutrient loss by leaching. Li et al. [16] compared conventional fertilization with exponential fertilization to find the most effective method of fertilization during the early growth stage following seedling emergence. The results showed that turfgrass seedlings with the exponential fertilization technique exhibited significantly higher biomass accumulation, total nitrogen (N) concentration, and N content per seedling than those treated with the conventional fertilization method. Most of the studies on exponential fertilization planting have used seedling traits, nutrient dynamics, biomass accumulation, and the degree of N/P/K accumulation as measures. This paper investigates the pattern of influence of fertilizer application methods on agronomic traits and soil nutrients in *Lactuca sativa*.

SP, SSs, soluble solids content (SST), VC, and EN, EP, and EK were selected as test indicators of *Lactuca sativa* quality. SP is an important nutrient and osmoregulation for vegetables and can significantly affect the ability of cells to retain water [17]. SSs are the basis of plant metabolism and an important source of energy for plants during growth and development, regulating important growth processes such as plant senescence and leaf formation [18]. SSTs are an important indicator of how much of the key nutrients in fruit and vegetables are present in the plant [19]. VC is an important component of plant cells and is important in identifying the quality of *Lactuca sativa* [20]. The EN, elemental phosphorus (EP), and EK are the main components of proteins and chlorophyll in plants, which are widely involved in plant metabolism as catalysts for enzymes and also play an important role in plant photosynthesis and the production of new cells. A lack of the basic EN, EP, and EK will stagnate plant growth and development. The EN, EP, and EK are therefore used as one of the measures of quality in *Lactuca sativa.*

Soil nutrients are a composite indicator of all aspects of soil properties. Understanding the effects of different fertilization methods on soil chemistry is important for fertilizing the next crop. SAN, SAP, SAK, and soil organic matter (SOM) were selected as indicators of soil chemical properties [21]. Nitrogen is one of the most important nutrients for plant growth and development. It is transported and transformed in the soil in many ways and is an important indicator of soil fertility. Phosphorus is one of the three essential nutrients for plant growth. SAP is the most effective part of the soil phosphorus pool for crops and is directly available for crop uptake and use. SAK is the main form of potassium available in the soil for plant uptake and has a significant impact on crop yield and quality. SOM is an important component of the solid phase fraction of the soil and is one of the main sources of plant nutrition, contributing positively to the activity of microorganisms and soil organisms as well as to the decomposition of nutrient elements in the soil [22].

Growing vegetables in greenhouses and studying crop growth patterns under different fertilizer application situations will not only help solve a number of environmental and economic problems caused by over-fertilization in vegetable production in China, but also provide a completely new solution to fertilizer application methods. This paper addresses the problem of the mismatch between fertilizer application and the growth characteristics of vegetables in northern vegetable greenhouses; *Lactuca sativa* was used as a test subject. The effect of fertilizer application methods on soil nutrients was also investigated by further analyzing the effect of different fertilization methods on effective phosphorus, fast-acting potassium, and alkaline-digested nitrogen in the soil.

2. Materials and Methods

2.1. Plant Materials and Growth Conditions

The experiments were conducted in the greenhouse at the Facility Agriculture Base of Jilin Agricultural University in Changchun, Jilin Province (125°42′ E, 43°82′ N). The site has a temperate monsoon climate with four distinct seasons throughout the year, an average temperature of 25 °C in June, an average frost-free period of 145 days, an average growing season of 130 days, and a year-round rainfall of 860.3 mm. The experiment was carried out in a greenhouse at a temperature of 10–38 °C and an air relative humidity of 45–65%. The soil type in the test site was black soil, and the average soil properties were taken from the 0–40 cm soil layer before the experiment. Its physical and chemical properties were as follows: soil PH (1:2.5 soil: water) was 6.6, organic matter 16.3332 g/kg, bulk density 1.42 g/cm^3, soil moisture content 11.8%, alkaline nitrogen 109.66 mg/kg, fast-acting phosphorus 43.08 mg/kg, fast-acting potassium 136.18 mg/kg. A panoramic view of the testing ground is shown in Figure 1a.

Figure 1. Overview of the test site and irrigation tillage methods. (**a**) Greenhouse for the experiment. (**b**) Ridge culture. (**c**) Trickle irrigation. (**d**) Row spacing and plant spacing measurement diagram.

The type of fertilizer used is 40% compound with 60% urea [23] (compound fertilizer elemental content of 15% N, 15% P_2O_5, 15% K_2O, urea N content of 46%). The fertilizer was applied in March 2022 in a single application in the greenhouse at the time of land preparation, using a row crop, as shown in Figure 1b.

2.2. Design of Experiment

The effects of five different fertilizer application methods, namely exponential fertilization, linear fertilization, average fertilization, one-time application, and no fertilization, on PLH, LL, LW, number of leaves (NOL), SPAD, yield, SP, SS, SST, VC, EN, EP, and EK of *Lactuca sativa.*

The experiment was carried out in a randomized complete group design. Five types of fertilization were formulated for this study: control group (CG): no fertilization treatment, one-time fertilization (OF): all fertilizer needed is applied at once at the first application, linear fertilization (LF): the amount of fertilizer applied to the crop accumulates over time in a linear trend, average fertilization (AF): a more traditional method of fertilization, where equal amounts of fertilizer are applied in equal amounts of time, exponential fertilization (EF): nutrients are supplied at a rate almost equal to the crop growth rate, with an exponentially increasing trend. An overview of fertilizer application is shown in Table 1. A schematic diagram is shown in Figure 1c.

Table 1. Overview of Fertilization Method.

Fertilization Model	Symbol	Model Equation
Control Group	CG	None
One-time Fertilization	OF	None
Linear Fertilization	LF	$N_t = kt$ (where t is the number of processing days and k is a constant)
Average Fertilization	AF	$N_T = a$ (where a is a constant)
Exponential Fertilization	EF	$N_T = N_s(e^{rT} - 1) - N_{(T-1)}$ (N_T represents the amount of nitrogen applied at the time of t fertilization under the relative increase rate r. where N_s is the initial nitrogen content of *Lactuca sativa* before exponential fertilization. $N_{(T-1)}$ represents the total amount of nitrogen applied including the $T - 1$ fertilization)

There were 3 groups in the trial site; each group had 5 plots of 5 m^2 (5 m long and 1 m wide) and each plot was applied with 1 fertilization method. The experiment plots were arranged in three completely randomized groups. Fertilizations were applied at 10-day intervals and three fertilizer applications were performed. A diagram of the row spacing and plant spacing measurements is shown in Figure 1d. The measured N content of *Lactuca sativa* seed was 2.436% [24] and the ideal *Lactuca sativa* dry matter N content was 4.831% [25], with a biomass of 199.8 g for a 1 m^2 planting area [26]. The amount of fertilizer required for this trial was 21.61 g per square meter of seed sown, which was converted to a combination of 40% compound fertilizer and 60% urea at 49.7 g. The specific fertilizer application rates are shown in Table 2.

Table 2. Fertilization amount of different treatment.

Times	Date	OF	CG	LF	AF	EF
1	3.8	49.7	0	8.28	16.57	7.2
2	3.18	0	0	16.57	16.57	15.27
3	4.28	0	0	24.85	16.57	27.23
Total		49.7	0	49.7	49.7	49.7

2.3. Plant Sampling and Analysis

When the plants were 1 leaf and 1 heart, the seedlings were set at a distance of 10 cm between the plants and 10 cm between the rows and when the plants were 3 leaves and 1 heart, the plants were randomly selected and the basic morphological indicators were measured plants were randomly selected and the basic morphological indicators were measured, including basic morphological indicators, PLH, LL, LW, leaf number (LN), and SPAD for *Lactuca sativa*. Samples were taken every 4 days a total of 8 times. At the last sampling, the total yield of *Lactuca sativa* was measured.

The quality of *Lactuca sativa* was analyzed under different fertilization treatments. VC content was determined by titration with 2-6 dichloroindophenol [27], SP content was determined by Kormas Brilliant Blue G-250 staining [28], SSs were determined by anthrone colorimetry [29], SSTs were measured by hand-held refractometer [30], nitrogen content was determined by the Kjeldahl method [31], phosphorus content was determined by p-diphenol-sodium sulfite reduction [32], and potassium content was determined by flame atomic absorption spectrometry [33]. Soil indicators were measured on the day the *Lactuca sativa* was harvested. Soil samples were taken for each treatment using a soil auger. Three identical soil samples were taken from the 0–40 cm soil layer and three replicate tests were conducted. Physical and chemical analysis of soil samples after was carried out after natural air drying. SAN was determined by the semi-micro Kjeldahl method. Soil available phosphorus was measured by 0.5 mol/L $NaHCO_3$ leaching and the molybdenum-antimony colorimetric method. Soil available potassium was measured by 1 mol/L NH_4OAC leaching-flame photometry. SOM was measured by the potassium dichromate volumetric method—external heating. Each test was repeated three times and averaged. Figure 2 shows a schematic diagram of the sampling measurements for *Lactuca sativa* and soil.

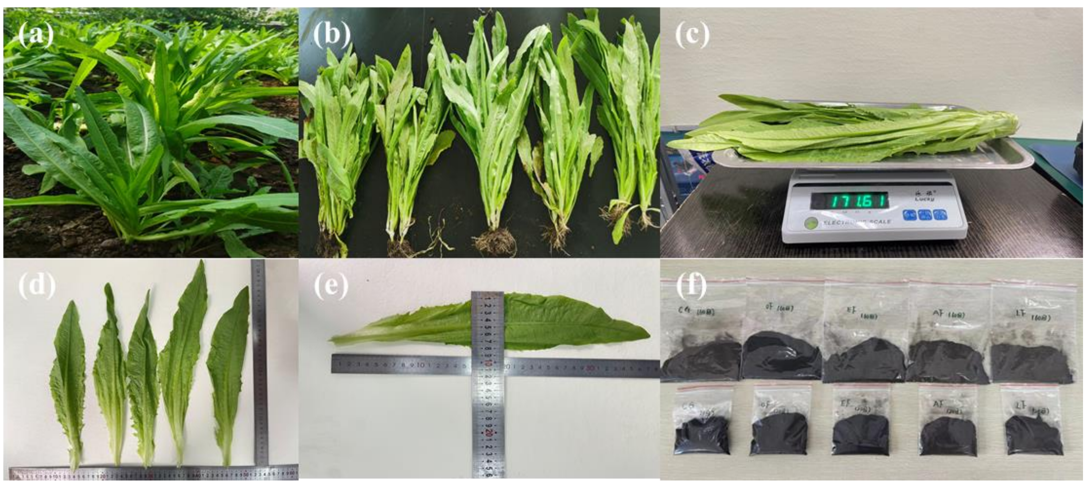

Figure 2. Sampling measurement diagram of *Lectuca sativa* and soil. (**a**) *Letuca sativa* field photo. (**b**) Sampling photo. (**c**) Single plant weight measurement. (**d**) Plant height measurement. (**e**) Leaf width measurement. (**f**) Soil sampling photo.

2.4. Data Analysis

Analysis of variance (ANOVA) and least significant difference (LSD) were used to analyze the data in SPSS. ANOVA was used to analyze the variability of the measured data and to determine whether each test factor had a significant influence on the tested indicators. LSD was primarily used to determine whether there is a significant difference between different levels of the test factor and to compare the means of the different levels.

3. Results and Analysis

3.1. Effect of Different Fertilization Treatments on Agronomic Traits of Lactuca sativa L.

Agronomic traits for *Lactuca sativa* generally include PLH, LL, LW, LN, and SPAD. PLH, LL, and LW are the more visual agronomic traits and can be compared by simple measurements. In order to clearly show the growth of the *Lactuca sativa*, the data were sampled at 15-day intervals and plotted in Figure 3. The results of the experiment are shown in Figure 3a–e, where data were recorded at the final growth stage and the variability of the measured data was analyzed to determine whether different fertilization methods had a significant effect on the agronomic traits of *Lactuca sativa.* All the *Lactuca sativa* in each plot was cut and collected along the ground after maturity, was cleaned of soil, and weighed. The yields of *Lactuca sativa* using different fertilization methods were obtained by averaging the yields of the respective replicate plots, as shown in Figure 3f.

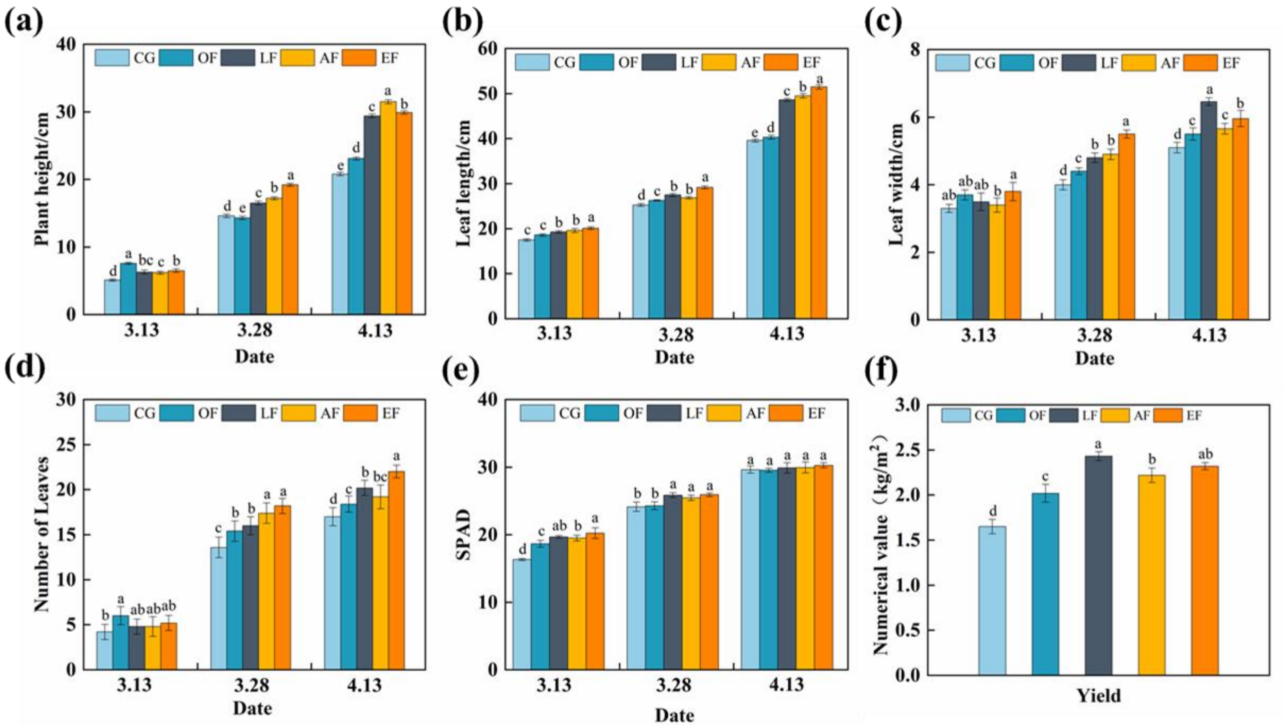

Figure 3. Effect of different fertilization methods on plant height, leaf length, leaf width, leaf number, SPAD, and yield of *Lactuca sativa*. (**a**) Plant height. (**b**) Leaf length. (**c**) Leaf width. (**d**) Leaf number. (**e**) SPVD. (**f**) Yield. CG is the control group. OF is one-time fertilization. LF is linear fertilization. AF is average fertilization. EF is exponential fertilization. The letters a–e in a column indicate significant differences at $p < 0.05$.

The results from the ANOVA showed that different fertilization methods significantly affected the PLH, LL, LW, and LN of the agronomic traits, but not the SPAD values. Figure 3a shows the effect of different fertilization methods on the height of *Lactuca sativa.* At the time of harvest, the heights of the final plants were 11.06%, 41.35%, 51.44%, and 43.75% higher with the OF, LF, AF, and EF methods, respectively, than the that of CG. The highest final PLH was 31.5 cm, treated with the AF fertilization method. Figure 3b shows the effect of different fertilization methods on the LL of *Lactuca sativa*, which varied significantly in the late stages of growth. At the final measurement, LLs were 1.77%, 22.73%, 25%, and 30.05% greater with treatment following the OF, LF, AF, and EF methods, respectively, than that of CG. The maximum LL was 51.5 cm with EF treatment. Figure 3c shows the effect of different fertilization methods on *Lactuca sativa* LW, which did not differ significantly in the early growth stages. The differences in LW were more significant in the middle and late stages of *Lactuca sativa* growth. The LWs with the OF, LF, AF, and EF treatments were 7%, 25.68%, 10.89%, and 15.95% greater than that of CG at the last measurement. The maximum LW was 6.7 cm with the LF treatment. Figure 3d shows the effect of the different fertilization methods on the NOL of *Lactuca sativa.* In the early stages of *Lactuca sativa* growth, the NOL with the OF treatment was significantly higher than those with the other four treatments, whereas the growth trends of *Lactuca sativa* with the LF, AF, and EF treatments were more similar as well as the NOL. The growth trend of *Lactuca sativa* LN with the OF treatment tended to be gradually slow, leading to a lower number with the OF treatment than the LF, AF, and EF treatments, but a higher number than that of CG. The final LN ranked in descending order was EF, LF, AF, OF, CG. The maximum NOL per plant was 22, recorded for those treated with the EF method, which was 29.41% higher than the minimum value. Figure 3e shows the effect of different fertilization methods on SPAD in *Lactuca sativa*, which was found to be insignificant by ANOVA at the confidence level of 0.05 ($p > 0.05$). Figure 3e also shows the yield variation of *Lactuca sativa* under different fertilization methods. Yield increases of 22.42%, 47.27%, 34.55%, and 40.61% were achieved with the four treatments, OF, LF, AF, and EF, respectively, compared to that of CG. The highest *Lactuca sativa* yield, 2.43 kg/cm^2, was achieved with the LF treatment.

3.2. Effect of Different Fertilization Treatments on Yield of Lactuca sativa L.

A non-destructive sampling of *Lactuca sativa* at the maturity stage was performed. Due to a large number of quality indicators measured, 10 uniformly growing *Lactuca sativa* plants were selected from each plot and cut along the ground. All above-ground parts were bagged whole, transported by road in insulated boxes with ice bags, and brought back to the laboratory for freezing. After experimenting upon the *Lactuca sativa* plants according to the fertilization methods described in Section 2.3, the data from each group of tests were recorded. The results of the tests are presented in Figure 4a–f.

According to the results from the ANOVA, different fertilization methods significantly affected the quality indicators of *Lactuca sativa* at a confidence level of 0.05 ($p < 0.05$). Figure 4a shows the effects of different fertilization methods on the SP and SS content of *Lactuca sativa*. The SP content with OF, LF, AF, and EF treatment increased by 26.67%, 33.33%, 53.33%, and 53.33%, respectively, compared to that of CG. The AF and EF methods are slightly better when differentiated by SP content of *Lactuca sativa* SS increased by 43.75%, 168.75%, 75%, and 175% using the OF, LF, AF, and EF methods, respectively, compared to that of the CG, LF, and EF methods, which were much better for SS in *Lactuca sativa*. Figure 4b shows the effect of different fertilization methods on the SST of *Lactuca sativa*. The SST with OF, LF, AF, and EF treatment increased by 62.65%, 134.34%, 146.99%, and 136.75%, respectively, compared to that of the CG. SST continued to increase with increasing application frequency. The AF method performed the best SST index for *Lactuca sativa*. Figure 4c shows the effect of different fertilization methods in the content of VC of *Lactuca sativa*. The amount of VC with the four fertilization methods, OF, LF, AF, and EF, increased by 10.11%, 22.19%, 17.91%, and 25.94%, respectively, compared to the CG. The LF, AF, and EF methods showed a significant increase trend compared to that of the CG and OF method. The EF method was the best in terms of VC amount in *Lactuca sativa*. Figure 4d–f shows the effects of different fertilization methods on EN, EE, and EK content in *Lactuca sativa*. For the OF, LF, AF, and EF methods, EN increased by 18.27%, 42.31%, 28.85%, and 51.92%, EK increased by 23.08%, 28.67%, 42.66%, and 45.45%, and EP increased by 6.64%, 8.96%, 12.57%, and 12.68%, respectively, compared to that of the CG. The EF method was optimal, distinguished by the content of EN, EP, and EK in *Lactuca sativa*.

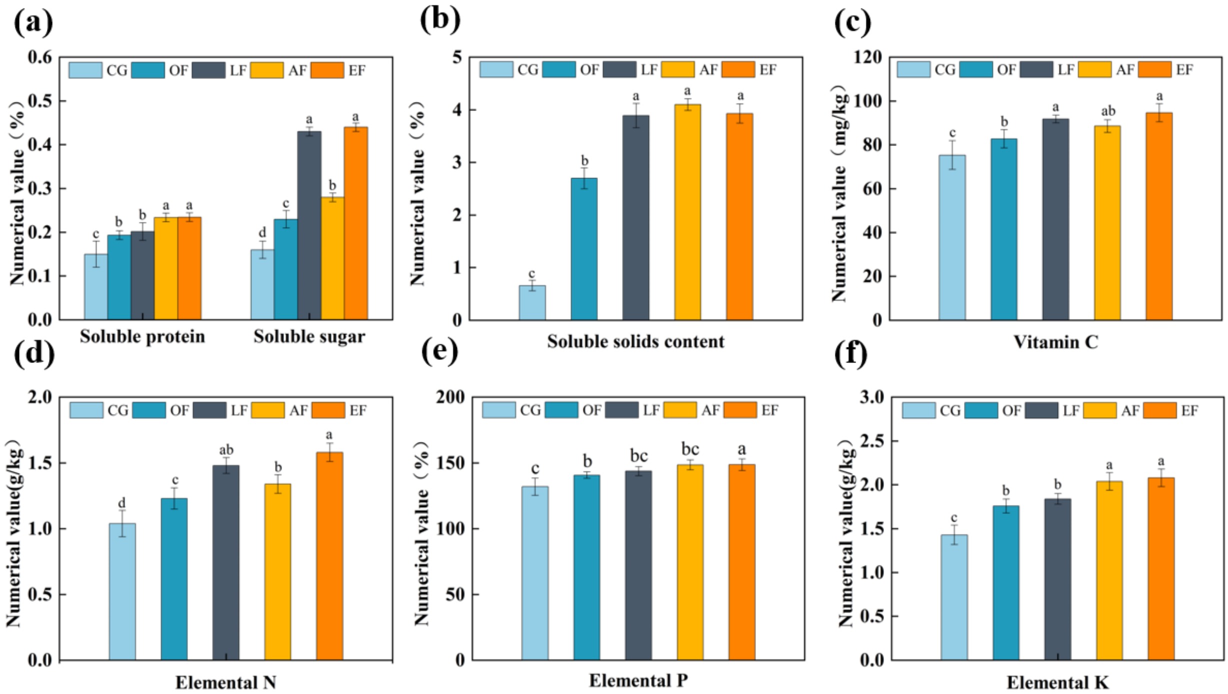

Figure 4. Effects of different fertilization methods on soluble protein, soluble sugar, soluble solids content, vitamin C, elemental N, elemental P, and elemental K of Lactuca sativa. (**a**) Soluble protein and soluble sugar. (**b**) Soluble solids content. (**c**) Vitamin C. (**d**) Elemental N. (**e**) Elemental P. (**f**) Elemental K. CG is control group. OF is one-time fertilization. LF is linear fertilization. AF is average fertilization. EF is exponential fertilization. The letters a–d in a column indicate significant differences at $p < 0.05$.

3.3. Effects of Different Fertilization Methods on Soil Nutrients

Soil indicators were measured on the day the *Lactuca sativa* was harvested. Soil samples were taken using a soil auger. Three replicate samples were taken at a depth of 20 cm for soils with the same fertilization method. Soil samples are naturally air-dried and then analyzed for physical and chemical properties. They were also analyzed for nutrient-related indicators according to the experimental method described in Section 2.3. The results of the tests are presented in Figure 5a–d.

Different fertilization methods had a significant effect on the SAN, SAP, and SAK at the confidence level of 0.05 ($p < 0.05$). For the OF, LF, AF and EF methods, the SAN was 15.31%, 25.96%, 18.41%, and 35.75% higher than the CG, and 8.20%, 18.19%, 12.18%, and 27.38% higher than the initial soil data RD, respectively. The SAP was 15.5%, 26.2%, 20.9%, and 29.13% higher with OF, LF, AF, and EF treatment, respectively, than that of CG, and 4.29%, 13.95%, 9.17%, and 16.81% higher than RD, respectively. The SAK was 10.88%, 40.13%, 34.01%, and 42.99% higher using the OF, LF, AF, and EF methods, respectively, than that of CG, and 2.67%, 29.75%, 24.08%, and 28.96% higher than that of RD, respectively. The SOM content of those with OF, LF, AF, and EF treatment was 9.55%, 26.08%, 18.62%, and 29.3% higher than that of CG and 14.88%, 8.08%, and 17.82% higher than that of RD, respectively. The maximum SOM content occurred at 19.24 g/kg using the EF method.

The above results show that different fertilization methods play different roles in improving soil nutrition. The five fertilization methods improved the soil nutrients of *Lactuca sativa* after planting in the descending order of EF, LF, AF, OF, and CG.

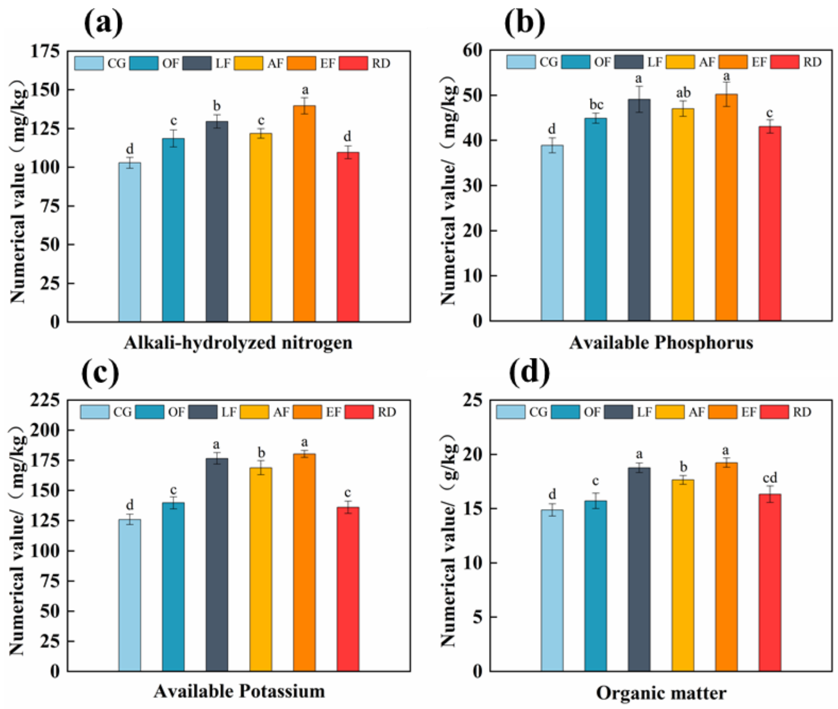

Figure 5. Effect of different fertilization methods on soil alkali-hydrolyzable nitrogen, soil available phosphorus, soil available potassium, and soil organic matter. (**a**) Soil alkali-hydrolyzable nitrogen. (**b**) Soil available phosphorus. (**c**) Soil available potassium. (**d**) Soil organic matter CG is the control group. OF is one-time fertilization. LF is linear fertilization. AF is average fertilization. EF is exponential fertilization. RD is the initial soil data. The letters a–d in a column indicate significant differences at $p < 0.05$.

4. Discussions

4.1. Exponential Fertilization Methods (EF) Enhance Basic Agronomic Traits and Yield in Lactuca sativa L.

The total amount of fertilizer applied to *Lactuca sativa* was the same for the five fertilization methods. At the end of the experiment, there were significant differences in most indicators between the no fertilization method and the remaining four fertilization methods. Exponential fertilization (EF) performed better than one-time fertilization (OF), linear fertilization (LF), average fertilization (AF), and no fertilization as a control group (CG) in promoting soil nutrient uptake in *Lactuca sativa*, combining all agronomic trait indicators.

Appropriate fertilization is an effective promoter of physiological activity and metabolism in *Lactuca sativa*, whereas inappropriate fertilization can lead to retarded development of *Lactuca sativa* [34]. The largest amount of fertilizer was applied at the beginning of the one-time fertilization (OF) method, but the advantage was not obvious throughout the growth process. The height of the *Lactuca sativa* was greater in all other fertilization methods than in the linear application (LF). A one-time fertilization in the early stages of *Lactuca sativa* does not give the best results. Excessive fertilizer application results in large amounts of fertilizer leaching and reduced fertilizer utilization [35]. At the same time, the high concentration of fertilizer in the soil tends to cause the salt content inside the plant's root system to differ from the outside, creating an osmotic effect that prevents the plant's roots from absorbing water and inhibits plant growth [36]. The above phenomena are reflected in the PLH, LL, LW and yield of *Lactuca sativa*. In this study, *Lactuca sativa* is a short-growing leafy vegetable crop. The agronomic traits of *Lactuca sativa* generally showed an "increasing then decreasing" trend treating with the one-time fertilization (OF) method [34].

The nutrients required for *Lactuca sativa* growth gradually increased over time and the exponential fertilization (EF) method takes advantage. The agronomic traits of *Lactuca* *sativa* are higher in the later stages with the exponential fertilization (EF) method than with the other fertilization methods. The daily growth of *Lactuca sativa* cannot be met by the one-time fertilization (OF) of all fertilization methods. *Lactuca sativa* growth is better served by increasing the frequency and planning the amount of fertilizer applied.

4.2. Exponential Fertilization (EF) Improves Lactuca sativa L. Quality

Lactuca sativa quality is one of the most important indicators and fertilization method is an important way of improving it. Plant growth and development require a balanced supply of nutrients. The fertilization method, as the main measure of anthropogenic nutrient supplementation, can make a significant contribution to plant growth and yield increase if properly formulated. Conversely, inadequate fertilization or excessive fertilization that does not match the nutrient requirements of plants will not promote nutrient up-take and will not be conducive to nutritional growth and yield improvement [37]. There-fore, appropriate fertilization methods can significantly improve plant growth and quality. In this study, it was shown that different fertilization methods can affect the SP, SSs, SST, VC, and EN, EP, and EK content of *Lactuca sativa* to different degrees.

Although the total amount of fertilizer remained constant across all fertilization methods, there was a significant increase in SP and SSs in *Lactuca sativa* as the number of applications and the amount of fertilizer applied per application increased. This is mainly due to the fact that EN, EP, and EK in fertilizers are directly related to the synthesis, conversion, and metabolism of some substances in *Lactuca sativa* [38]. Fertilization methods to *Lactuca sativa* all improved the quality of SP, particularly using the AF and EF methods, which provided nutrients in line with the growth requirements of *Lactuca sativa*, resulting in higher SP than the other methods. The results of this study showed that the SS and VC contents were higher in all fertilization methods except the control group (CG), which is due to the fact that timely and appropriate fertilization could promote the uptake of fertilizer by *Lactuca sativa* and transfer a large number of nutrients to the fruits, thus increasing the SS and VC.

The SST is not only one of the main indicators of *Lactuca sativa* quality but also an important measure of its carbon metabolism level [39]. The SST includes SSs, acid, etc. In this study, the SST of *Lactuca sativa* increased with the gradual application of different fertilizers, but the difference in SST among the LF, AF, and EF methods was not significant. This may be due to the fact that all three fertilization methods were three variable applications based on the growth requirements of *Lactuca sativa*, making no significant differences among the three fertilization methods in the quality indicator, SST, of the *Lactuca sativa*.

In this experiment, the effects of the different fertilization methods on VC, EN, and EP of *Lactuca sativa* were more or less the same for the other qualities of *Lactuca sativa*, except for EK. All three quality indicators are better with the exponential fertilization (EF) method than with the other fertilization methods, indicating that the exponential fertilization (EF) method helps the *Lactuca sativa* to grow at each stage by controlling the amount of fertilizer applied at each stage according to the growth characteristics. As EK is involved in protein synthesis in plants, the trend in SP also shows that the EF and AF methods have approximately the same effect on EK and SP in *Lactuca sativa*, followed by linear application of the LF method, which indicated that continuous fertilization during the growing phase of *Lactuca sativa* is better than a single application and that EF fertilization is more optimal than the LF and AF methods.

4.3. Exponential Fertilization (EF) Method Enhances the Chemical Properties of the Soil

Soil provides a constant source of nutrients for plants growth and its chemical properties are constantly changing as crops grow. Plants need to take up the nutrients they need to grow and develop from the soil; therefore, good plant growth and development depends on soil fertility and nutrient levels [40]. In this study, soil fertility was measured before *Lactuca sativa* was planted and compared with soil fertility at the end of planting and harvesting. It was found that the levels of SAN, SAP, SAK, and SOM in the soil after treating with fertilization methods were higher than the initial chemical properties of the soil, indicating that the appropriate fertilization method had a catalytic effect on the levels of SAN, SAP, and SAK.

In terms of SAN variation, the one-time fertilization (OF) method resulted in a lower level of SAN measured after harvest because the fertilizer was applied at once in the pre-growth phase of *Lactuca sativa* and was partially decomposed and absorbed by the *Lactuca sativa* during its growth and partially metabolized by soil micro-organisms [41]. The LF, AF, and EF methods have a higher residual nitrogen than the other fertilization methods because the fertilizer is applied three times [42]. SAN levels were higher in the EF and LF methods than in the AF method because of the higher third fertilizer application. In summary, alkaline nitrogen use was the highest using the EF method than in the other methods.

Different fertilization methods were applied to *Lactuca sativa* as it grew and developed. The OF method was a one-off application of excess fertilizer in the pre-growth phase; the limited absorption and decomposition capacity of the soil and the ability of the plants to absorb nutrients made the excess fertilizer leach out, resulting in slow growth of the *Lactuca sativa* and low levels of SAP in the soil when measured after the *Lactuca sativa* harvest. In contrast, the LF and AF methods, which applied phosphorus fertilizer to the soil in three separate applications, reduced fertilizer wastage but contributed less to the soil phosphorus pool than EF. This is probably because the linear application of the LF method caused fertilizer leaching in the early stages with too much fertilizer, and too little fertilizer in the later stages was not sufficient for plant growth [43]. The AF method applied equal amounts of fertilizer to the *Lactuca sativa* at each stage, which could similarly cause waste due to too much fertilizer in the early stages and impact growth with too little fertilizer in the later stages. In conclusion, the EF method resulted in the best performance in terms of effective soil phosphorus levels within a reasonable range.

The different fertilization methods increase the amount of SAK by increasing the frequency of fertilizer application, as the total amount of fertilizer used is consistent. In this context, the LF, AF, and EF methods significantly increased the SAP within a reasonable range compared to the OF method, which effectively promoted plant growth. The LF and EF methods tended to have similar SAK levels due to a similar fertilization amount. However, the EF method performed slightly better than LF method due to the fact that the EF method was more suitable for the growth pattern of the *Lactuca sativa* and resulted in the best performance of SAK levels.

An appropriate fertilization method can effectively improve SOM content, increase some of the carbon and nitrogen components in the soil that are beneficial for uptake by individual plants, and enhance the effective nutrients in the soil [44]. This study found that the trends in SOM content and other soil indicators were more or less the same for the different fertilization methods, indicating that the LF, AF, and EF methods were all better than the OF and EF methods. Therefore, choosing an appropriate fertilization method that matches the growth pattern of *Lactuca sativa* will optimize soil nutrient enhancement and create a good seedbed environment for the growth of the next crop, under the condition of meeting the reasonable growth of *Lactuca sativa*.

4.4. Optimum Choice of Fertilizer Application

Through relevant experiments, it was observed that the exponential fertilization method promoted the PLH, LL, LW, yield, SS, SP, SST, VC, EN, EP, and EK in *Lactuca sativa*. Furthermore, beneficial changes occurred in the soil structure and soil nutrients after fertilization, with increased levels of SAN, SAP, SAK, and SOM. Table 3 presents the ranking of the effects of different fertilization methods on *Lactuca sativa* and soil-related indicators. By measuring and calculation the indicators of *Lactuca sativa* treated with each fertilization method, it was determined that the optimal fertilization method for *Lactuca sativa* is exponential fertilization. Exponential fertilization had the most favorable comprehensive effects on the basic agronomic traits, yield, quality, and soil chemical properties of *Lactuca sativa*, resulting in the most significant improvements. Therefore, the exponential fertilization method was designated as the best fertilization method for *Lactuca sativa* cultivation in northern greenhouse environments.

Table 3. Ranking of the effects of different fertilization methods on *Lactuca sativa* L. and soil nutrients.

Fertilization Methods	EF	AF	LF	OF	CG
plant height	4	5	3	2	1
leaf length	5	4	3	2	1
leaf width	4	3	5	2	1
leaf number	5	3	4	2	1
SPAD	0	0	0	0	0
yield	4	3	5	2	1
soluble protein content	5	5	3	2	1
soluble sugar	5	3	4	2	1
soluble solids	4	5	3	2	1
vitamin C	5	3	4	2	1
elemental N	5	3	4	2	1
elemental P	5	4	3	2	1
elemental K	5	4	3	2	1
soil alkali-hydrolyzed nitrogen	5	3	4	2	1
soil available phosphorus	5	3	4	2	1
soil available potassium	5	3	4	2	1
soil organic matter	5	3	4	2	1
total	72	57	60	32	16

5. Conclusions

The results of the trial showed that exponential fertilization (EF) was the best fertilizer application method for *Lactuca sativa* compared to the other four fertilizer application methods. Basic agronomic traits, yield, quality, and post-harvest soil nutrient enhancement were most pronounced in *Lactuca sativa* under the exponential fertilization approach. The main reason for the above changes is that the exponential fertilization application can reasonably match the growth characteristics of *Lactuca sativa* and can effectively reduce the pollution of the soil and the environment caused by fertilizer application, which is of great importance for the promotion of soil conservation tillage. In future studies on the nutrient distribution ratio of fertilizers for *Lactuca sativa*, it is recommended that the fertilizer composition of the fertilizers used should be studied in detail. This further improves the agronomic characteristics, yield, and quality of the *Lactuca sativa* and reduces the damage to soil nutrients caused by irrational fertilizer application.

Author Contributions: Conceptualization, L.C. (Limei Chen); methodology, W.L.; software, W.H.; validation, L.Z.; formal analysis, M.Z.; investigation, D.L.; resources, L.C. (Lin Chen); data curation, J.W.; writing—original draft preparation, W.L.; writing—review and editing, W.L. and Y.W.; visualization, L.C. (Limei Chen) and J.Z.; funding acquisition, L.C. (Limei Chen). All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by the Key R&D Project of Jilin Provincial Science and Technology Department (20220202103NC).

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We are very grateful to Wang Hongbin from the School of Resources and Environment, Jilin Agricultural University for providing us with the soil-related experimental apparatus.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Sun, Y.; Hu, R.; Zhang, C. Does the adoption of complex fertilizers contribute to fertilizer overuse? Evidence from rice production in China. *J. Clean. Prod.* **2019**, *219*, 677–685. [CrossRef]
2. Zhan, X.; Shao, C.; He, R.; Shi, R. Evolution and Efficiency Assessment of Pesticide and Fertiliser Inputs to Cultivated Land in China. *Int. J. Environ. Res. Public Health* **2021**, *18*, 3771. [CrossRef] [PubMed]
3. Cui, N.; Cai, M.; Zhang, X.; Abdelhafez, A.A.; Zhou, L.; Sun, H. Runoff loss of nitrogen and phosphorus from a rice paddy field in the east of China: Effects of long-term chemical N fertilizer and organic manure applications. *Glob. Ecol. Conserv.* **2020**, *22*, e01011. [CrossRef]
4. Rombel, A.; Krasucka, P.; Oleszczuk, P. Sustainable biochar-based soil fertilizers and amendments as a new trend in biochar research. *Sci. Total Environ.* **2022**, *816*, 151588. [CrossRef]
5. Zhuang, Y.; Ruan, S.; Zhang, L.; Chen, J.; Li, S.; Wen, W. Effects and potential of optimized fertilization practices for rice production in China. *Agron. Sustain. Dev.* **2022**, *42*, 32. [CrossRef]
6. Wang, J.; Lu, G.; Guo, X.; Wang, Y.; Ding, S.; Wang, D. Conservation tillage and optimized fertilization reduce winter runoff losses of nitrogen and phosphorus from farmland in the Chaohu Lake region, China. *Nutr. Cycl. Agroecosyst.* **2015**, *101*, 93–106. [CrossRef]
7. Martinez, S.; Sanchez-Moreno, S.; Gabriel, J.L.; Alvarez, C.; Delgado, M.d.M. Valorization of a Bio-Stabilized Municipal Solid Waste Amendment for Faba Bean (*Vicia faba* L.) Fertilization. *Agriculture* **2021**, *11*, 1109. [CrossRef]
8. Tedeschi, A.; Volpe, M.G.; Polimeno, F.; Siano, F.; Maglione, G.; Di Tommasi, P. Soil Fertilization with Urea Has Little Effect on Seed Quality but Reduces Soil N_2O Emissions from a Hemp Cultivation. *Agriculture* **2020**, *10*, 240. [CrossRef]
9. Martinez, S.; Luis Gabriel, J.; Allende-Montalban, R.; San-Juan-Heras, R.; del Mar Delgado, M. The Application of a Bio-Stabilized Municipal Solid Waste-Based Fertilizer for Buckwheat Production. *Agriculture* **2022**, *12*, 776. [CrossRef]
10. Wang, R.; Wang, Y.; Zhang, Z.; Pan, H.; Lan, L.; Huang, R. Effects of Exponential N Application on Soil Exchangeable Base Cations and the Growth and Nutrient Contents of Clonal Chinese Fir Seedlings. *Plants* **2023**, *12*, 851. [CrossRef]
11. Li, G.; Wang, J.; Oliet, J.A.; Jacobs, D.F. Combined pre-hardening and fall fertilization facilitates N storage and field performance of Pinus tabulaeformis seedlings. *Iforest-Biogeosciences For.* **2016**, *9*, 483–489. [CrossRef]
12. Wu, J.; Tong, G.; Guo, R.; Ye, Z.; Jin, J.; Lin, H. N-Exponential Fertilization Could Affect the Growth and Nitrogen Accumulation of Metasequoia glyptostroboides Seedling in a Greenhouse Environment. *Phyton-Int. J. Exp. Bot.* **2022**, *91*, 2211–2220. [CrossRef]
13. Ni, M.; Gao, Z.; Chen, H.; Chen, C.; Yu, F. Exponential Fertilization Regimes Improved Growth and Nutrient Status of *Quercus nuttallii* Container Seedlings. *Agronomy* **2022**, *12*, 669. [CrossRef]
14. Wang, X.; Hu, Y.; Liaquat, F.; Zhang, X.; Ye, K.; Qin, J. Effects of Nitrogen Exponential Fertilization on Growth and Nutrient Concentration of Hydrangea macrophylla Seedlings. *Phyton-Int. J. Exp. Bot.* **2022**, *91*, 395–407. [CrossRef]
15. Schulz, D.G.; Ajala, M.C.; Horbach, M.A.; Malavasi, U.C.; Malavasi, M.d.M. Exponential Nitrogen Fertilization of Luehea divaricata Mart. Seedlings. *Floresta E Ambiente* **2021**, *28*, e20180426. [CrossRef]
16. Li, S.Y.; Wilson, M.A.; Sun, X.Y. Evaluation of Exponential Fertilization Technique for Cultivation of Turfgrass during Early Growth Period. *Commun. Soil Sci. Plant Anal.* **2012**, *43*, 716–729. [CrossRef]
17. Sun, Y.D.; Luo, W.R.; Liu, H.C. Effects of different nitrogen forms on the nutritional quality and physiological characteristics of Chinese chive seedlings. *Plant Soil Environ.* **2014**, *60*, 216–220. [CrossRef]
18. Wang, L.; Zhang, S.; Li, J.; Zhang, Y.; Zhou, D.; Li, C. Identification of key genes controlling soluble sugar and glucosinolate biosynthesis in Chinese cabbage by integrating metabolome and genome-wide transcriptome analysis. *Front. Plant Sci.* **2022**, *13*, 1043489. [CrossRef]
19. Zhang, G.; Fu, Q.; Fu, Z.; Li, X.; Matetic, M.; Bakaric, M.B. A Comprehensive Peach Fruit Quality Evaluation Method for Grading and Consumption. *Appl. Sci.* **2020**, *10*, 1348. [CrossRef]
20. Fenech, M.; Amaya, I.; Valpuesta, V.; Botella, M.A. Vitamin C Content in Fruits: Biosynthesis and Regulation. *Front. Plant Sci.* **2019**, *9*, 2006. [CrossRef]
21. Cairo-Cairo, P.; Diaz-Martin, B.; Rodriguez-Urrutia, A. Soil quality indicators in Vertisols under sugarcane. *Arch. Agron. Soil Sci.* **2017**, *63*, 1477–1488. [CrossRef]
22. Kolchanova, K.; Tolpeshta, I.; Izosimova, Y. Adsorption of Fulvic Acid and Water Extractable Soil Organic Matter on Kaolinite and Muscovite. *Agronomy* **2021**, *11*, 2420. [CrossRef]
23. Wan, L.-J.; Tian, Y.; He, M.; Zheng, Y.-Q.; Lyu, Q.; Xie, R.-J. Effects of Chemical Fertilizer Combined with Organic Fertilizer Application on Soil Properties, Citrus Growth Physiology, and Yield. *Agriculture* **2021**, *11*, 1207. [CrossRef]
24. Ortega-Blu, R.; Mercedes Martinez-Salgado, M.; Ospina, P.; Maria Garcia-Diaz, A.; Fincheira, P. Nitrate Concentration in Leafy Vegetables from the Central Zone of Chile: Sources and Environmental Factors. *J. Soil Sci. Plant Nutr.* **2020**, *20*, 964–972. [CrossRef]

25. Silva, L.M.; Cruz, L.P.; Pacheco, V.S.; Machado, E.C.; Purquerio, L.F.V.; Ribeiro, R.V. Energetic efficiency of biomass production is affected by photoperiod in indoor lettuce cultivation. *Theor. Exp. Plant Physiol.* **2022**, *34*, 265–276. [CrossRef]
26. Yang, H.-x.; Bu, H.-y.; Ge, W.-j.; Wang, X.-j.; Xu, D.-h.; Xia, Y.-b. Influence of altitude on main seed reserves of common species in alpine meadow on the northeastern Tsinghai-Tibet Plateau. *Shengtaixue Zazhi* **2016**, *35*, 2299–2312.
27. Bieniasz, M.; Dziedzic, E.; Kaczmarczyk, E. The effect of storage and processing on vitamin C content in Japanese quince fruit. *Folia Hortic.* **2017**, *29*, 83–93. [CrossRef]
28. Turfan, N.; Ayan, S.; Celik, E.N.Y.; Ozel, H.B.; Onat, S.M. Age-related Changes of Some Chemical Components in the Leaves of Sweet Chestnut (*Castanea sativa* Mill.). *Bioresources.* **2020**, *15*, 4337–4352. [CrossRef]
29. Fang, L.; Wei, K.; Feng, L.; Tu, K.; Peng, J.; Wang, J. Optical Absorption and Scattering Properties at 900–1650 nm and Their Relationships with Soluble Solid Content and Soluble Sugars in Apple Flesh during Storage. *Foods* **2020**, *9*, 1881. [CrossRef]
30. Masithoh, R.E.; Haff, R.; Kawano, S. Determination of soluble solids content and titratable acidity of intact fruit and juice of satsuma mandarin using a hand-held near infrared instrument in transmittance mode. *J. Near Infrared Spectrosc.* **2016**, *24*, 83–88. [CrossRef]
31. Roell, G.; Hartung, J.; Graeff-Hoenninger, S. Determination of Plant Nitrogen Content in Wheat Plants via Spectral Reflectance Measurements: Impact of Leaf Number and Leaf Position. *Remote Sens.* **2019**, *11*, 2794. [CrossRef]
32. Gliszczynska-Swiglo, A.; Rybicka, I. Fast and sensitive method for phosphorus determination in dairy products. *J. Consum. Prot. Food Saf.* **2021**, *16*, 213–218. [CrossRef]
33. Brodowska, M.S.; Kurzyna-Szklarek, M. Evaluation of phosphorus and potassium content in plant organs as a result of different fertilizer ratios. *J. Elem.* **2019**, *24*, 1229–1240.
34. Zhao, J.; Huang, R.; Yang, K.; Ma, C.; Zhang, Q. Effects of Nitrogen and Phosphorus Fertilization on Photosynthetic Properties of Leaves and Agronomic Characters of Alfalfa over Three Consecutive Years. *Agriculture* **2022**, *12*, 1187. [CrossRef]
35. Zhao, H.; Li, X.; Jiang, Y. Response of Nitrogen Losses to Excessive Nitrogen Fertilizer Application in Intensive Greenhouse Vegetable Production. *Sustainability.* **2019**, *11*, 1513. [CrossRef]
36. Rudack, K.; Seddig, S.; Sprenger, H.; Koehl, K.; Uptmoor, R.; Ordon, F. Drought stress-induced changes in starch yield and physiological traits in potato. *J. Agron. Crop Sci.* **2017**, *203*, 494–505. [CrossRef]
37. Oh, T.-S.; Kim, S.-M.; Kim, C.-H. The Effect of Organic Fertilizer According to the Duration and Amount of Soil Chemical Changes on Yield Components of Rice. *Korean J. Crop Sci.* **2014**, *59*, 209–215. [CrossRef]
38. Lyu, Y.; Porat, R.; Yermiyahu, U.; Heler, Y.; Holland, D.; Dag, A. Effects of nitrogen fertilization on pomegranate fruit, aril and juice quality. *J. Sci. Food Agric.* **2020**, *100*, 1678–1686. [CrossRef]
39. Wang, R.; Shi, X.-G.; Wei, Y.-Z.; Yang, X.-E.; Uoti, J. Yield and quality responses of citrus (*Citrus reticulate*) and tea (*Podocarpus fleuryi* Hickel.) to compound fertilizers. *J. Zhejiang Univ. Sci. B* **2006**, *7*, 696–701. [CrossRef]
40. Hagemann, N.; Joseph, S.; Schmidt, H.-P.; Kammann, C.I.; Harter, J.; Borch, T. Organic coating on biochar explains its nutrient retention and stimulation of soil fertility. *Nat. Commun.* **2017**, *8*, 1089. [CrossRef]
41. Hei, Z.; Xiang, H.; Zhang, J.; Liang, K.; Zhong, J.; Li, M. Intercropping of Rice and Water Mimosa (*Neptunia oleracea* Lour.): A Novel Model to Control Pests and Diseases and Improve Yield and Grain Quality while Reducing N Fertilizer Application. *Agriculture* **2022**, *12*, 13. [CrossRef]
42. Chen, B.; Yang, H.; Song, W.; Liu, C.; Xu, J.; Zhao, W. Effect of N fertilization rate on soil alkali-hydrolyzable N, subtending leaf N concentration, fiber yield, and quality of cotton. *Crop J.* **2016**, *4*, 323–330. [CrossRef]
43. Pereira, N.S.; Alves, A.R., Jr.; Celedonio, W.F.; Rodrigues, E.A.; Chaves, S.W.P.; Medeiros, J.F. Phosphate fertilization influences macronutrient accumulation in watermelon cv Magnum. *Hortic. Bras.* **2018**, *36*, 346–352. [CrossRef]
44. Song, W.; Shu, A.; Liu, J.; Shi, W.; Li, M.; Zhang, W. Effects of long-term fertilization with different substitution ratios of organic fertilizer on paddy soil. *Pedosphere* **2022**, *32*, 637–648. [CrossRef]