agriculture

MDPI

Article

Adaptation Strategies for Hemp in Alkaline Salt Environments: Fertilizer Management for Nutrient Uptake and Optimizing Growth

Yunshu Ye, Haoyu Wang, Panpan Zhang and Yuhong Zhang *

Key Laboratory of Forest Plant Ecology of Ministry of Education, Northeast Forestry University, Harbin 150040, China; 18445171189@163.com (Y.Y.); www763400876@163.com (H.W.); zhangpanpan0610@163.com (P.Z.)
* Correspondence: pzhangyh@nefu.edu.cn

Abstract: Global soil salinization has become an increasingly severe challenge for agricultural production, particularly affecting the cultivation of economic crops in marginal lands. Industrial hemp (*Cannabis sativa* L.), despite its economic potential, exhibits a notable sensitivity to salt-alkaline stress, limiting its expansion in saline-alkali regions. This study investigated the regulatory effects of nitrogen (N), phosphorus (P), and potassium (K) fertilizers on hemp growth and nutrient homeostasis under alkaline salt stress. Using a "3414" orthogonal experimental design, we evaluated fourteen NPK combinations under 200 mM $NaHCO_3$ stress, a concentration determined through preliminary experiments to simulate moderate alkaline stress. Plant growth parameters, biomass partitioning, and mineral nutrient profiles were analyzed after treatment with three biological replicates. The N1P2K2 treatment (N 120 mg·L^{-1}, P 238 mg·L^{-1}, K 348 mg·L^{-1}) significantly enhanced plant performance, increasing shoot biomass by 45.3% and root biomass by 38.7% compared to the control. This optimal combination maintains the K^+/Na^+ ratio in leaves above 1.2 and regulated Ca^{2+}/Mg^{2+} homeostasis, maintaining a ratio of 2.8–3.2, indicating improved salt tolerance. Notably, excessive fertilizer applications (>400 mg·L^{-1} total nutrients) exacerbated salt injury, reducing biomass accumulation by 25–30% and disrupting ion homeostasis. Our findings reveal the critical thresholds for NPK application in hemp under alkaline stress and provide practical fertilization strategies for sustainable hemp cultivation in saline-alkali regions.

Keywords: *Cannabis sativa* L.; $NaHCO_3$ stress; NPK fertilization; nutrient distribution

Academic Editor: Guisheng Zhou

Received: 15 December 2024
Revised: 3 January 2025
Accepted: 6 January 2025
Published: 8 January 2025

Citation: Ye, Y.; Wang, H.; Zhang, P.; Zhang, Y. Adaptation Strategies for Hemp in Alkaline Salt Environments: Fertilizer Management for Nutrient Uptake and Optimizing Growth. *Agriculture* **2025**, *15*, 125. https://doi.org/10.3390/agriculture15020125

1. Introduction

On a global scale, soil salinization is an increasingly severe problem, with the latest estimates suggesting that approximately 950 million hectares of land have been severely affected. This land degradation phenomenon is not only the result of natural environmental changes but is also a direct consequence of inappropriate human agricultural practices. In particular, inappropriate tillage methods and excessive fertilization strategies in modern agriculture have not only exacerbated the development of existing soil salinization but have also triggered large-scale secondary salinization where originally non-saline land gradually becomes saline soils due to human activities. This vicious circle not only leads to a significant reduction in land use efficiency but also seriously affects the healthy growth and production quality of crops, thereby threatening global crop health security and the long-term sustainability of agricultural ecosystems [1–3]. Hemp (*Cannabis sativa* L.) is

widely cultivated worldwide as an important economic crop with multiple uses for its fiber, oil, and medicinal compounds [4,5]. However, due to its sensitivity to saline-alkali environments, it faces major challenges for promotion and cultivation in these areas [6]. Therefore, there is an urgent need to develop effective management strategies to improve the growth and production performance of hemp under saline-alkali conditions.

In recent years, with the increasing impact of climate change and land degradation, researchers have increasingly focused on the growth mechanisms and coping strategies of plants under adverse conditions. Saline-alkali stress has multiple effects on plant growth, including the reduction of photosynthetic efficiency, impairment of nutrient uptake, disruption of intracellular ion homeostasis, hormonal imbalance, restriction of root growth, and reduction of antioxidant defense system functions. The combined effects of these factors have a profound impact on plant growth [7,8]. To address these challenges, fertilization management, as an effective measure to improve soil and plant nutritional status, has been extensively studied and applied in various crops, such as potato (*Solanum tuberosum*), sorghum (*Sorghum bicolor*) and tomato (*Solanum lycopersicum*) [9–11].

In particular, the application of the three main elements, namely nitrogen (N), phosphorus (P), and potassium (K), has been shown to significantly improve the chemical properties of saline-alkali soils and increase the adaptability of plants to adverse conditions [12]. For example, N fertilizers mainly promote plant growth and leaf formation because N is a key element in the composition of proteins, nucleic acids, and other life molecules and is particularly important for stem and leaf growth [13]. P fertilizers mainly affect root development and the formation of flowers and fruits because P plays an important role in energy conversion processes (such as the formation and use of ATP) and cell division, thus helping in plant root development and energy storage [14]. K fertilizers play an important role in regulating the water balance of plants and improving plant resistance to disease. They also ensure the stability of photosynthesis and nutrient transport. K can help plants better regulate stomatal opening and closing, thereby influencing plant water use efficiency and photosynthesis [15–17]. At the same time, there are also certain interactions and dependencies between them. For example, an adequate supply of N can promote the synthesis of more chlorophyll, thereby improving photosynthesis, while improved photosynthesis requires sufficient K to maintain correspondingly high-efficiency water and nutrient transport. Meanwhile, an adequate supply of P is also essential to ensure a sufficient energy supply to support all plant growth activities, including N and K utilization processes [18,19]. Therefore, the optimal proportions and application rates of these nutrients under specific adverse conditions, especially for a specialty crop such as hemp, merit further research.

Despite these known benefits, the interactions of N, P, and K fertilizers on hemp under alkaline stress remain poorly understood. Previous studies have primarily focused on single nutrient responses or binary interactions [9,10,20,21], but several key questions remain unanswered: (1) What is the optimal N, P, and K ratio for hemp growth under specific alkaline stress conditions? (2) How do different N, P, and K combinations affect nutrient allocation and ion homeostasis? (3) Above what threshold concentration does fertilization become detrimental?

This study employed the "3414" experimental design method to systematically evaluate the effects of different N, P, and K fertilizer combinations on hemp growth, biomass, nutrient distribution, and ion homeostasis under alkaline salt stress conditions. The "3414" experimental design, as a three-factor, four-level incomplete orthogonal regression design method, has the advantages of comprehensive factors, flexible levels, simple operation, and efficient analysis and is widely used in agricultural experiments [22,23]. Using this method, this study can evaluate the main effects of three fertilization factors at four levels with fewer

treatment combinations, meeting the professional requirements for fertilizer management decision-making and providing strong experimental method support for in-depth analysis of the regulatory mechanism of fertilization on dry biomass and nutrient accumulation and distribution, and revealing the relationship between biomass and nutrients. These findings not only fill the gap in hemp fertilization research under alkaline salt stress conditions but also provide an important theoretical basis and practical guidance for sustainable and stress-resistant cultivation of hemp on marginal lands.

2. Materials and Methods

2.1. Plant Materials and Growth Conditions

This study used the industrial hemp cultivar "Hemp No. 5" (provided by the Heilongjiang Academy of Agricultural Sciences). Seeds were surface-sterilized with 75% (*v*/*v*) ethanol for 30 s, followed by 10% sodium hypochlorite for 10 min, and then thoroughly rinsed five times with sterile distilled water. The sterilized seeds were germinated in a substrate composed of soil, vermiculite, and perlite (3:1:1, *v*/*v*/*v*), which was autoclaved at 121 °C for 20 min. The substrate had the following characteristics: pH of 6.5 ± 0.2, electrical conductivity (EC) of 0.8 ± 0.1 dS·m^{-1} (measured in a 1:5 soil-water suspension using a portable conductivity meter, model DDS-307A, Shanghai Precision Scientific Instrument Co., Ltd., Shanghai, China). Seven days after germination, when the cotyledons were fully expanded, uniform seedlings were transplanted into plastic pots (16 cm diameter × 17 cm height) containing a sterilized mixture of soil and vermiculite (3:1, *v*/*v*). Each pot had drainage holes at the bottom to prevent waterlogging. The soil properties were as follows: pH 7.2 (measured in a 1:25 soil-water suspension using a pH meter, model PHS-3C, Shanghai Precision Scientific Instrument Co., Ltd., Shanghai, China), electrical conductivity (EC) 0.5 dS·m^{-1}, organic matter 15.3 g·kg^{-1} (determined by the potassium dichromate volumetric method) [24], total nitrogen 0.82 g·kg^{-1} (determined via the Kjeldahl method), available phosphorus 15.6 mg·kg^{-1}, and available potassium 125 mg·kg^{-1} (P and K contents were determined using inductively coupled plasma mass spectrometry (ICP-MS 7850, Agilent Technologies, Santa Clara, CA, USA). After thinning at the two-leaf stage, two seedlings per pot were maintained.

The pot experiment was conducted in a greenhouse at Northeast Forestry University under the following seedling culture conditions: day/night temperatures of 25/20 ± 1 °C, relative humidity of 60 ± 5%, a photoperiod of 16 h, and a light intensity that gradually increased from 200 µmol·m^{-2}·s^{-1} to 800 µmol·m^{-2}·s^{-1} during the first 2 h of the photoperiod and gradually decreased during the last 2 h. Soil moisture was managed by weighing the pots (depth: 17 cm) and adding water to maintain an average volumetric water content (VWC) of 70–80% throughout the entire soil volume."

2.2. Alkaline Stress Treatment

Based on preliminary experiments evaluating the physiological responses to $NaHCO_3$ concentrations (0, 50, 100, 200, and 300 mM), 200 mM was selected as the optimal stress level [25,26]. At this concentration, leaf malondialdehyde (MDA) levels increased significantly [27], being 85% higher than the control group, while plant survival remained above 90%. Alkaline stress treatment was applied to 25-day-old, uniformly growing seedlings (at 25 days, the plants have passed the early seedling stage, with growth stabilizing and plant size becoming suitable for stress treatment and cultivation in pots). $NaHCO_3$ solution (200 mM, pH 8.7 ± 0.1, EC 21.3 ± 0.2 dS·m^{-1}) was applied every 4 days at 250 mL per application for a total of six applications. The solution was applied in the morning (8:00–9:00 A.M.) to avoid potential heat stress interactions. The EC of the leachate was monitored after each application to ensure consistent stress levels.

After the stress treatment, based on the optimal nitrogen (N), phosphorus (P), and potassium (K) element concentrations for hemp growth obtained from previous experiments, a modified Hoagland nutrient solution [28,29] containing 0.24 $g \cdot L^{-1}$ N, 0.238 $g \cdot L^{-1}$ P, and 0.348 $g \cdot L^{-1}$ K was prepared, and different N, P, and K ratio treatments (Table 1) were set up using the "3414" orthogonal experimental design. The experiment included three factors (N, P, and K), each with four levels: 0 (no fertilization), 1 (50% of the optimal fertilization level), 2 (optimal fertilization level), and 3 (150% of the optimal fertilization level). The optimal fertilization level was defined as the N, P, and K fertilization level that maximized the plant biomass in the pre-experiment and served as the basis for determining the different fertilization levels in the main experiment. Among these 14 treatments groups, treatments T2, T3, T6, and T11 represented the four fertilization levels of N; T4, T5, T6, and T7 represented the four fertilization levels of P; and T8, T9, T6, and T10 represented the four fertilization levels of K. The concentrations of N, P, and K were controlled by adjusting the amounts of NH_4NO_3, NaH_2PO_4, and K_2SO_4 in the nutrient solution (other components of the nutrient solution are shown in Table 2). Each treatment had three replicates, for a total of 42 pots. The nutrient solution was changed every 3 days for a total of seven treatments (21 days). Growth and physiological indicators were measured at the end of the treatment.

Table 1. The "3414" fertilization experiment rates.

No.	Treatment	N ($g \cdot L^{-1}$)	P ($g \cdot L^{-1}$)	K ($g \cdot L^{-1}$)
T1	N0P0K0	0 (0)	0 (0)	0 (0)
T2	N0P2K2	0 (0)	2 (0.238)	2 (0.348)
T3	N1P2K2	1 (0.120)	2 (0.238)	2 (0.348)
T4	N2P0K2	2 (0.240)	0 (0)	2 (0.348)
T5	N2P1K2	2 (0.240)	1 (0.119)	2 (0.348)
T6	N2P2K2	2 (0.240)	2 (0.238)	2 (0.348)
T7	N2P3K2	2 (0.240)	3 (0.357)	2 (0.348)
T8	N2P2K0	2 (0.240)	2 (0.238)	0 (0)
T9	N2P2K1	2 (0.240)	2 (0.238)	1 (0.174)
T10	N2P2K3	2 (0.240)	2 (0.238)	3 (0.522)
T11	N3P2K2	3 (0.360)	2 (0.238)	2 (0.348)
T12	N1P1K2	1 (0.120)	1 (0.119)	2 (0.348)
T13	N1P2K1	1 (0.120)	2 (0.238)	1 (0.174)
T14	N2P1K1	2 (0.240)	1 (0.119)	1 (0.174)

Treatment numbers represent no (0), low (1 = 2 × 0.5), medium (2), and high (3 = 2 × 1.5) levels of fertilization, respectively (values in parentheses represent a specific amount of fertilization).

Table 2. Formulation of elements in nutrient solutions.

Element Type	Reagent Formula	Concentration ($mmol \cdot L^{-1}$)
Macroelement	$MgSO_4 \cdot 7H_2O$	406
	$CaCl_2$	424
Microelement	H_3BO_3	0.05
	$MnSO_4 \cdot H_2O$	0.01
	$Na_2MoO_4 \cdot 2H_2O$	0.001
	$CuSO_4 \cdot 5H_2O$	0.001
	$ZnSO_4 \cdot 7H_2O$	0.001
Molysite	$FeSO_4 \cdot 7H_2O$	0.05
	EDTA-2Na·$2H_2O$	0.05

The entire experiment was conducted from May to September 2023, with three independent biological replicates performed at 15-day intervals. Each replicate followed the same seed sterilization, germination, and stress treatment scheme. Environmental

conditions were continuously monitored using an automatic climate control system and maintained consistently across replicates.

2.3. Growth Parameters and Biomass Analysis

Plant height was measured from the soil surface to the apical growing point using a measuring tape, while stem diameter was determined at 5 cm above the soil surface using digital calipers (CD-15CP, Mitutoyo, Kawasaki, KAN, Japan). The maximum root length was measured after carefully washing the root systems free of substrate. For biomass determination, plants were separated into roots, stems, and leaves. Root systems were gently washed with deionized water to remove substrate particles, briefly blotted with paper towels, and their fresh weights were recorded. All plant parts were then oven-dried at 70 °C for several hours until constant weight was achieved (±0.01 g variation between two consecutive measurements at 12 h intervals). Dry weights were determined using an analytical balance (BSA124S-CW, Sartorius, Göttingen, Germany). Root/crown ratio = underground dry biomass mass/seedling aboveground dry biomass mass × 100%.

2.4. Mineral Nutrient Analysis

Dried plant samples were ground to a fine powder using a mortar and passed through a 0.25 mm sieve. Total nitrogen content was determined using an automatic Kjeldahl analyzer (KDN-19K, Shanghai Xianqian Instrument Co., Ltd., Shanghai, China) following acid digestion. For each sample, 0.2 g of dried material was digested with a mixture of H_2SO_4 and H_2O_2 at 260 °C.

For other mineral elements, samples (0.1 g) were digested in a mixture of ultra-pure HNO_3 and H_2O_2 (4:1, v/v) using a graphite digester (YXGD-I-36, Yunxiang (Tianjin) Instruments Ltd., Tianjin, China). The digestion program was set as follows: ramp up to 180 °C over 15 min, then hold at 180 °C for 180 min. The concentrations of Na^+, K^+, Ca^{2+}, Mg^{2+}, and P were analyzed using inductively coupled plasma mass spectrometry (ICP-MS 7850, Agilent Technologies, Santa Clara, CA, USA). Quality control was performed using a certified reference material (GBW10015, GSB-6, National Institute of Metrology, Beijing, China) analyzed alongside the samples. The recovery rates for all elements ranged from 95% to 105%.

2.5. Statistical Analysis

All data are presented as the mean ± standard deviation (SD) of three independent biological replicates. Prior to analysis, data were tested for homogeneity of variance using Levene's test. One-way analysis of variance (ANOVA) was performed using SPSS software (version 26.0, IBM, Armonk, NY, USA). When ANOVA showed significant differences, means were compared using Duncan's multiple range test at $p < 0.05$. The results of the homogeneity of variance test and significance analysis are presented in Tables S1 and S2, respectively, in the Supplementary Materials. For the analysis of the orthogonal experimental design, the range analysis method (Range Analysis) was used to determine the effect of different factor levels on the response variable. This method was used to identify the optimal combination of factors and their influence order. The range analysis calculations were performed using Excel 2021 (Microsoft, Redmond, WA, USA). By comparing the range values of each factor level (i.e., the difference between the maximum and minimum mean values at each level), the significance of the factors was quantitatively assessed [30,31]. Figures were generated using Origin Pro 2022 (OriginLab Corporation, Northampton, MA, USA).

3. Results

3.1. Effects of NPK on the Growth of Hemp Under $NaHCO_3$ Stress

3.1.1. Effects of Different NPK Combinations on Growth Indicators and Biomass of Hemp Under $NaHCO_3$ Stress

The interaction of N, P, and K significantly affected the growth and biomass allocation of hemp under $NaHCO_3$ stress (Table 3, Figure 1A). Among all treatments, N1P2K2 (3#) increased plant height, stem diameter, and root length by 22.40%, 18.67%, and 33.25%, respectively, compared to the control (1#, N0P0K0), reaching the optimum levels. The N2P0K2 treatment (4#) resulted in the highest number of effective leaves, which increased by 48.28% compared to the control. The 3# treatment increased root, leaf, and total plant dry weight by 1.53%, 190.20%, and 177.79%, respectively. This treatment gave the best performance in terms of biomass.

Table 3. Growth parameters of N, P, and K and their interactions on growth and development of hemp under $NaHCO_3$ stress.

Treatment	Plant Height (cm)	Stem Diameter (mm)	Root Length (cm)	Number of Effective Leaves
1#N0P0K0	45.07 ± 2.67 cde	6.3 ± 0.02 fg	24.89 ± 0.38 de	9.67 ± 0.67 ef
2#N0P2K2	47.53 ± 3.84 bc	6.19 ± 0.04 gh	26.11 ± 0.84 cde	11.67 ± 0.33 cd
3#N1P2K2	55.17 ± 0.58 a	7.48 ± 0.04 a	33.17 ± 1.73 a	13.67 ± 0.33 ab
4#N2P0K2	51.53 ± 1.2 ab	6.29 ± 0.01 g	21.04 ± 0.87 fg	14.33 ± 0.67 a
5#N2P1K2	54.1 ± 0.45 a	7.23 ± 0.02 b	28.91 ± 0.13 b	13 ± 0.58 abc
6#N2P2K2	51.83 ± 0.86 ab	6.81 ± 0.03 cd	28.68 ± 0.44 bc	12.33 ± 0.33 bcd
7#N2P3K2	46.37 ± 1.47 cd	6.06 ± 0.04 hi	20.86 ± 0.31 fgh	11 ± 0.58 de
8#N2P2K0	45.83 ± 0.94 cde	6.48 ± 0.07 e	27.25 ± 0.39 bcd	9.67 ± 0.33 ef
9#N2P2K1	39.23 ± 0.55 f	6.43 ± 0.09 ef	25.1 ± 0.81 de	11 ± 0.58 de
10#N2P2K3	33.17 ± 0.67 g	6.45 ± 0.07 e	25.09 ± 1.93 de	11.67 ± 0.88 cd
11#N3P2K2	41.17 ± 0.98 ef	6.18 ± 0.02 gh	23.48 ± 0.66 ef	13 ± 0.58 abc
12#N1P1K2	42.17 ± 0.58 def	6.92 ± 0.02 c	19.42 ± 0.57 gh	9 ± 0.58 f
13#N1P2K1	45.33 ± 1.82 cde	6.76 ± 0.03 e	18.25 ± 0.61 h	10.67 ± 0.33 def
14#N2P1K1	49.13 ± 0.55 bc	6.03 ± 0.03 i	20.25 ± 0.05 gh	11 ± 0.58 de

Note: The values in each column represent Mean ± SD (standard deviation). Different lowercase letters indicate significant differences between treatments at $p < 0.05$.

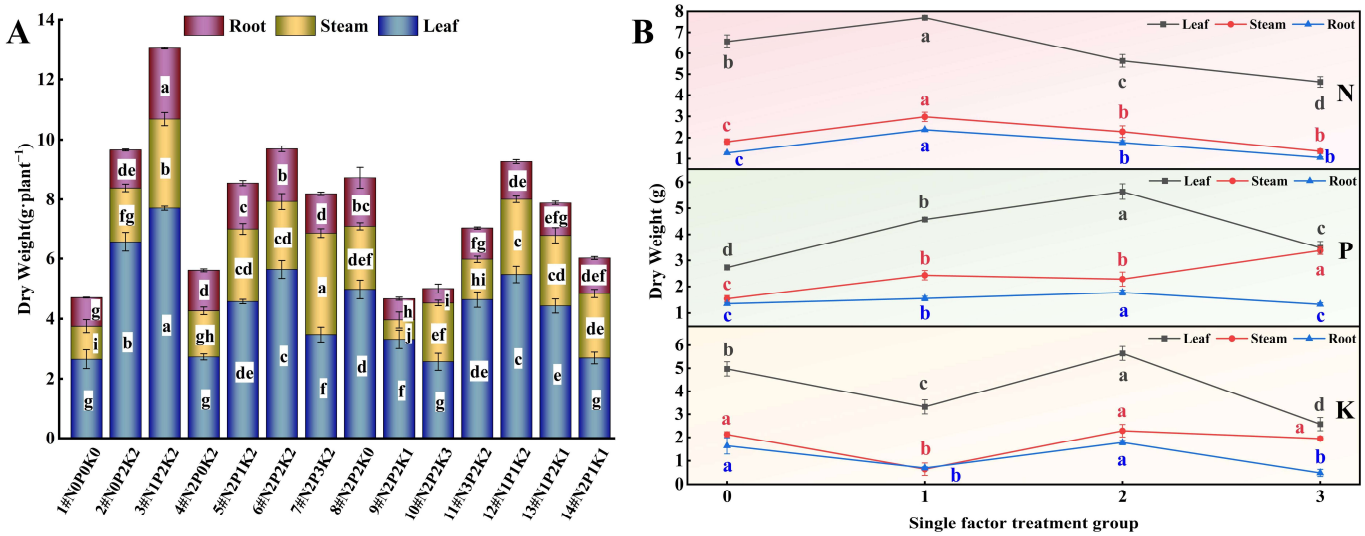

Figure 1. Effects of nitrogen (N), phosphorus (P), and potassium (K) on hemp biomass under $NaHCO_3$ stress. (**A**) Fourteen sets of NPK ratios (#1–#14); (**B**) The single factor of N, P, and K fertilizer. Different lowercase letters indicate significant differences between treatments for the same plant organ at $p < 0.05$.

In the single-factor N experiment (Table 3, Figure 1B), plant height, stem diameter, root length, and root, stem, and total plant dry weight showed a quadratic response, first increasing and then decreasing with increasing N application (N1 > N2 > N0 > N3). The number and dry weight of leaves were highest in the N1 treatment, followed by N3, N2, and N0. The N1 level (120 mg·L^{-1}) increased various growth parameters by 16.06–86.13% compared to the no-N control (2#N0P2K2), while excessive N application (N3, 360 mg ·L^{-1}) led to a decrease of 0.11–13.39%.

P treatments induced different responses in different plant organs (Table 3, Figure 1B). With increasing P application, plant height, stem diameter, and root length showed a trend of first increasing and then decreasing (P1 > P2 > P0 > P3), while the number of effective leaves decreased continuously (P0 > P1 > P2 > P3). The P1 treatment (119 mg·L^{-1}) increased plant height, stem diameter, and root length by 4.98%, 14.94%, and 37.42%, respectively, compared to the no-P control (4#), while the P3 treatment (522 mg·L^{-1}) decreased them by 10.03%, 3.66%, and 0.84%, respectively. Root dry weight was highest in the P2 treatment, followed by P1, P0, and P3. Leaf and total dry weight were highest in the P2 treatment, followed by P1, P3, and P0. Stem dry weight increased with increasing P concentration (P3 > P2 > P1 > P0).

The single-factor K experiment showed (Table 3, Figure 1B) that with increasing K application, plant height, root length, and root and leaf dry weight showed a trend of first increasing and then decreasing (K2 > K0 > K1 > K3). Stem diameter, stem dry weight, and total dry weight were highest in the K2 treatment, followed by K0, K3, and K1. The K2 treatment (348 mg·L^{-1}) increased various growth parameters by 5.04–13.48% compared to the no-K control (8#N2P2K0), reaching the optimum levels, while excessive K application (K3, 522 mg·L^{-1}) inhibited growth.

Furthermore, the nutrient treatments significantly altered the root-crown ratio, with the N1 treatment resulting in the highest root-crown ratio, which is crucial for nutrient acquisition under stress. With the exception of T1, all treatments significantly increased organ and total dry biomass, indicating that balanced fertilization is key to alleviating alkaline stress.

3.1.2. Range Analysis of the Effect of NPK Fertilization on Growth Indicators of Hemp Under $NaHCO_3$ Stress

The extreme difference analysis method was used to analyze the effects of different fertilization methods on the growth indicators of hemp under alkali salt stress (Table 4). The results showed that N had the greatest impact on stem thickness, P had the greatest impact on the dry weight of the aboveground part, and K had the greatest impact on leaf plant height, root length, number of leaves, dry weight of the underground part, and total plant dry weight.

Table 4. Range analysis of the effect of NPK fertilization on growth indicators of hemp under $NaHCO_3$ stress.

Growth Indicators	Range Value			Fertilizer Effect Ordination
	N	P	K	
Plant height	6.3889	3.5583	15.5667	K > N > P
Stem diameter	0.8689	0.6678	0.2533	N > P > K
Root length	2.0267	5.0283	4.8733	K > N > P
Number of leaves	2.3333	1.000	2.5833	K > N > P
Whole plant biomass	3.0300	3.0575	3.8792	K > N > P
Aboveground biomass	2.6800	2.9038	2.8688	P > K > N
Underground biomass	0.5233	0.1939	0.0104	K > P > N

3.2. Effects of N, P, and K Application on the Ionic Content of Hemp Under $NaHCO_3$ Stress

3.2.1. Na^+

Under the interaction of N, P, and K (Figure 2A), there were significant differences in the Na^+ content in the roots, stems, and leaves of alkali-stressed hemp among the 14 fertilization treatments. The root Na^+ content was lowest under the N2P2K3 treatment (10#), which was 82.86% lower than the blank control (1#, N0P0K0). The stem and leaf Na^+ content were lowest under the N2P2K2 treatment (6#), which were 66.34% and 68.19% lower than the blank control, respectively.

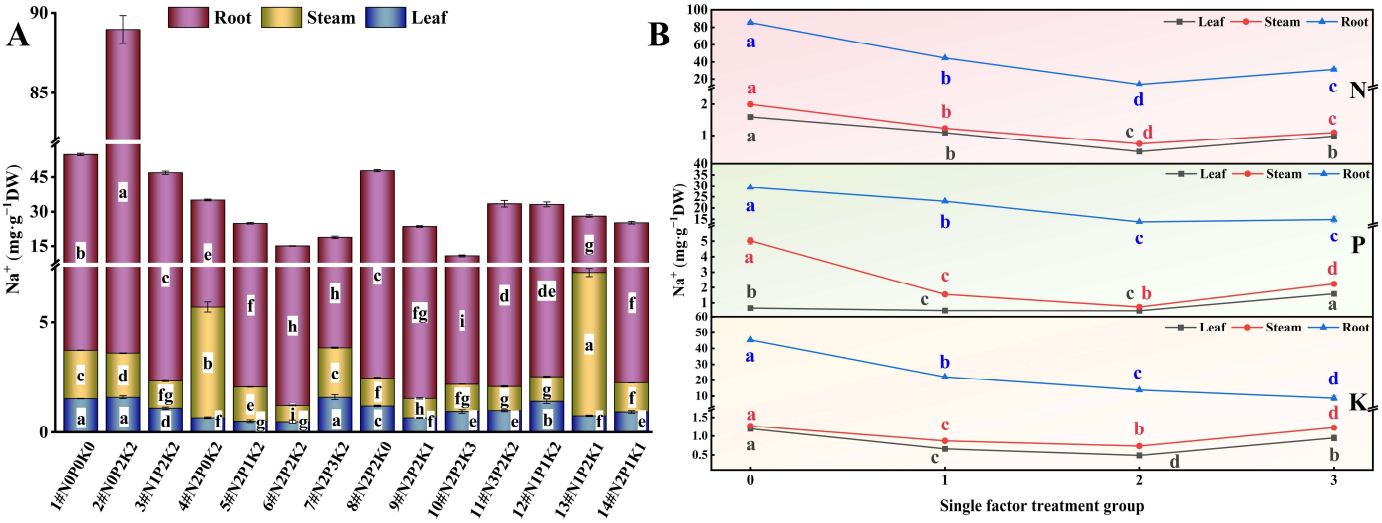

Figure 2. Effects of N, P, and K application on Na^+ content in hemp under $NaHCO_3$ stress. (**A**) Fourteen sets of NPK ratios (#1–#14); (**B**) The single factor of N, P, and K fertilizer. Different lowercase letters indicate significant differences between treatments for the same plant organ at $p < 0.05$.

When examining the N effect alone (Figure 2B), the Na^+ content in various organs of alkali-stressed hemp followed the order of N0 > N1 > N3 > N2. With increasing N application, the Na^+ content in roots, stems, and leaves gradually decreased, reaching the lowest level at N2. This indicates that N application can reduce the accumulation of Na^+ in alkali-stressed hemp.

In the single-factor P experiment (Figure 2B), under alkali stress, the root Na^+ content of hemp followed the order of P0 > P1 > P3 > P2, the stem Na^+ content followed P0 > P3 > P1 > P2, and the leaf Na^+ content followed P3 > P0 > P1 > P2. With increasing P application, the Na^+ content in roots and stems gradually decreased, reaching the lowest level at P2. The leaf Na^+ content first decreased and then increased, also reaching the lowest level at P2. These results suggest that a moderate level of P application is most beneficial for reducing the Na^+ content in various organs of alkali-stressed hemp, but excessive P application may increase Na^+ accumulation in leaves.

The results of the single-factor K experiment (Figure 2B) showed that the root Na^+ content of alkali-stressed hemp followed the order of K0 > K1 > K2 > K3, while the stem and leaf Na^+ content followed K0 > K3 > K1 > K2. The Na^+ content in various organs under K application was lower than the no-K control, with the root Na^+ content being lowest at the K3 level and the stem and leaf Na^+ content being lowest at the K2 level. These findings indicate that K application helps to reduce the Na^+ level in alkali-stressed hemp.

Overall, the Na^+ content in various organs of hemp followed the order of root > stem > leaf.

3.2.2. K^+

Under the interaction of N, P, and K (Figure 3A), there were significant differences in the K^+ content in the roots, stems, and leaves of alkali-stressed hemp among the 14 fertilization treatments. The root K^+ content was highest under the N3P2K2 treatment (11#), which was 214.33% higher than the control (1#, N0P0K0). The stem K^+ content was highest under the N2P2K2 treatment (6#), which was 69.71% higher than the control. The leaf K^+ content reached its maximum under the N2P1K2 treatment (5#), which was 293.61% higher than the control.

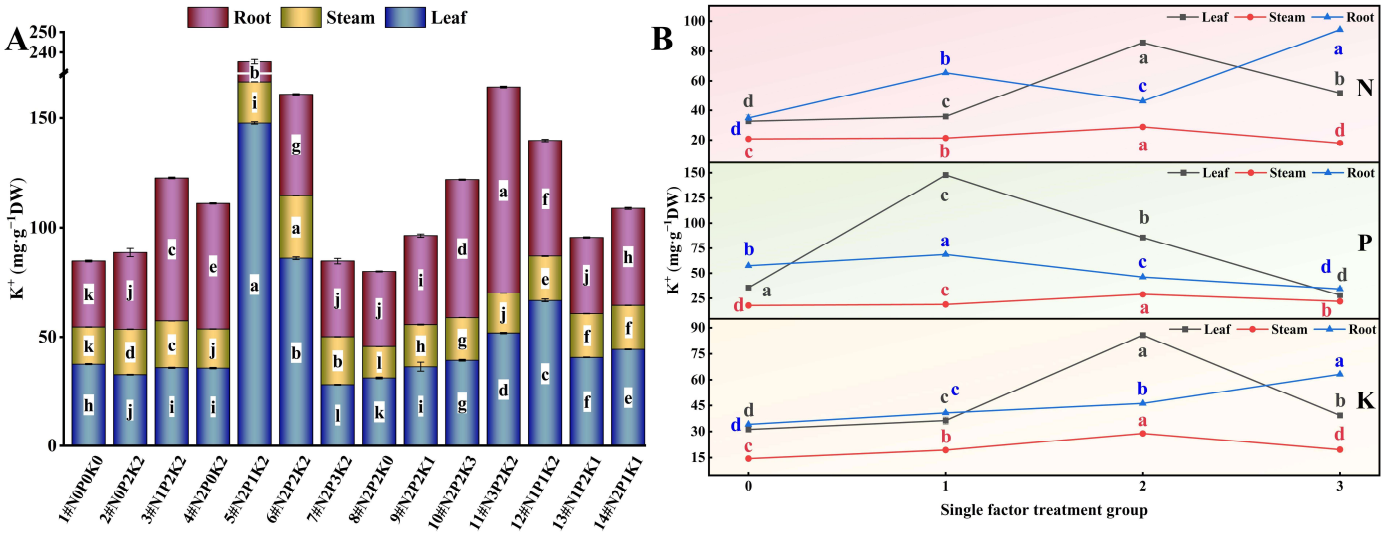

Figure 3. Effects of N, P, and K application on K^+ content in hemp under $NaHCO_3$ stress. (**A**) Fourteen sets of NPK ratios (#1–#14); (**B**) The single factor of N, P, and K fertilizer. Different lowercase letters indicate significant differences between treatments for the same plant organ at $p < 0.05$.

When examining the N effect alone (Figure 3B), the root K^+ content of alkali-stressed hemp followed the order of N3 > N1 > N2 > N0, the stem K^+ content followed N2 > N1 > N0 > N3, and the leaf K^+ content followed N2 > N3 > N1 > N0. With increasing N application, the root K^+ content gradually increased, reaching its maximum at the N3 level, while the stem and leaf K^+ content was highest at the N2 level. These results suggest that high levels of N application are most beneficial for increasing the root K^+ content of alkali-stressed hemp, while moderate levels of N application are more effective in increasing the stem and leaf K^+ content.

In the single-factor P experiment (Figure 3B), the root K^+ content of alkali-stressed hemp followed the order of P1 > P0 > P2 > P3, the stem K^+ content followed P2 > P3 > P1 > P0, and the leaf K^+ content followed P1 > P2 > P0 > P3. With increasing P application, the root and leaf K^+ content showed a trend of first increasing and then decreasing, reaching the lowest level at P3. The stem K^+ content under each P application treatment was higher than the no-phosphorus control, reaching its maximum at the P2 level. These findings indicate that excessive application of phosphorus fertilizer will reduce the K^+ level in the roots and leaves of alkali-stressed hemp, while moderate P application is most beneficial for increasing the stem K^+ content.

The results of the single-factor K experiment (Figure 3B) showed that under alkali stress, the root K^+ content of hemp followed the order of K3 > K2 > K1 > K0, while the stem and leaf K^+ content followed K2 > K3 > K1 > K0. With increasing K application, the K^+ content in various organs gradually increased, with the root K^+ content being highest at the K3 level and the stem and leaf K^+ content reaching their maximum at the K2 level. These

results demonstrate that high levels of K application are most beneficial for increasing the K^+ level in various organs of alkali-stressed hemp.

Overall, under alkali salt stress, with the application of N, P, and K fertilizers in different proportions, the K^+ content in various organs of hemp followed the order of root > stem > leaf.

3.2.3. N

Under the interaction of N, P, and K (Figure 4A), there were significant differences in the N content in the roots, stems, and leaves of alkali-stressed hemp among the 14 fertilization treatments. The root N content was highest under the N3P2K2 treatment (11#), which was 53.34% higher than the blank control (1#, N0P0K0). The stem and leaf N contents were highest under the N2P2K2 treatment (6#), which were 53.47% and 103.89% higher than the blank control, respectively.

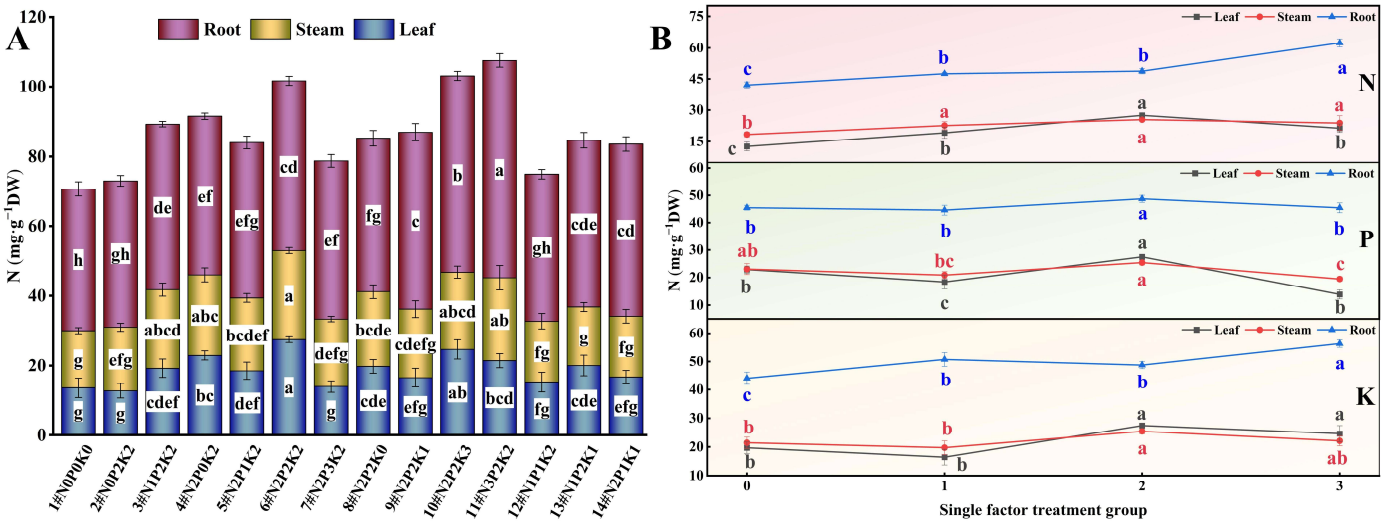

Figure 4. Effects of N, P, and K application on N content in hemp under $NaHCO_3$ stress. (**A**) Fourteen sets of NPK ratios (#1–#14); (**B**) The single factor of N, P, and K fertilizer. Different lowercase letters indicate significant differences between treatments for the same plant organ at $p < 0.05$.

When examining the N effect alone (Figure 4B), the root N content of alkali-stressed hemp followed the order of N3 > N2 > N1 > N0, while the stem and leaf N content followed N2 > N3 > N1 > N0. With increasing N application, the root N content gradually increased, reaching its maximum at the N3 level. The stem and leaf N content showed a trend of first increasing and then decreasing, reaching the highest level at N2. These results indicate that N application can increase the N level in various organs of alkali-stressed hemp, with high N levels being beneficial for root N accumulation and moderate N levels being more effective in increasing the stem and leaf nitrogen content.

In the single-factor P experiment (Figure 4B), the root N content of alkali-stressed hemp followed the order of P2 > P0 ≈ P3 > P1, while the stem and leaf nitrogen content followed P2 > P0 > P1 > P3. With increasing P application, the nitrogen content in various organs showed a trend of first decreasing and then increasing, reaching the highest level at P2. These findings suggest that moderate P application is most beneficial for increasing the N level in the roots, stems, and leaves of alkali-stressed hemp.

The results of the single-factor K experiment (Figure 4B) showed that under alkali stress, the root N content of hemp followed the order of K3 > K1 > K2 > K0, while the stem and leaf N content followed K2 > K3 > K0 > K1. The root, stem, and leaf N content under each K application treatment were higher than the no-K control, with the root N content being highest at the K3 level and the stem and leaf N content reaching their maximum

at the K2 level. These results demonstrate that high K levels are beneficial for root N accumulation, while moderate K levels are more effective in increasing the stem and leaf N levels.

Overall, under alkali salt stress, the N content in various organs of hemp followed the order of root > stem > leaf.

3.2.4. P

Under the interaction of N, P, and K (Figure 5A), there were significant differences in the P content in the roots, stems, and leaves of alkali-stressed hemp among the 14 fertilization treatments. The root and leaf P content were highest under the N2P3K2 treatment (7#), which were 178.34% and 130.09% higher than the blank control (1#, N0P0K0), respectively. The stem P content reached its maximum under the N3P2K2 treatment (11#), which was 122.51% higher than the blank control.

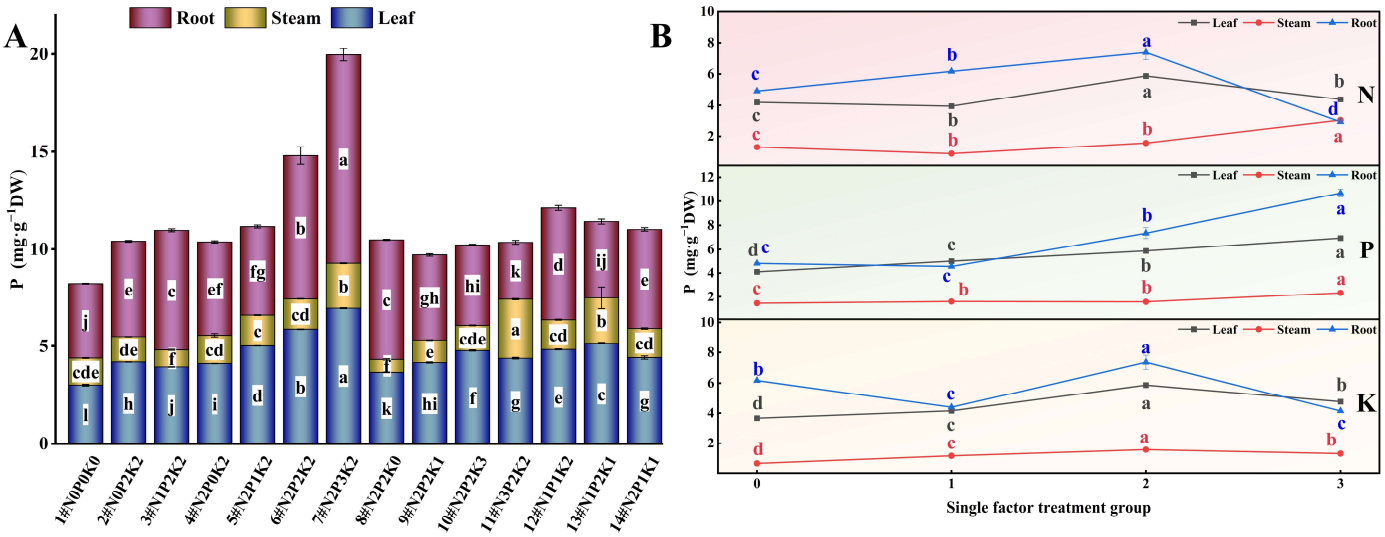

Figure 5. Effects of N, P, and K application on P content in hemp under $NaHCO_3$ stress. (**A**) Fourteen sets of NPK ratios (#1–#14); (**B**) The single factor of N, P, and K fertilizer. Different lowercase letters indicate significant differences between treatments for the same plant organ at $p < 0.05$.

When examining the N effect alone (Figure 5B), the root P content of alkali-stressed hemp followed the order of N2 > N1 > N0 > N3, the stem P content followed N3 > N2 > N0 > N1, and the leaf P content followed N2 > N3 > N0 > N1. With increasing N application, the root and leaf P content showed a trend of first increasing and then decreasing, reaching the lowest level at N3, while the stem P content showed a trend of first decreasing and then increasing, reaching the lowest level at N1. These results suggest that low to moderate N levels are beneficial for increasing the root P level of alkali-stressed hemp, while moderate to high N levels are more effective for stem and leaf P accumulation.

In the single-factor P experiment (Figure 5B), the root P content of alkali-stressed hemp followed the order of P3 > P2 > P0 > P1, the stem phosphorus content followed P3 > P1 > P2 > P0, and the leaf P content followed P3 > P2 > P1 > P0. With increasing P application, the root P content showed a trend of first decreasing and then increasing, the leaf P content gradually increased, and the P level in various organs reached its highest under the P3 treatment. These findings indicate that high P conditions are most beneficial for increasing the P content in the roots, stems, and leaves of alkali-stressed hemp.

The results of the single-factor K experiment (Figure 5B) showed that under alkali stress, the root P content of hemp followed the order of K2 > K0 > K1 > K3, the effect of each K application treatment on stem P content was not significant, and the stem and leaf

phosphorus content both followed K2 > K3 > K1 > K0. With increasing K application, the root phosphorus content first decreased and then increased, reaching its highest at the K2 level. Although the stem and leaf P content were both higher than the no-K control, they also reached their maximum under the K2 treatment. These results demonstrate that moderate K application is most beneficial for increasing the P level in various organs of alkali-stressed hemp.

Overall, under alkali salt stress, the P content in various organs of hemp followed the order of root > leaf > stem.

3.2.5. Ca^{2+} and Mg^{2+}

Under the interactive effects of N, P, and K (Figures 6A and 7A), the Ca^{2+} and Mg^{2+} contents in the roots, stems, and leaves of alkali-stressed hemp varied significantly among the 14 fertilization treatments. The N2P3K2 treatment (7#) resulted in the maximum Ca^{2+} and Mg^{2+} contents in roots, which were 361.31% and 265.97% higher, respectively, than in the control (1#, N0P0K0). Stems had the highest Ca^{2+} content under the N3P2K2 treatment (11#), 59.84% higher than the control, while the N2P2K2 treatment (6#) resulted in the highest Mg^{2+} content in stems, a 66.70% higher than the control. Leaves showed the maximum Ca^{2+} and Mg^{2+} contents under the N2P2K2 treatment (6#), exceeding the control by 106.94% and 178.32%, respectively.

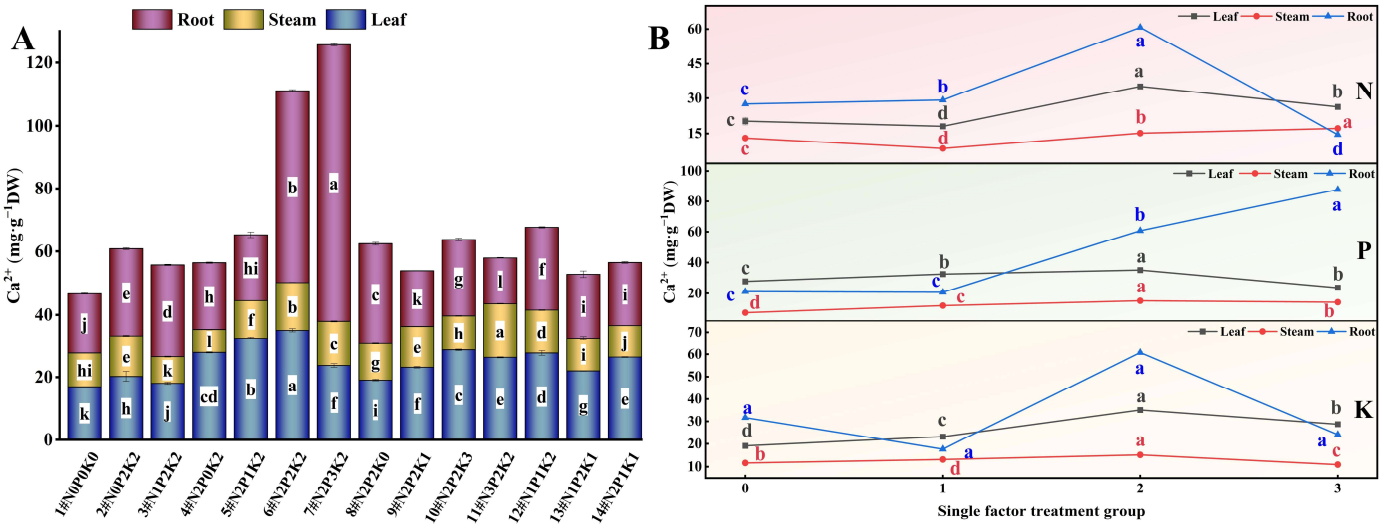

Figure 6. Effects of N, P, and K application on Ca^{2+} content in hemp under $NaHCO_3$ stress. (**A**) Fourteen sets of NPK ratios (#1–#14); (**B**) The single factor of N, P, and K fertilizer. Different lowercase letters indicate significant differences between treatments for the same plant organ at $p < 0.05$.

Considering the effect of N alone (Figures 6B and 7B), the Ca^{2+} and Mg^{2+} contents in the roots of alkali-stressed hemp decreased in the order N2 > N1 > N0 > N3. The Ca^{2+} content in stems decreased in the order N3 > N2 > N0 > N1, while the Ca^{2+} content in leaves and the Mg^{2+} content in stems and leaves followed the order N2 > N3 > N0 > N1. With increasing N application, the Ca^{2+} and Mg^{2+} contents in roots first increased and then decreased, with the lowest values at the N3 level. Conversely, the Ca^{2+} and Mg^{2+} contents in stems and leaves first decreased and then increased, showing the minimum values at the N1 level. The N2 treatment resulted in the highest Mg^{2+} content in all organs. These results suggest that low to moderate N levels favor Ca^{2+} accumulation in the roots of alkali-stressed hemp, while medium to high N levels favor Ca^{2+} accumulation in stems and leaves. Moderate N application is most effective in simultaneously increasing Mg^{2+} levels in the roots, stems, and leaves of alkali-stressed hemp.

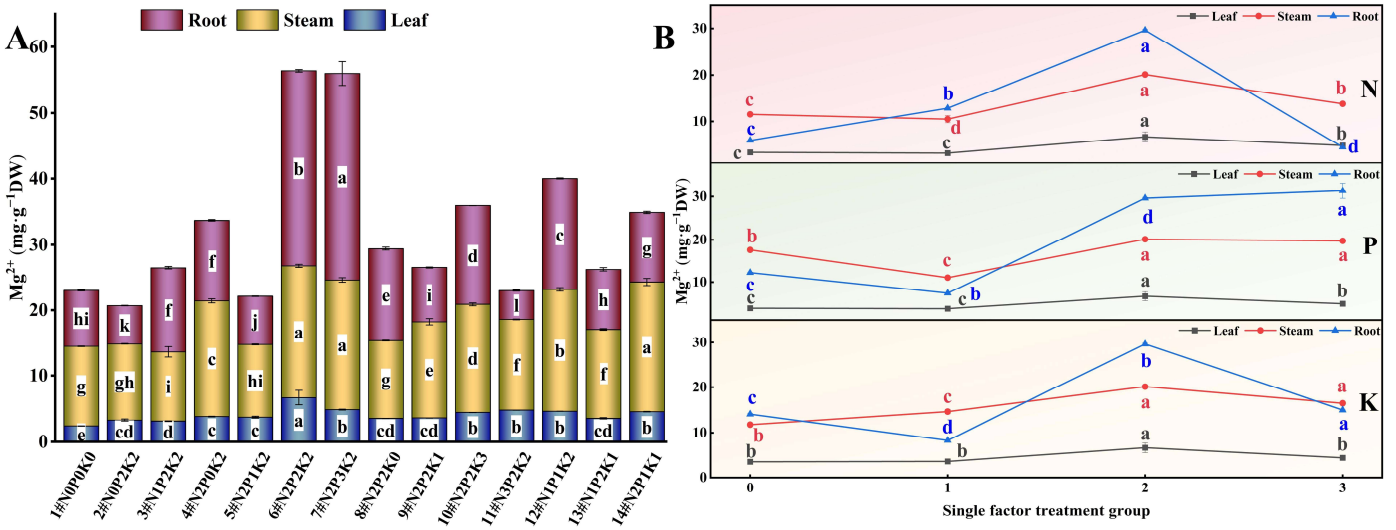

Figure 7. Effects of N, P, and K application on Mg^{2+} content in hemp under $NaHCO_3$ stress. (**A**) Fourteen sets of NPK ratios (#1–#14); (**B**) The single factor of N, P, and K fertilizer. Different lowercase letters indicate significant differences between treatments for the same plant organ at $p < 0.05$.

In the single-factor P experiment, the Ca^{2+} and Mg^{2+} contents in the roots of alkali-stressed hemp decreased in the order P3 > P2 > P0 > P1. The Ca^{2+} content in stems followed the order P2 > P3 > P1 > P0, while in leaves, it decreased in the order P2 > P1 > P0 > P3. With increasing P application, the Ca^{2+} and Mg^{2+} contents in roots first decreased and then increased, peaking at the P3 level. However, the Ca^{2+} content in leaves first increased and then decreased, with the lowest value under the P3 treatment. These results indicate that medium to high levels of P increase Ca^{2+} accumulation in the roots of alkali-stressed hemp, but excessive P may decrease foliar Ca^{2+} content. The Mg^{2+} contents in stems and leaves decreased in the order P2 > P3 > P0 > P1. With increasing P, the Mg^{2+} contents in stems and leaves first increased and then decreased, reaching a maximum at the P2 level, suggesting that medium to high P levels increase Mg^{2+} contents in different organs of alkali-stressed hemp.

The single-factor K experiment showed that under alkali stress, the Ca^{2+} content in kenaf roots decreased in the order K2 > K0 > K3 > K1, while in stems, it followed the order K2 > K1 > K3 > K0. The Ca^{2+} and Mg^{2+} contents in leaves and the Mg^{2+} contents in roots and stems decreased in the order K2 > K3 > K1 > K0. The K2 treatment resulted in the highest Ca^{2+} and Mg^{2+} contents in all organs, with the Ca^{2+} contents in stems and leaves exceeding those in the no-K control. The Mg^{2+} levels in roots, stems, and leaves exceeded those of the no-K control in all K treatments. These results demonstrate that moderate K application is the most effective way to increase the Ca^{2+} and Mg^{2+} levels in different organs of alkali-stressed hemp.

Overall, under alkali salt stress, the Ca^{2+} content in different hemp organs decreased in the order roots > leaves > stems, while the Mg^{2+} content followed the order roots > stems > leaves.

3.2.6. Range Analysis of N, P, and K Fertilizers on Nutrient Content of Hemp Under $NaHCO_3$ Stress

Extreme difference analysis (Table 5) of fertilization methods revealed significant effects on nutrient elements in hemp under alkaline salt stress. Element N had the most significant effected on N, P, and Ca^{2+} in stems; N, K, and Na^+ in roots; and N and Mg^{2+} in leaves. Element P mainly affected P, Ca^{2+}, and Mg^{2+} in roots; Na^+, P, and K^+ in leaves; and Na^+ and Mg^{2+} in stems. Element K mainly affected K^+ in stems and Ca^{2+} in leaves.

Table 5. Range analysis of the effect of NPK fertilization on the nutrient content of hemp under $NaHCO_3$ stress in each organ.

Nutrient Content	Range Value			Fertilizer Effect Ordination
	N	P	K	
Root N content	21.0436	6.8537	13.9480	N > K > P
Steams N content	6.3261	2.5876	4.0593	N > K > P
Leaves N content	8.3115	6.3254	8.0423	N > K > P
Root P content	2.9703	6.3518	1.7472	P > N > K
Steams P content	1.7101	0.9210	0.7003	N > P > K
Leaves P content	1.2637	3.3864	1.5669	P > K > N
Root K content	61.9413	20.9437	31.0935	N > K > P
Steams K content	2.5429	4.5110	5.3109	K > P > N
Leaves K content	20.9482	58.0640	26.1786	P > K > N
Root Na^+ content	45.6194	25.1850	39.3616	N > K > P
Steams Na^+ content	1.8559	2.2741	1.6712	P > N > K
Leaves Na^+ content	0.6877	0.6431	0.5842	P > K > N
Root Ca^{2+} content	20.9695	67.6636	16.6434	P > N > K
Steams Ca^{2+} content	6.2693	5.0973	1.7447	N > P > K
Leaves Ca^{2+} content	8.4764	6.4670	10.7035	K > N > P
Root Mg^{2+} content	11.6652	20.9703	5.7352	P > N > K
Steams Mg^{2+} content	4.5920	5.7073	4.5376	P > N > K
Leaves Mg^{2+} content	1.9355	1.7621	1.4610	N > P > K

4. Discussion

4.1. Optimal N, P, and K Ratios for Hemp Growth Under Alkaline Stress

This study has demonstrated that under specific alkaline stress conditions (sodium bicarbonate, $NaHCO_3$, 200 mM), the optimal NPK ratio for hemp growth is N1P2K2, which corresponds to nitrogen (N) at 120 mg·L^{-1}, phosphorus (P) at 238 mg·L^{-1}, and potassium (K) at 348 mg·L^{-1}. Under these conditions, the biomass of hemp stems and roots exhibited an increase of 45% and 39%, respectively, in comparison with the control group. Concurrently, the K^+/Na^+ ratio in leaves exhibited a favorable level of >1.2. These results suggest that a balanced NPK supply is crucial for enhancing the salt tolerance and productivity in hemp. Consistent with these observations, analogous research findings have been documented in other plant species, including ryegrass (*Lolium multiflorum*), *Sorghum bicolor*, and *Sulla carnosa* [10,32,33].

N is a significant component of chlorophyll, proteins, and enzymes, playing a vital role in plant growth and stress adaptation. This study found that a moderate level of N supply (N1, 120 mg·L^{-1}) significantly promoted plant height, stem diameter, root length, and biomass accumulation in various organs of hemp under alkaline stress. However, a high N supply (N3, 360 mg·L^{-1}) exhibited some inhibitory effects. This finding is consistent with the results of related studies on wheat and *Solanum lycopersicum*, where an appropriate N supply can improve plant salt tolerance by promoting growth and biomass accumulation [34,35]. The enhancing effect of N on plant salt tolerance and growth may be closely related to its promotion of photosynthetic capacity, osmotic regulation, and antioxidant defense mechanisms [9,19].

P is also an essential element that influences the growth of hemp under conditions of alkaline stress. In this study, the supply of P was found to have a significant impact on hemp growth, with low to moderate levels of P supply (P1-P2, 119–238 mg·L^{-1}) having a promotive effect on plant development. Among the treatments, the P2 level (238 mg·L^{-1}) resulted in the greatest values of plant height, stem diameter, root length, and root dry weight in hemp. This result aligns with the findings in chickpea research, where low P conditions led to enhanced salt tolerance through stimulated root development and improved

nutrient acquisition [21]. The observed promotion of root growth by P may be attributed to its role in enhancing cell division, cell elongation, and lateral root formation [36,37].

K, the most prevalent cation within plant cells, plays a pivotal role in enzyme activation. In the context of alkaline stress, an adequate supply of K (K2, 348 mg·L^{-1}) has been shown to promote significant increases in plant height, stem diameter, root length, organ dry weight, and leaf number in hemp. This K-induced growth enhancement phenomenon has also been documented in salt stress studies on peanut, wheat, and other crops [38–40].

4.2. Effects of N, P, and K Nutritional Combinations on Nutrient Allocation and Ion Homeostasis

Research has demonstrated that diverse combinations of N, P, and K exert a substantial influence on the absorption and allocation patterns of nutrients in hemp under conditions of alkaline stress. For example, the N2P2K3 and N2P2K2 treatments effectively reduced the Na^+ content in roots and increased the K^+ content in stems, respectively, significantly improving the K^+/Na^+ ratio. These results imply that by optimizing NPK nutrition, the absorption and transport of Na^+ can be regulated, and the acquisition and allocation capacity of K^+ can be enhanced, thereby improving ion homeostasis under salt stress [41]. Additionally, balanced fertilization has been shown to enhance the absorption of other mineral nutrients (e.g., N, P, Ca^{2+}, and Mg^{2+}), which are crucial for maintaining the overall nutritional status and salt tolerance of hemp [42,43].

From the perspective of specific nutrients, the supply of N has a significant impact on the accumulation patterns of Na^+ and K^+ in different organs of hemp. The study demonstrated that at the N2 level, the Na^+ content in roots can be effectively reduced, while the K^+ content in stems was increased, significantly improving the K^+/Na^+ ratio. This finding suggests that effective N management practices can enhance ion balance under salt stress conditions by constraining Na^+ absorption and transport processes and by promoting K^+ acquisition and distribution. The potential mechanisms underlying this phenomenon include the regulation of Na^+/K^+ transporter activity by N, the promotion of compatible solute synthesis, and the enhancement of cell wall strength [44–47].

P plays a key role in various aspects of plant biology, including energy metabolism, signal transduction, and biomass production. It has been demonstrated that P has a substantial influence on the absorption and distribution of mineral nutrients in hemp under conditions of alkaline stress. The study demonstrated that the P2 treatment augmented the N and P content in roots while diminishing Na+ accumulation and sustaining a higher K^+/Na^+ ratio in stems and leaves. It has been documented that an adequate supply of P can enhance the selective absorption of K^+ and Na^+ by roots and restrict Na^+ influx by modulating the activity of plasma membrane H^+-ATPase and cell wall properties [14]. Furthermore, the application of P has been shown to enhance the levels of Ca^{2+} and Mg^{2+} in hemp organs, thereby contributing to the stabilization of cell membrane structure and the mitigation of salt stress-induced oxidative damage [48].

K plays a crucial role in maintaining cell turgor, enhancing photosynthesis, and activating stress response genes [49]. The study found that as the K supply increased, the Na^+ content in roots, stems, and leaves gradually decreased, while the K^+ content and K^+/Na^+ ratio significantly increased. Among the various treatments evaluated, the K3 treatment (522 mg·L^{-1}) was found to be the most effective in reducing Na^+ accumulation in roots and significantly enhancing the selective absorption of K^+/Na^+ by roots. This finding indicates that sufficient K nutrition can impede Na^+ uptake, promote Na^+ exclusion, and enhance K^+ absorption by regulating multiple ion transporters and channels [50]. Furthermore, the application of K has been shown to increase the content of N, P, Ca^{2+}, and Mg^{2+} in hemp organs, thereby underscoring the pivotal role of K in enhancing the overall nutritional status and augmenting salt tolerance of hemp [15,16].

4.3. Harmful Effects and Threshold Concentrations of Excessive Fertilization

This study determined the critical thresholds for NPK application in hemp under alkaline stress. Excessively high fertilizer concentrations (total nutrients > 400 mg·L^{-1}) have been shown to exacerbate salt damage, reducing biomass accumulation by 25–30% and disrupting ion homeostasis. This detrimental effect may be attributed to elevated soil salinity, nutritional imbalance, and oxidative stress [51]. Furthermore, elevated nitrogen levels (N3, 360 mg·L^{-1}) have been observed to impede plant height, stem diameter, root length, and organ biomass in hemp. This effect is possibly due to ammonium toxicity, intracellular pH disturbance, and the accumulation of reactive oxygen species (ROS) under alkaline conditions [52]. A similar phenomenon was observed with excessive phosphorus (P3, 357 mg·L^{-1}), which was found to reduce root growth and leaf calcium content. This effect may be attributed to phosphorus-induced zinc deficiency, alterations in root structure, and impaired calcium signaling [53]. Furthermore, excessive K application (K3, 522 mg·L^{-1}) has been shown to inhibit growth, possibly due to ionic antagonism, osmotic stress, and disruption of cellular metabolic processes [54]. Consequently, when cultivating hemp in saline-alkali soil, it is imperative to meticulously regulate the application of NPK fertilizers to avoid exceeding the crop tolerance threshold and to ensure efficient nutrient utilization and sustainable production.

In summary, this study provides a systematic understanding of the effects of N, P, and K fertilizer management on the growth and mineral nutrition of hemp under alkaline salt stress. However, the study is not without limitations. For instance, the optimal NPK ratio may vary depending on the hemp genotype, growth stage, and specific saline-alkali stress conditions [11,55]. Consequently, further exploration is necessary to ascertain the optimal NPK ratio for hemp cultivation in diverse saline-alkali soils and environmental conditions. Future research endeavors should prioritize a comprehensive examination of the combined effects of NPK fertilizers and ancillary agronomic measures, such as irrigation, mulching, and soil improvement, on diverse hemp genotypes throughout their entire growth cycle under authentic saline-alkali soil conditions. The development of more precise, efficient, and sustainable integrated management techniques for hemp in saline-alkali land is expected to promote the restoration and utilization of saline-alkali land and the healthy development of the hemp industry.

5. Conclusions

This study provides novel insights into the effects of NPK fertilization on the growth, ion homeostasis, and mineral nutrition of hemp under alkaline salt stress. The results emphasize the key role of balanced NPK nutrition, particularly the N1P2K2 treatment, in enhancing the salt tolerance and biomass production of hemp. The potential physiological mechanisms involve the coordinated regulation of ion absorption, transport, and compartmentalization, as well as the improvement of overall nutritional status and antioxidant defense. These findings may help in the development of targeted fertilization strategies to help grow hemp in saline-alkali areas. Combining balanced fertilization with other agronomic practices could be a good way to increase the sustainability and profitability of hemp production in salt-affected agroecosystems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture15020125/s1.

Author Contributions: Conceptualization, Y.Z. and Y.Y.; data curation, Y.Z.; data analysis, Y.Y.; investigation, Y.Y. and H.W.; methodology, Y.Y. and P.Z.; validation, Y.Z.; formal analysis, Y.Y. and P.Z.; software, Y.Y. and H.W.; writing—original draft, Y.Y.; writing—review and editing, Y.Z., P.Z. and H.W.; supervision, Y.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by Heilongjiang Provincial Key Research and Development Program "Leading the Charge with Open Competition (Jie Bang Gua Shuai)" project (2024ZXJ02B06).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors have no competing interests to declare that are relevant to the content of this article.

References

1. Jones, A.D.; Ejeta, G. A new global agenda for nutrition and health: The importance of agriculture and food systems. *Bull. World Health Organ.* **2016**, *94*, 228–229. [CrossRef] [PubMed]
2. Zhou, B.; Liang, C.; Chen, X.; Ye, S.; Peng, Y.; Yang, L.; Duan, M.; Wang, X. Magnetically-treated brackish water affects soil water-salt distribution and the growth of cotton with film mulch drip irrigation in Xinjiang, China. *Agric. Water Manag.* **2022**, *263*, 107487. [CrossRef]
3. Hu, H.; Liu, H.; Liu, F. Seed germination of hemp (*Cannabis sativa* L.) cultivars responds differently to the stress of salt type and concentration. *Ind. Crop. Prod.* **2018**, *123*, 254–261. [CrossRef]
4. Manaia, J.P.; Manaia, A.T.; Rodriges, L. Industrial hemp fibers: An overview. *Fibers* **2019**, *7*, 106. [CrossRef]
5. Amaducci, S.; Scordia, D.; Liu, F.; Zhang, Q.; Guo, H.; Testa, G.; Cosentino, S. Key cultivation techniques for hemp in Europe and China. *Ind. Crop. Prod.* **2015**, *68*, 2. [CrossRef]
6. Liu, J.; Qiao, Q.; Cheng, X.; Du, G.; Deng, G.; Zhao, M.; Liu, F. Transcriptome differences between fiber-type and seed-type *Cannabis sativa* variety exposed to salinity. *Physiol. Mol. Biol. Plants* **2016**, *22*, 429–443. [CrossRef] [PubMed]
7. Jia, X.; Zhu, Y.; Zhang, R.; Zhu, Z.; Zhao, T.; Cheng, L.; Gao, L.; Liu, B.; Zhang, X.; Wang, Y. Ionomic and metabolomic analyses reveal the resistance response mechanism to saline-alkali stress in *Malus halliana* seedlings. *Plant Physiol. Biochem.* **2020**, *147*, 77–90. [CrossRef] [PubMed]
8. Yang, C.; Shi, D.; Wang, D. Comparative effects of salt and alkali stresses on growth, osmotic adjustment and ionic balance of an alkali-resistant halophyte *Suaeda glauca* (Bge.). *Plant Growth Regul.* **2008**, *56*, 179–190. [CrossRef]
9. Michalska, A.; Wojdyło, A.; Bogucka, B. The influence of nitrogen and potassium fertilisation on the content of polyphenolic compounds and antioxidant capacity of coloured potato. *J. Food Compos. Anal.* **2016**, *47*, 69–75. [CrossRef]
10. Guo, X.; Wu, Q.; Zhang, Z.; Zhu, G.; Zhou, G. Nitrogen and phosphorus counteracted the adverse effects of salt on sorghum by improving ROS scavenging and osmotic regulation. *Agronomy* **2023**, *13*, 1020. [CrossRef]
11. Singh, M.; Singh, V.P.; Prasad, S.M. Responses of photosynthesis, nitrogen and proline metabolism to salinity stress in *Solanum lycopersicum* under different levels of nitrogen supplementation. *Plant Physiol. Biochem.* **2016**, *109*, 72–83. [CrossRef]
12. Bouras, H.; Choukr-Allah, R.; Amouaouch, Y.; Bouaziz, A.; Devkota, K.P.; El Mouttaqi, A.; Bouazzama, B.; Hirich, A. How does quinoa (*Chenopodium quinoa* Willd.) respond to phosphorus fertilization and irrigation water salinity? *Plants* **2022**, *11*, 216. [CrossRef]
13. Iqbal, N.; Umar, S.; Khan, N.A. Nitrogen availability regulates proline and ethylene production and alleviates salinity stress in mustard (*Brassica juncea*). *J. Plant Physiol.* **2015**, *178*, 84–91. [CrossRef] [PubMed]
14. Talbi Zribi, O.; Abdelly, C.; Debez, A. Interactive effects of salinity and phosphorus availability on growth, water relations, nutritional status and photosynthetic activity of barley (*Hordeum vulgare* L.). *Plant Biol.* **2011**, *13*, 872–880. [CrossRef]
15. Huang, W.; Lin, M.; Liao, J.; Li, A.; Tsewang, W.; Chen, X.; Sun, B.; Liu, S.; Zheng, P. Effects of potassium deficiency on the growth of tea (*Camelia sinensis*) and strategies for optimizing potassium levels in soil: A critical review. *Horticulturae* **2022**, *8*, 660. [CrossRef]
16. Munir, A.; Shehzad, M.T.; Qadir, A.A.; Murtaza, G.; Khalid, H.I. Use of potassium fertilization to ameliorate the adverse effects of saline-sodic stress condition (ECw: SARw Levels) in rice (*Oryza sativa* L.). *Commun. Soil Sci. Plant Anal.* **2019**, *50*, 1975–1985. [CrossRef]
17. Wang, M.; Zheng, Q.; Shen, Q.; Guo, S. The critical role of potassium in plant stress response. *Int. J. Mol. Sci.* **2013**, *14*, 7370–7390. [CrossRef]
18. Zhao, D.-Y.; Zhang, X.-L.; Zhao, S.-P.; Liu, G.-L.; Zhang, Z.-W.; Zhao, W.-F.; Li, X.-P.; Khan, S.A.; Siddique, K.H.M. Biomass allocation and nutrients utilization in wheat as affected by phosphorus placement and salt stress. *Agronomy* **2023**, *13*, 1570. [CrossRef]
19. Reinbott, T.M.; Blevins, D.G. Phosphorus and temperature effects on magnesium, calcium, and potassium in wheat and tall fescueleaves. *Agron. J.* **1994**, *86*, 523–529. [CrossRef]

20. Liu, K.; Zhang, T.Q.; Tan, C.S.; Astatkie, T. Responses of fruit yield and quality of processing tomato todrip rrigation and ferilizers phosphorus and potassium. *Agron. J.* **2011**, *103*, 1339–1345. [CrossRef]
21. Kaci, H.S.-A.; Haddadj, A.C.; Aid, F. Enhancing of symbiotic efficiency and salinity tolerance of chickpea by phosphorus supply. *Acta Agric. Scand. Sect. B-Soil Plant Sci.* **2018**, *68*, 534–540. [CrossRef]
22. Chen, Z.; Ma, H.; Xia, J.; Hou, F.; Shi, X.; Hao, X.; Hafeez, A.; Han, H.; Luo, H. Optimal pre-plant irrigation and fertilization canimprove biomass accumulation by maintaining the root and leaf productive capacity of cotton crop. *Sci. Rep.* **2017**, *7*, 17168. [CrossRef] [PubMed]
23. Chen, B.; Wang, Q.; Ye, Z.; Stiles, S.; Feng, G. Optimisation of phosphorus fertilisation promotes biomass and phosphorus nutrientaccumulation, partitioning and translocation in three cotton (*Gossypium hirsutum*) genotypes. *Crop Pasture Sci.* **2020**, *71*, 56–69. [CrossRef]
24. *GB 9834-1988*; Standardization Administration of China. Method for Determination of Soil Organic Matter. China Standard Press: Beijing, China, 1988.
25. Cao, K.; Sun, Y.; Zhang, X.; Zhao, Y.; Bian, J.; Zhu, H.; Wang, P.; Gao, B.; Sun, X.; Hu, M. The miRNA–mRNA regulatory networks of the response to $NaHCO_3$ stress in industrial hemp (*Cannabis sativa* L.). *BMC Plant Biol.* **2023**, *23*, 509. [CrossRef] [PubMed]
26. Yuan, H.; Si, H.; Ye, Y.; Ji, Q.; Wang, H.; Zhang, Y. Arbuscular Mycorrhizal Fungi-Mediated Modulation of Physiological, Biochemical, and Secondary Metabolite Responses in Hemp (*Cannabis sativa* L.) under Salt and Drought Stress. *J. Fungi* **2024**, *10*, 283. [CrossRef] [PubMed]
27. Wei, T.J.; Li, G.; Wang, M.M.; Jin, Y.Y.; Zhang, G.H.; Liu, M.; Yang, H.Y.; Jiang, C.J.; Liang, Z.-W. Physiological and transcriptomic analyses reveal novel insights into the cultivar-specific response to alkaline stress in alfalfa (*Medicago sativa* L.). *Ecotoxicol. Environ. Saf.* **2021**, *228*, 113017. [CrossRef]
28. Wei, X.; Zhou, W.; Long, S.; Guo, Y.; Qiu, C.; Zhao, X.; Wang, Y. Effects of Different N, P, and K Rates on the Growth and Cannabinoid Content of Industrial Hemp. *J. Nat. Fibers* **2023**, *20*, 2159605. [CrossRef]
29. Liu, J.; Chen, W.; Wang, H.; Peng, F.; Chen, M.; Liu, S.; Chu, G. Effects of NPK fertilization on photosynthetic characteristics and nutrients of pecan at the seedling stage. *J. Soil Sci. Plant Nutr.* **2021**, *21*, 2425–2435. [CrossRef]
30. Chen, K.; Ma, L.; Chen, C.; Liu, N.; Wang, B.; Bao, Y.; Liu, Z.; Zhou, G. Long-term impact of N, P, K fertilizers in different rates on yield and quality of *Anisodus tanguticus* (Maxinowicz) Pascher. *Plants* **2023**, *12*, 2102. [CrossRef]
31. Yang, Z.-J.; Wu, X.-H.; Chen, L.-H.; Huang, L.-M.; Chen, Y.; Wu, J.; El-Kassaby, Y.A.; Grossnickle, S.C.; Feng, J.-L. Fertilization regulates accumulation and allocation of biomass and nutrients in Phoebe bournei seedlings. *Agriculture* **2021**, *11*, 1187. [CrossRef]
32. Shao, A.; Sun, Z.; Fan, S.; Xu, X.; Wang, W.; Amombo, E.; Yin, Y.; Li, X.; Wang, G.; Wang, H. Moderately low nitrogen application mitigate the negative effects of salt stress on annual ryegrass seedlings. *PeerJ* **2020**, *8*, e10427. [CrossRef] [PubMed]
33. Hafsi, C.; Falleh, H.; Saada, M.; Ksouri, R.; Abdelly, C. Potassium deficiency alters growth, photosynthetic performance, secondary metabolites content, and related antioxidant capacity in *Sulla carnosa* grown under moderate salinity. *Plant Physiol.Biochem.* **2017**, *118*, 609–617. [CrossRef] [PubMed]
34. Ahanger, M.A.; Qin, C.; Begum, N.; Maodong, Q.; Dong, X.X.; El-Esawi, M.; El-Sheikh, M.A.; Alatar, A.A.; Zhang, L. Nitrogen availability prevents oxidative effects of salinity on wheat growth and photosynthesis by up-regulating the antioxidants and osmolytes metabolism, and secondary metabolite accumulation. *BMC Plant Biol.* **2019**, *19*, 479. [CrossRef]
35. Siddiqui, M.H.; Mohammad, F.; Khan, M.N.; Al-Whaibi, M.H.; Bahkali, A.H. Nitrogen in Relation to Photosynthetic Capa city and Accumulation of Osmo protectant and Nutrients in Brassica Genotypes Grown Under Salt Stress. *Agric. Sci. China* **2010**, *9*, 671–680. [CrossRef]
36. Xia, Z.; Zhang, S.; Wang, Q.; Zhang, G.; Fu, Y.; Fu, Y.; Lu, H.; Lu, H. Effects of root zone warming on maize seedling growth and photosynthetic characteristics under different phosphorus levels. *Front. Plant Sci.* **2021**, *12*, 746152. [CrossRef] [PubMed]
37. Zhang, D.; Zhang, C.; Tang, X.; Li, H.; Zhang, F.; Rengel, Z.; Whalley, W.R.; Davies, W.J.; Shen, J. Increased soil phosphorus availability induced by faba bean root exudation stimulates root growth and phosphorus uptake in neighbouring maize. *New Phytol.* **2016**, *209*, 823–831. [CrossRef]
38. Shi, X.; Zhou, D.; Guo, P.; Zhang, H.; Dong, J.; Ren, J.; Jiang, C.; Zhong, C.; Zhao, X.; Yu, H. External potassium mediates the response and tolerance to salt stress in peanut at the flowering and needling stages. *Photosynthetica* **2020**, *58*, 1141–1149. [CrossRef]
39. Gul, M.; Wakeel, A.; Steffens, D.; Lindberg, S. Potassium-induced decrease in cytosolic Na^+ alleviates deleterious effects of salt stress on wheat (*Triticum aestivum* L.). *Plant Biol.* **2019**, *21*, 825–831. [CrossRef]
40. Rady, M.M.; Mossa, A.-T.H.; Youssof, A.M.; Osman, A.S.; Ahmed, S.M.; Mohamed, I.A. Exploring the reinforcing effect of nano-potassium on the antioxidant defense system reflecting the increased yield and quality of salt-stressed squash plants. *Sci. Hortic.* **2023**, *308*, 111609. [CrossRef]
41. Chen, W.; Hou, Z.; Wu, L.; Liang, Y.; Wei, C. Effects of salinity and nitrogen on cotton growth in arid environment. *Plant Soil* **2010**, *326*, 61–73. [CrossRef]
42. Munns, R. Comparative physiology of salt and water stress. *Plant Cell Environ.* **2002**, *25*, 239–250. [CrossRef] [PubMed]

43. Liu, L.; Miao, Q.; Wang, H.; Xue, Y.; Qi, S.; Zhang, J.; Li, J.; Meng, Q.; Cui, Z. Optimizing phosphorus application for winter wheat production in the coastal saline area. *Agronomy* **2022**, *12*, 2966. [CrossRef]
44. Chen, Z.; Pottosin, I.I.; Cuin, T.A.; Fuglsang, A.T.; Tester, M.; Jha, D.; Zepeda-Jazo, I.; Zhou, M.; Palmgren, M.G.; Newman, I.A. Root plasma membrane transporters controlling K^+/Na^+ homeostasis in salt-stressed barley. *Plant Physiol.* **2007**, *145*, 1714–1725. [CrossRef] [PubMed]
45. Tester, M.; Davenport, R. Na^+ tolerance and Na^+ transport in higher plants. *Ann. Bot.* **2003**, *91*, 503–527. [CrossRef] [PubMed]
46. Yang, Z.; Tan, S.; Yang, Q.; Chen, S.; Qi, C.; Liu, X.; Liang, J.; Wang, H. Nitrogen Application Alleviates Impairments for *Jatropha curcas* L. Seedling Growth under Salinity Stress by Regulating Photosynthesis and Antioxidant Enzyme Activity. *Agronomy* **2023**, *13*, 1749. [CrossRef]
47. Giambalvo, D.; Amato, G.; Borgia, D.; Ingraffia, R.; Librici, C.; Lo Porto, A.; Puccio, G.; Ruisi, P.; Frenda, A.S. Nitrogen availability drives mycorrhizal effects on wheat growth, nitrogen uptake and recovery under salt stress. *Agronomy* **2022**, *12*, 2823. [CrossRef]
48. Li, L.; Tang, C.; Rengel, Z.; Zhang, F.S. Calcium, magnesium and microelement uptake as affected by phosphorus sources andinterspecific root interactions between wheat and chickpea. *Plant Soil* **2004**, *261*, 29–37. [CrossRef]
49. Zhang, L.; Jiang, Q.; Zong, J.; Guo, H.; Liu, J.; Chen, J. Effects of Supplemental Potassium on the Growth, Photosynthetic Characteristics, and Ion Content of Zoysia matrella under Salt Stress. *Horticulturae* **2023**, *10*, 31. [CrossRef]
50. Gao, Y.; Li, D. Assessing leaf senescence in tall fescue (*Festuca arundinacea* Schreb.) under salinity stress using leaf spectrum. *Eur. J. Hortic. Sci* **2015**, *80*, 170–176. [CrossRef]
51. Mauchamp, A.; Mésleard, F. Salt tolerance in Phragmites australis populations from coastal Mediterranean marshes. *Aquat. Bot.* **2001**, *70*, 39–52. [CrossRef]
52. Elhanafi, L.; Houhou, M.; Rais, C.; Mansouri, I.; Elghadraoui, L.; Greche, H. Impact of excessive nitrogen fertilization on the biochemical quality, phenolic compounds, and antioxidant power of *Sesamum indicum* L. seeds. *J. Food Qual.* **2019**, *2019*, 9428092. [CrossRef]
53. Tang, H.; Niu, L.; Wei, J.; Chen, X.; Chen, Y. Phosphorus limitation improved salt tolerance in maize through tissue mass density increase, osmolytes accumulation, and Na^+ uptake inhibition. *Front. Plant Sci.* **2019**, *10*, 856. [CrossRef] [PubMed]
54. Daoud, B.; Pawelzik, E.; Naumann, M. Different potassium fertilization levels influence water-use efficiency, yield, and fruit quality attributes of cocktail tomato—A comparative study of deficient-to-excessive supply. *Sci. Hortic.* **2020**, *272*, 109562. [CrossRef]
55. Duan, M.; Chang, S.X. Nitrogen fertilization improves the growth of lodgepole pine and white spruce seedlings under low salt stress through enhancing photosynthesis and plant nutrition. *For. Ecol. Manag.* **2017**, *404*, 197–204. [CrossRef]