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Effects of Electrostatic Field and CO_2 Interaction on Growth and Physiological Metabolism in Asparagus

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Abstract

Asparagus (*Asparagus officinalis* L.) is a highly nutritious vegetable rich in various bioactive compounds. Ensuring both yield improvement and quality preservation is a shared goal for producers and researchers. As novel green yield-enhancing technologies in facility agriculture, electrostatic fields and elevated CO_2 application hold significant potential. This study investigated the effects of the interaction between electrostatic fields and elevated CO_2 on the growth and physiological characteristics of asparagus. The results demonstrated that the combined treatment of electrostatic fields and elevated CO_2 significantly increased total yield, tender stem number, and single tender stem weight of asparagus, while also shortening the harvesting period and promoting rapid shoot growth. Additionally, the treatment markedly enhanced the total chlorophyll content in asparagus leaves, improving photosynthetic capacity. By boosting antioxidant enzyme activities (e.g., SOD, APX) and reducing malondialdehyde (MDA) levels, the treatment maintained the redox homeostasis of asparagus shoots, effectively mitigating oxidative damage. In terms of nutrient accumulation, the interaction between electrostatic fields and elevated CO_2 significantly promoted the synthesis and accumulation of key nutrients, including soluble sugars, reducing sugars, soluble proteins, total phenolics, total flavonoids, and ascorbic acid, thereby substantially improving the nutritional quality of asparagus. Comprehensive analysis using fuzzy membership functions revealed that the combined treatment of electrostatic fields and elevated CO_2 outperformed individual treatments in enhancing asparagus growth and physiological characteristics. This study provides important theoretical insights and technical support for the efficient and sustainable cultivation of asparagus in facility agriculture.

Keywords: asparagus; electrostatic field; CO_2; growth and physiology

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Academic Editor: Francesco Marinello

Received: 10 March 2025
Revised: 24 June 2025
Accepted: 26 June 2025
Published: 30 June 2025

Citation: Liu, X.; Liang, L.; Chen, P.; Peng, W.; Guo, K.; Huang, X.; Qin, C.; Luo, Z.; Ouyang, K.; Jiang, C.; et al. Effects of Electrostatic Field and CO_2 Interaction on Growth and Physiological Metabolism in Asparagus. *Agriculture* **2025**, *15*, 1416. https://doi.org/10.3390/agriculture15131416

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1. Introduction

Asparagus (*Asparagus officinalis* L.), a perennial herbaceous species belonging to the genus Asparagus in the Liliaceae family, is cultivated worldwide for its edible young shoots. As a traditional medicinal herb, asparagus has various pharmacological properties, including antioxidant [1], anti-inflammatory [2], antitumor [3], antiepileptic [4], immune-boosting [5], antidiabetic [6], hypolipidemic [7], and hypotensive effects [8]. The tender shoots contain various compounds such as thiophene, thiazole, aldehydes, ketone vanillin,

asparagusic acid, and its methyl and ethyl esters, which can be used as flavors [9]. Furthermore, asparagus is a popular vegetable, rich in polysaccharides, polyphenols, flavonoids, vitamin C, anthocyanins, saponins, and all types of essential amino acids [1,5,10,11].

Modern facility agriculture utilizes controllable external electric fields, constructed based on atmospheric electrical principles within plant growth environments, which can promote metabolic processes, seed germination, rapid growth, and resistance to diseases and environmental stresses in plants [12,13]. It has been demonstrated that electric fields can facilitate seed germination in crops such as Daikon radish [14], wheat [15], and potato [16], while also promoting the rapid growth in lettuce [17], cotton [18], and pea [19]. Notably, the effect of electric fields on plant germination and growth depends on the plant species. The presence of electric fields positively influences radish germination and growth, while reducing germination rates in oat seeds [20]. Substantial research reveals that electric field application can elevate free radical levels and enhance antioxidant enzyme activities. For instance, after treatment with high-voltage electric fields, pomegranate demonstrated significantly enhanced activities of superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase (APX). The content of secondary metabolites in plants is significantly increased under electric field treatment [21]; anthocyanins and phenolic compounds in blueberries increased by 10% and 25%, respectively, after pulsed electric field treatments [22]. Furthermore, electric field exposure improves photosynthetic efficiency, root vitality, and mineral absorption in kale [23]. The technology also affects trace metal content in plants, as demonstrated by significant accumulation and uptake of Cu in lettuce roots and shoots under 10 Hz and 50 Hz alternating current electrical field [24]. Moratto et al. demonstrated that the application of weak external electric fields significantly reduces the attachment of *Phytophthora palmivora* zoospores to *Medicago truncatula* roots, providing new approaches and methods for agricultural disease control [25].

CO_2 is an essential substance in plant growth and metabolism, directly involved in photosynthesis. Higher concentrations of CO_2 enhance photosynthesis, thereby promoting plant growth [26]. The current atmospheric CO_2 concentration is 413 ppm, as retrieved from the National Oceanic and Atmospheric Administration's Global Monitoring Laboratory (https://www.esrl.noaa.gov/gmd/ccgg/trends/global.html (accessed on 27 March 2024)) for the year 2020. Under relatively enclosed facility cultivation conditions, the supplementation of CO_2 can promote vegetable growth, enhance photosynthesis, and improve both quality and yield [27–29]. The increase in CO_2 concentration stimulates the accumulation of polyphenols, flavonoids, organic acids, and others, while reducing nitrogen-containing compounds. It also upregulates genes related to the biosynthetic pathways of secondary metabolites, photosynthesis, carbohydrate metabolism, growth and development, as well as stress response genes [30]. Ainsworth et al. demonstrated that the increase in CO_2 concentration leads to higher expression of transcripts involved in cell growth and cell proliferation in the growing leaves of soybean [31]. According to Abzar [32], elevated CO_2 concentrations promote rice seed germination, seedling growth, and seedling vitality under greenhouse conditions. Different plant species respond differently to various CO_2 concentrations, and the conclusions may vary depending on the plant species. Some studies have also shown that elevated CO_2 levels significantly increase protein concentration in beans [33] but inhibit the nutritional quality of lettuce and spinach [34]. In addition, CO_2 increment can regulate the expression of antioxidant enzymes. For example, exposure to elevated CO_2 concentrations (2% and 5%) in wheat resulted in a significant decrease in malondialdehyde (MDA) levels. SOD activity was highest at 0.5% CO_2 but decreased at 2% and 5% CO_2. APX activity increased with CO_2 concentration, while CAT activity increased at 1% CO_2 and then decreased at higher CO_2 concentrations [35]. Four cruciferous vegetable seedlings (Chinese cabbage, bok choy, radish, and red young radish) exposed

to elevated CO_2 show induced expression of ascorbic acid biosynthetic genes, resulting in increased ascorbic acid accumulation and enhanced SOD activity [36].

Exposure to electric fields has been shown to enhance CO_2 uptake in plants, which increases photosynthetic efficiency and growth rates, ultimately resulting in significantly higher yields under greenhouse conditions [37]. Despite its promise, this technology has seen limited application in asparagus; we therefore investigated the interaction between spatial electric fields and CO_2 on both growth and physiological traits. By analyzing physiological and biochemical indicators, including stem diameter, yield, growth duration of harvestable shoots, chlorophyll content, antioxidant enzymes (such as superoxide dismutase, peroxidase, catalase, ascorbate peroxidase, polyphenol oxidase, malondialdehyde), and nutrients (soluble sugars, reducing sugar, soluble proteins, amino acids, nitrates, ascorbic acid, total flavonoids, total phenolics, cellulose), we aimed to clarify asparagus's response to electric fields and CO_2, providing a theoretical basis for high-quality, high-yield asparagus production.

2. Materials and Methods

2.1. Plant Material and Experimental Devices

The experiment was conducted from September 2023 to June 2024 in an experimental greenhouse with controllable light and temperature conditions at the Chengdu Academy of Agriculture and Forestry Sciences, Sichuan Province, China (103°51′ E, 30°42′ N). Three-year-old cultivated asparagus Fengdao No. 2 was used as the experimental material. Plants were cultivated in plastic flowerpots with a mixed substrate consisting of organic soil, peat, vermiculite, and perlite in a volumetric ratio of 4:2:1:1. Each flowerpot retained 2 to 3 asparagus mother stems, approximately 120 cm in height, to ensure a consistent nutrient supply, and were regularly irrigated with Hoagland nutrient solution. Each treatment consisted of 11 pots, and the experiment was replicated three times.

The greenhouse environment was maintained with a light intensity of 8000 Lux, a temperature range of 19 °C to 27 °C, and relative humidity of 53% to 73%, with real-time monitoring of environmental parameters using FALA IOT S21A2 carbon dioxide detector (Xuzhou Fala Electronic Technology Co., Ltd., Xuzhou, China). The electrostatic device was composed of a generator, electrode wires, insulators, and a main power supply. Four insulators were aligned in a single row at 60 cm intervals. The device operated in an intermittent cyclic mode (30 min operation/15 min idle). The CO_2 supplementation system consisted of a CO_2 gas cylinder, timer, and controller, and CO_2 was supplemented daily from 09:00 to 15:00 to achieve target concentrations, while ventilation was activated during non-supplementation periods to maintain ambient airflow.

2.2. Experimental Design

In this experiment, an elevated CO_2 concentration of 800 ppm was selected. Four treatment groups were established, with 11 pots per group, totaling 44 pots: Group A (Control): no electrostatic field, ambient CO_2 (400 ppm). Group B: no electric field, elevated CO_2 (800 ppm). Group C: electric field present, elevated CO_2 (800 ppm). Group D: electric field present, ambient CO_2 (400 ppm). These treatments were applied for 90 days following the end of the harvest period, under otherwise identical growth conditions. Daily growth monitoring was conducted, with Day 0 defined as the emergence of new tender 0 cm to 1.5 cm above the soil surface. Asparagus were harvested upon reaching a height of 25 cm. On the 60th day of treatment, plant samples were collected, including the main stems, as well as the leafy branches from the portion of the plant 60–90 cm above the ground. All samples were flash-frozen in liquid nitrogen and stored in a −80 °C ultra-low temperature freezer for subsequent physiological analyses.

2.3. Growth Parameters Determination

The time of Asparagus harvest was recorded as the number of days required for a tender stem to emerge to a plant height of 25 cm. The harvest timing data were statistically analyzed and visualized as percentage stacked column charts. The stem diameter of harvested young shoots was measured using a digital vernier caliper (accuracy: 0.01 mm) at a height of 2 cm above ground, and the average value was recorded as the tender stem diameter. Single tender stem fresh weight was determined by averaging triplicate measurements of harvested Asparagus with a 1/10,000 electronic balance. All data were statistically processed based on the number of Asparagus harvested per group.

2.4. Pigment Quantification

The concentrations of chlorophyll a, chlorophyll b, and carotenoids were determined by spectrophotometry [38]. Fresh leaf and branch samples (0.25 g) were homogenized in 96% ethanol containing quartz sand and $CaCO_3$. The homogenate was filtered and adjusted to a final volume of 50 mL in a brown volumetric flask. The absorbance of the supernatant was measured at 470, 645, and 663 nm using a Multiskan FC Microplate Reader (Thermo Fisher Scientific, Waltham, MA, USA). The average concentrations of the photosynthetic pigments were calculated using the relevant formulas. Three technical replicates and three biological replicates were performed for each experimental group.

2.5. Determination of Nutrients and Secondary Metabolites

The tender stems, main stems, and leafy branches were used to determine the content of nutrients and secondary metabolites. Total soluble sugars were measured using the anthrone–sulfuric acid method [39]. A 0.05 g dried sample was extracted with 80% ethanol, decolorized, and made up to volume. A total of 1 mL of the extract was mixed with the anthrone reagent and heated in a boiling water bath to develop color. The absorbance was measured at 625 nm, and the total soluble sugar content was calculated using a glucose standard curve. The reducing sugar content was measured using the 3,5-dinitrosalicylic acid (DNS) method [40]. A 0.5 g dry sample was mixed with ddH_2O, shaken, and centrifuged. The supernatant was reacted with the DNS reagent. The absorbance was measured at 520 nm, and the reducing sugar content was calculated based on a glucose standard curve. The soluble protein content was determined using the Coomassie Brilliant Blue staining method [39]. The absorbance was measured at 595 nm, and the soluble protein content was calculated based on a bovine serum albumin standard curve. Using ultrasonic extraction [41–44], the total soluble phenolic content was determined referring to Wu's Folin–phenol method [45]. Fresh tissue was ground in liquid nitrogen, then 80% methanol was added. Ultrasonic extraction was then performed under dark conditions (40 kHz, 30 min), and centrifuged. The supernatant was mixed with Folin–phenol reagent and sodium carbonate to develop color. After a 1-h reaction in the dark, the absorbance was measured at 725 nm, and the soluble phenolic content was calculated using a Catechol standard curve. The cellulose content was measured using a programmed analysis method [46]. The absorbance was measured at 620 nm, and the sugar content was calculated based on a glucose standard curve, with the result multiplied by a factor of 0.9 to obtain the cellulose content. The amino acid and flavonoid contents were measured using the Amino Acid (AA) Content Assay Kit and Plant Flavonoids Content Assay Kit provided by Beijing Boxbio Science & Technology Co., Ltd. (Beijing, China). The content of ascorbic acid was determined by ultraviolet spectrophotometry [47]. The nitrate content was determined using ultraviolet spectrophotometry [48].

2.6. Antioxidant Capacity Determination

The determination of antioxidant capacity was performed according to the method described by Wu [45]. The 0.5 g fresh tissue was fully homogenized with 5 mL (pH = 7.8) phosphate buffer, then centrifugated at 3000 rpm for 20 min, with the entire process carried out at 4 °C. Superoxide dismutase (SOD) activity was determined by the nitroblue tetrazolium assay, and peroxidase (POD) activity was determined by the guaiacol method. Catalase (CAT) activity was measured using a spectrophotometric method, and malondialdehyde (MDA) content was determined using the thiobarbituric acid (TBA) method [45]. Ascorbate peroxidase (APX) activity was measured using the hydrogen peroxide reduction method. Nitrate reductase (NR) activity was measured using the NADH reduction method [49], where the enzyme-catalyzed reaction was terminated by adding sulfanilamide solution, followed by incubation with N-1-naphthylethylenediamine solution. After 15 min of color development, the mixture was centrifuged at 4000 rpm for 5 min, and the absorbance of the supernatant was measured at 540 nm.

2.7. Comprehensive Evaluation Based on Fuzzy Membership Function Analysis

Fuzzy membership function analysis was performed on the measured indicators using Dai's method [50]. The calculation formula for the fuzzy membership function value is as follows:

$$\mathrm{Ui} = (\mathrm{Xi} - \mathrm{Xmin})/(\mathrm{Xmax} - \mathrm{Xmin}) \quad (1)$$

The calculation formula for the inverse fuzzy membership function value is as follows:

$$\mathrm{Ui} = 1 - (\mathrm{Xi} - \mathrm{Xmin})/(\mathrm{Xmax} - \mathrm{Xmin}) \quad (2)$$

Here, Xi represents the measured value of the indicator, while Xmax and Xmin denote the maximum and minimum values of that indicator across all treatments, respectively.

2.8. Statistical Analyses

All Experimental data were analyzed by using Excel 2021 software (Microsoft Corporation, Redmond, WA, USA), and statistical analyses were conducted using SPSS 25.0 statistical software (IBM Corporation, Armonk, NY, USA). Data graphs were created using Origin 2022 software (OriginLab Corporation, Northampton, MA, USA). The least significant difference (LSD) method was used for multiple comparisons, and significant differences ($p < 0.05$) were indicated by different letters. The data in the tables and figures are presented as mean ± standard deviation (Mean ± SEM).

3. Result Analysis

3.1. Growth Is Improved by Electric Stimulation and CO_2 Enrichment

To investigate the effects of increased carbon dioxide and electric fields on the harvest time of asparagus, a comparative analysis was conducted on the harvest time of different treatment groups after the emergence of tender stems (Figure 1). The harvest time for Group A (control group) and Group D (electric field alone group) spanned 3–6 days post-emergence, with the highest proportion of harvesting occurring on day 5. This indicates that the electric field exhibited negligible regulatory effects on asparagus growth during this stage. In contrast, Groups B and C showed a concentrated harvest window of 2–5 days post-emergence, with the highest proportion of harvesting occurring on day 4. Compared to Groups A and D, CO_2 supplementation advanced the harvest timing by 1 day, indicating that the application of carbon dioxide promotes the rapid growth and maturation of asparagus, leading to an earlier harvesting time. Comparing groups B and C, it was found that the harvest ratio of Group C was higher than that of Group B on the 2nd

and 5th day, indicating that the interaction between the electric field and CO_2 had a better effect on asparagus growth.

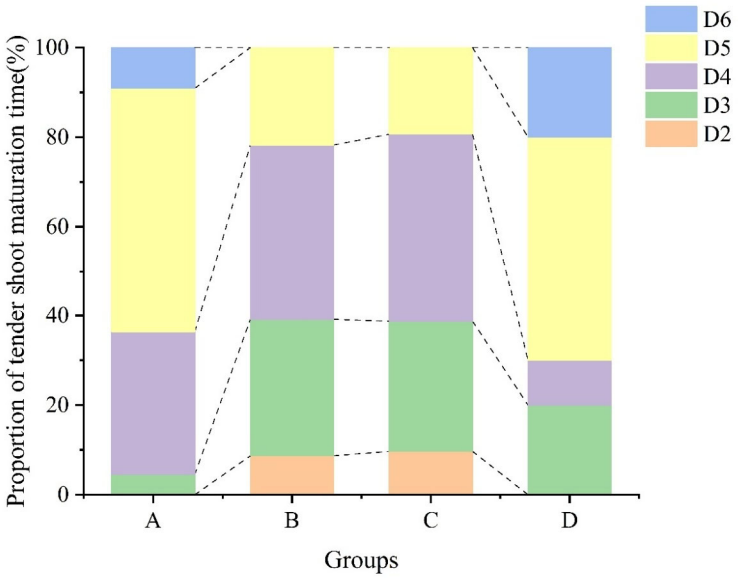


Figure 1. Effects of the interaction between electric field and carbon dioxide on the harvesting time distribution of mature asparagus spears. The horizontal coordinates A–D in the figure represent different treatment groups. A: Control group without electric field and carbon dioxide. B: Treatment group with elevated carbon dioxide but without electric field. C: Treatment group with both elevated electric field and carbon dioxide. D: Treatment group with electric field but without elevated carbon dioxide. The "D" in the legend represents the days when the asparagus tender stems break ground and can be harvested. For example, "D6" indicates that the asparagus tender stems reached harvestable height on the 6th day after breaking ground.

According to the data analysis in Table 1, all three treatments (B, C, and D) increased the total yield and single tender stem weight of asparagus. Total yield, tender stem number, and single tender stem weight in Groups B and C were significantly higher compared with those in Group A. Among them, Group B showed the highest total yield and tender stem number, with increases of 101.8% and 57.6%, respectively; however, there was no significant difference between Groups B and C. The diameter and weight of asparagus tender stems in Group D were significantly increased, but the number of harvested tender stems decreased slightly. To sum up, the total yield, tender stem number, and single tender stem weight of asparagus were significantly promoted by increasing carbon dioxide application, and the space electric field treatment mainly promoted the tender stem diameter and single tender stem weight of asparagus.

Table 1. Effects of the interaction between electrostatic field and carbon dioxide on total yield, tender stem diameter, tender stem number, and single tender stem weight of asparagus.

Treatment	Total Yield (g)	Tender Stem Diameter (mm)	Tender Stem Number	Single Tender Stem Weight (g)
A	104.93 ± 2.09 c	5.85 ± 0.06 b	22.00 ± 0.58 b	4.77 ± 0.07 d
B	211.77 ± 1.47 a	5.96 ± 0.13 b	34.67 ± 0.33 a	6.11 ± 0.06 c
C	208.13 ± 8.69 a	6.11 ± 0.15 b	32.33 ± 1.2 a	6.44 ± 0.07 b
D	117.56 ± 3.30 b	7.05 ± 0.11 a	17.67 ± 0.67 c	6.66 ± 0.06 a

Values are expressed as means ± SEM of three biological replicates. Different lowercase letters within a column indicate significant differences between groups ($p < 0.05$). A: Control group without electric field and carbon dioxide. B: Treatment group with elevated carbon dioxide but without electric field. C: Treatment group with both elevated electric field and carbon dioxide. D: Treatment group with electric field but without elevated carbon dioxide.

3.2. Electric Field and CO_2 Synergy Enhances Chlorophyll Content in Asparagus Cladodes

As shown in Table 2, Group C exhibited the highest contents of chlorophyll a, chlorophyll b, and total chlorophyll, which were significantly higher than those in Group A by 38.2%, 12.5%, and 27.2%, respectively. Notably, chlorophyll a content in Groups B, C, and D increased by 16.1%, 38.2%, and 3.3%, respectively. A significant increase in chlorophyll b content was only observed in Group C (12.5%). Total chlorophyll content was also significantly increased in Groups B and C by 8.7% and 27.2%, respectively, while the increase observed in Group D was not statistically significant. These results demonstrate that the synergistic interaction between the electric field and elevated CO_2 significantly enhances chlorophyll biosynthesis in asparagus leaves, whereas the electric field alone does not significantly increase total chlorophyll content.

Table 2. Effects of the interaction between electrostatic field and CO_2 on chlorophyll content in asparagus leaves. Unit: $mg \cdot g^{-1}$.

Treatment	Chlorophyll a	Chlorophyll b	Total Chlorophyll
A	1.27 ± 0.02 c	0.95 ± 0.01 b	2.23 ± 0.03 c
B	1.47 ± 0.02 b	0.94 ± 0.01 b	2.41 ± 0.03 b
C	1.76 ± 0.02 a	1.07 ± 0.01 a	2.83 ± 0.02 a
D	1.31 ± 0.02 c	0.95 ± 0.01 b	2.26 ± 0.03 c

Values are expressed as means ± SEM of three biological replicates. A: Control group without electric field and carbon dioxide. B: Treatment group with elevated carbon dioxide but without electric field. C: Treatment group with both elevated electric field and carbon dioxide. D: Treatment group with electric field but without elevated carbon dioxide. Different lowercase letters within a column indicate significant differences between groups ($p < 0.05$).

3.3. Effects of the Interaction Between Electrostatic Field and Carbon Dioxide on Antioxidant Capacity in Asparagus

This study investigated the effects of the interaction between electrostatic field and carbon dioxide on the antioxidant capacity of asparagus by measuring antioxidant enzymes and related chemical substances in the spears, main stems, and cladodes. Superoxide dismutase (SOD), a key enzyme in the antioxidant defense system, catalyzes the conversion of superoxide radicals (O_2^-) into hydrogen peroxide (H_2O_2). The experimental results showed that under Treatments B, C, and D, SOD enzyme activity in the spears, main stems, and cladodes of asparagus increased significantly (Figure 2A). Specifically, in the spears, Group B exhibited the highest SOD activity, which was 48.3% higher than that of the control group, followed by Groups D and C, with Group C showing significantly lower SOD activity compared to Groups B and D. In the main stems, Group D demonstrated the highest SOD activity, which was 53.9% higher than that of the control group. In the cladodes, Group B had the highest SOD activity, with no significant differences observed among Groups B, C, and D.

Peroxidase (POD) is closely associated with the antioxidant capacity of plants. It catalyzes the conversion of peroxides into other oxides, participates in various redox reactions, and scavenges hydroxyl radicals (·OH), thereby mitigating oxidative stress-induced cellular damage. As shown in Figure 2B, the POD enzyme activity varied significantly across different parts of the asparagus. In the spears, Group B exhibited the highest POD activity, which was 13.8% higher than that of the control group, while Groups C and D showed reductions of 17.1% and 5.5%, respectively. In the main stems, Group D demonstrated the highest POD activity, significantly exceeding that of the control group, whereas Group C had the lowest POD activity. In the cladodes, the POD activities of Groups B, C, and D were significantly lower than those of the control group, with Group C showing the lowest activity. These results indicate that the interaction between electrostatic field and carbon dioxide has varying effects on POD enzyme activity in different parts of the asparagus. While POD activity in the spears and main stems was enhanced under certain treatments, it

was generally reduced in the cladodes. This may be attributed to the differential response mechanisms of various plant parts to the treatments.

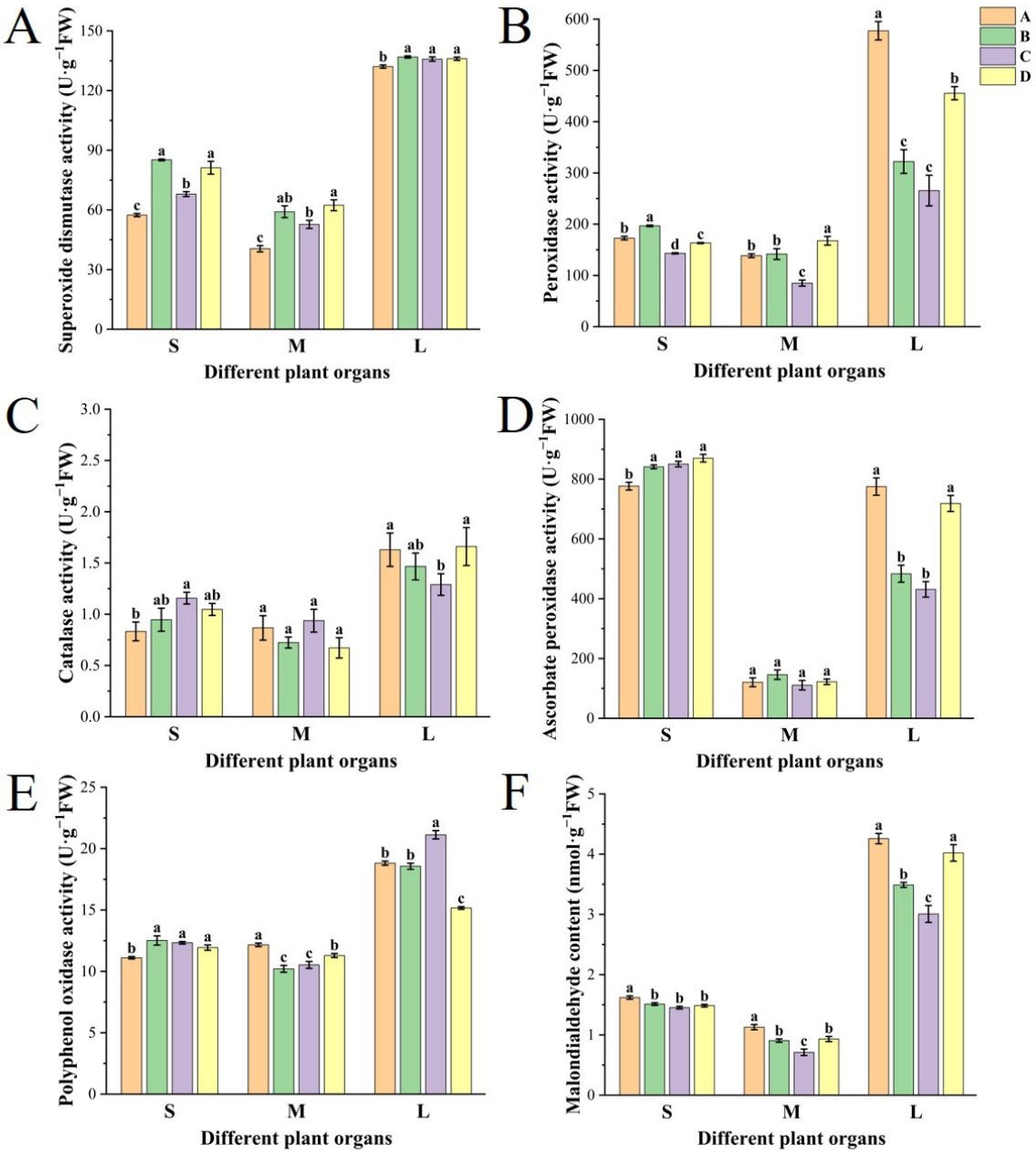


Figure 2. Effects of the interaction between electrostatic field and CO_2 on antioxidant capacity in different parts of asparagus. The alphanumeric labels (**A**–**F**) in the upper-left corner denote figure panel identifiers. (**A**) Superoxide dismutase (SOD); (**B**) peroxidase (POD); (**C**) catalase (CAT); (**D**) ascorbate peroxidase (APX); (**E**) polyphenol oxidase (PPO); and (**F**) malondialdehyde (MDA) content. Different lowercase letters at the top of the column bars in the same organ indicate significant differences between groups ($p < 0.05$). Distinct colors within the figure correspond to experimental treatments A–D. A: Control group without electric field and carbon dioxide. B: Treatment group with elevated carbon dioxide but without electric field. C: Treatment group with both elevated electric field and carbon dioxide. D: Treatment group with electric field but without elevated carbon dioxide. S: tender stem; M: main stem; L: cladodes. Values are expressed as means ± SEM of three biological replicates.

Catalase (CAT) is a key component of the plant antioxidant enzyme system, maintaining reactive oxygen species (ROS) metabolic balance by scavenging excess hydrogen

peroxide (H_2O_2) within cells. The experimental results demonstrated that the interaction between electrostatic field and CO_2 significantly enhanced CAT enzyme activity in the spears and main stems of the asparagus, with Group C showing the most pronounced effect (Figure 2C), increasing by 39.1% and 8.2%, respectively, compared to the control group. Specifically, in the spears, Group C exhibited the highest CAT activity, followed by Groups D and B, while the control group (Group A) had the lowest CAT activity. In the main stems, Group C also showed the highest CAT activity, whereas Groups B and D had slightly lower CAT activity than the control group, though the differences were not significant. In the cladodes, Group C had the lowest CAT activity, significantly lower than the control group, while Groups B and D also showed reduced CAT activity compared to the control, but the differences were not significant. These results indicate that the interaction between electrostatic field and CO_2 significantly regulates CAT enzyme activity in different parts of the asparagus. Specifically, CAT activity was notably enhanced in the spears and main stems, while it was generally reduced in the cladodes.

Ascorbate peroxidase (APX) is a key antioxidant enzyme in the reactive oxygen species (ROS) metabolic pathway of plants. It regulates cellular redox homeostasis by utilizing ascorbate (ASA) as a specific electron donor to maintain normal plant growth and synergizes with catalase (CAT) to scavenge hydrogen peroxide (H_2O_2), thereby protecting cells from oxidative damage. The experimental results (Figure 2D) showed that Treatments B, C, and D significantly enhanced APX activity in asparagus spears, with Group D exhibiting the highest activity, increasing by 7.7% (Group B), 8.7% (Group C), and 10.8% (Group D) compared to the control group. However, in the cladodes, APX activity in Groups B and C was significantly reduced by 37.6% and 44.4%, respectively, with Group C showing the lowest APX activity among all groups.

Polyphenol oxidase (PPO) consumes substrates by catalyzing the oxidation of phenolic compounds, which are important antioxidants in plants. Therefore, PPO enzyme activity is usually negatively correlated with the overall antioxidant capacity of plants. As shown in Figure 2E, Treatments B, C, and D significantly increased PPO enzyme activity in asparagus tender shoots. Specifically, in the tender stems, PPO enzyme activity in groups B, C, and D increased by 11.3%, 9.9%, and 6.9%, respectively, compared to the control group, but no significant differences were observed among the treatment groups. In the main stems, PPO enzyme activity in groups B, C, and D decreased by 16.1%, 13.5%, and 7.1%, respectively, with Group B showing the lowest activity. The enzyme activity in groups B and C was significantly lower than in Group D. In the cladodes, Group C showed the highest PPO enzyme activity, significantly higher than the other treatment groups, while Group D exhibited the lowest activity, with significant differences among groups. Enzyme activity in the tender shoots was significantly enhanced, while in the main stems and cladodes, it was either inhibited or showed differential responses. This tissue-specific effect may be related to differences in the regulation of phenolic metabolism pathways.

This study systematically evaluated the regulatory effects of Treatments B, C, and D on oxidative damage in asparagus organs by measuring malondialdehyde (MDA) content (Figure 2F). In spears, MDA levels in all treatment groups were significantly lower than those in the control group, with Group C showing the most pronounced reduction (10.3% decrease vs. A), indicating superior efficacy of Treatment C in mitigating oxidative stress. A consistent trend was observed in main stems, where Group C exhibited a 37.1% reduction in MDA content compared to the control, while Groups B and D showed decreases of 19.9% and 17.4%, respectively, further validating the enhanced antioxidant capacity induced by Treatment C. In leaves, MDA content was highest in the control, with Treatment C achieving the most significant reduction (29.4%), whereas Treatment D displayed limited efficacy (5.6% decrease), potentially due to differential physiological responses or regula-

tory mechanisms in leaves. These results demonstrate that Treatment C optimally reduces MDA accumulation across asparagus organs, particularly alleviating oxidative damage in main stems and leaves, likely through enhancing antioxidant metabolic pathways to attenuate membrane lipid peroxidation.

3.4. Effects of the Interaction Between Electrostatic Field and Carbon Dioxide on Nutrient Dynamics and Metabolic Regulation in Asparagus

As shown in Figure 3A, Treatments B, C, and D significantly promoted soluble sugar accumulation in asparagus. Among them, Group C exhibited the most pronounced accumulation effect across all organs: soluble sugar content in spears, main stems, and cladodes increased significantly by 11.1%, 28.2%, and 25.0%, respectively, compared to the control group (A). Specifically, in Group B, soluble sugar content in spears, main stems, and cladodes increased by 7.8%, 12.1%, and 12.8%, respectively, compared to Group A; in Group D, the corresponding increases were 5.8%, 19.3%, and 16.9%.

We observed in Figure 3B that Treatments B, C, and D significantly promoted reducing sugar accumulation in asparagus spears and main stems, exhibiting differential regulatory characteristics. In spears, the reducing sugar content in groups B, C, and D increased significantly by 29.5%, 22.9%, and 14.5%, respectively, compared to the control group (A), with Group B showing significantly higher accumulation than the other treatment groups. In main stems, Group C performed the best, significantly surpassing groups B and D. In contrast, cladodes exhibited an opposite trend: Group C had the highest reducing sugar content, while groups D and B were significantly lower than the control. Notably, under single treatments of electrostatic field (D) and CO_2 (B), reducing sugar accumulation in cladodes was suppressed, but their combined interaction (C) significantly reversed this inhibitory effect, likely due to synergistic activation of sugar transporter proteins (SWEET) enhancing phloem unloading [51].

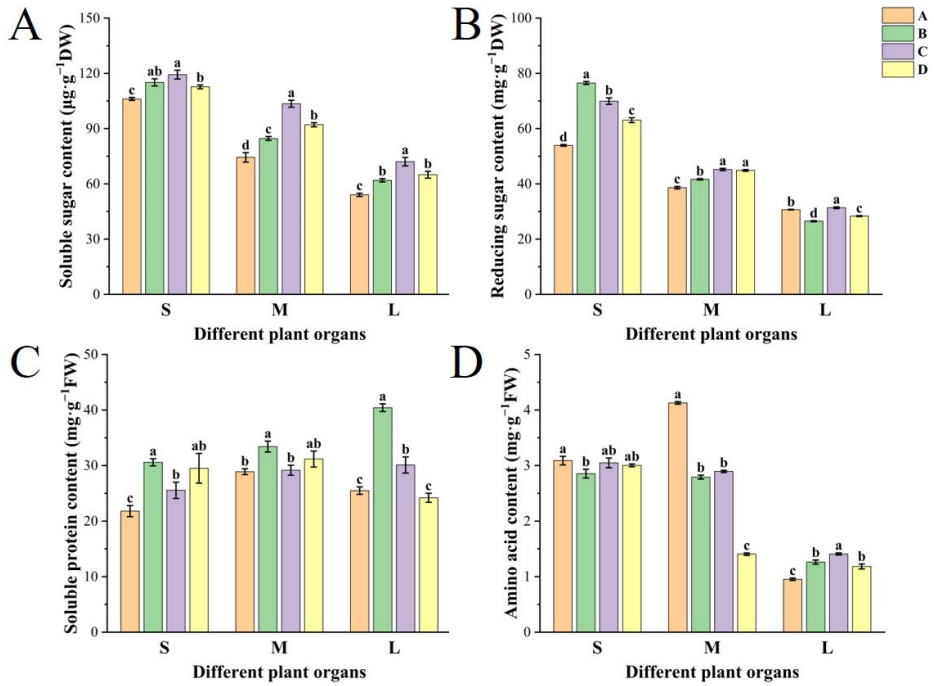


Figure 3. *Cont.*

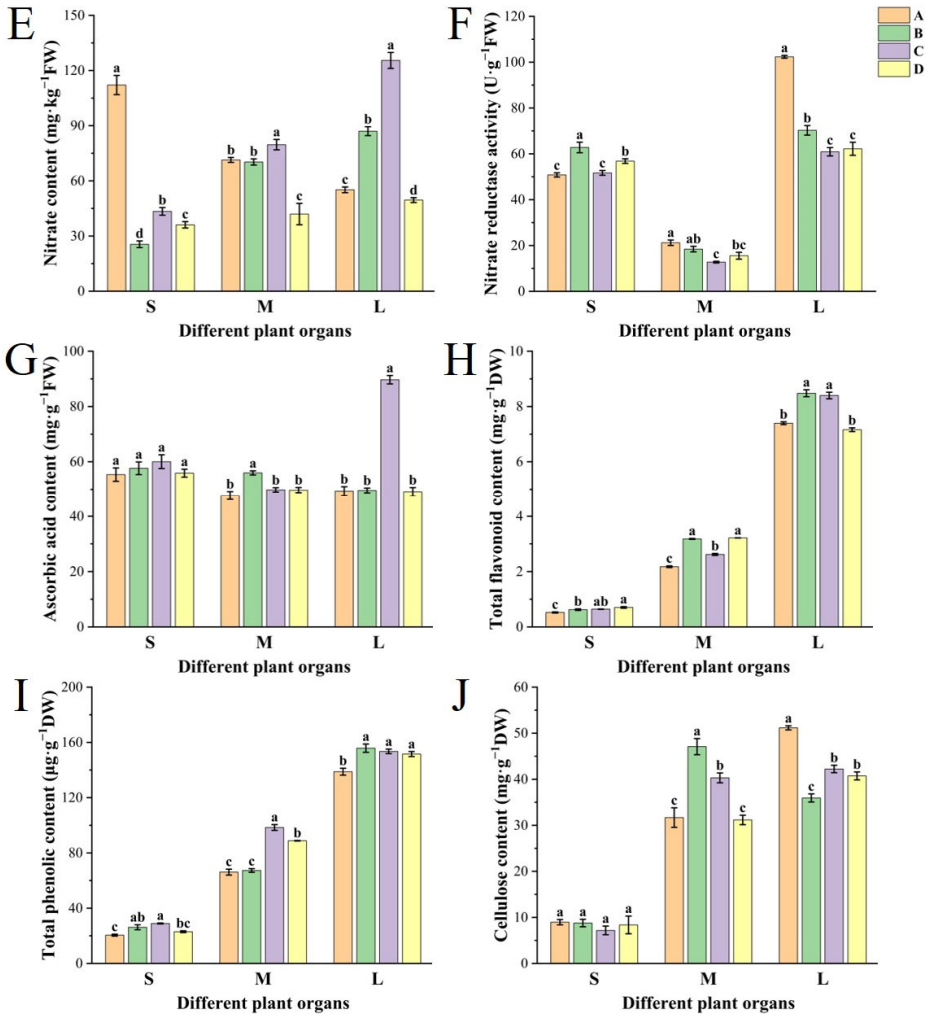


Figure 3. Effects of the interaction between electrostatic field and CO_2 on metabolism and nutritional components in asparagus. The alphanumeric labels (**A**–**J**) in the upper-left corner denote figure panel identifiers. (**A**) Soluble sugar content; (**B**) reducing sugar content; (**C**) soluble protein content; (**D**) amino acid content; (**E**) nitrate content; (**F**) nitrate reductase activity; (**G**) ascorbic acid content; (**H**) total flavonoid content; (**I**) total phenolic content; (**J**) cellulose content. Different lowercase letters at the top of the column bars in the same organ indicate significant differences between groups ($p < 0.05$). Distinct colors within the figure correspond to experimental treatments A–D. A: Control group without electric field and carbon dioxide. B: Treatment group with elevated carbon dioxide but without electric field. C: Treatment group with both elevated electric field and carbon dioxide. D: Treatment group with electric field but without elevated carbon dioxide. S: tender stem; M: main stem; L: cladodes. Values are expressed as means ± SEM of three biological replicates.

Soluble proteins, as critical functional components for plant growth and development, serve as the core material basis for regulating metabolic enzyme activity and signal transduction. As shown in Figure 3C, Treatments B, C, and D significantly enhanced soluble protein content in asparagus spears. Among them, Group B exhibited significantly higher soluble protein content in spears, main stems, and cladodes compared to other treatment groups. Specifically, in spears, Group C significantly increased soluble protein content by 14.7% compared to the control group (A), while the increases in main stems (+8.2%) and cladodes (5.4%) were not statistically significant. Group D showed the most significant increase in soluble protein content in spears, potentially due to the activation of voltage-gated ion channels (e.g., K^+/Ca^{2+} channels), which may enhance carbon–nitrogen metabolic flux and thereby promote protein synthesis [52]. However, no significant differences were observed in the main stems and cladodes. Notably, under the interaction of electric field

and CO_2, the accumulation of soluble proteins in spears and main stems was lower than that under single treatments (B and D).

Free amino acids (AA), as fundamental units of protein synthesis and nitrogen metabolism, play a critical role in plant growth and development. As shown in Figure 3D, Treatments B, C, and D significantly regulated amino acid accumulation in different organs of asparagus, exhibiting tissue-specific response patterns. In spears, Treatment B significantly reduced free amino acid content by 7.6% compared to the control group, while Treatments C and D did not cause significant changes. In main stems, Treatment D showed the greatest suppression of amino acid content (significantly decreased by 65.9% compared to the control), followed by Treatments B and C, which decreased by 32.4% and 29.9%, respectively, indicating a progressive hierarchical effect of the treatments on nitrogen allocation in stems. In contrast, cladodes exhibited a significant increase in amino acid content under all treatments, rising by 24.5% (B), 32.5% (C), and 19.5% (D) compared to the control. Notably, Treatment C achieved the highest amino acid accumulation in cladodes, suggesting that this treatment may preferentially activate nitrogen assimilation processes in photosynthetic tissues.

This study systematically evaluated the regulatory effects of Treatments B, C, and D on nitrogen metabolism by quantifying nitrate content across different organs of asparagus compared to the control group (A) (Figure 3E). In spears, the control group (A) exhibited the highest nitrate content (112.13 $mg \cdot kg^{-1}$ FW), while Treatment B achieved the most pronounced reduction (77.3%), followed by Treatments C (61.3%) and D (67.8%), indicating Treatment B's superior efficacy in suppressing nitrate accumulation. In main stems, Treatment C induced a significant nitrate increase (11.7%), whereas Treatment D reduced levels (41.2%). Notably, in cladodes, Treatment C caused a dramatic nitrate surge (127.7%), with minimal data variability (standard error of only 0.17), while Treatment D showed a reduction (10.2%). Overall, Treatment B effectively inhibited nitrate accumulation in spears, potentially enhancing food safety, while Treatment C significantly increased nitrate content in cladodes and main stems.

Nitrate reductase (NR) is a rate-limiting enzyme in nitrogen metabolism, catalyzing the reduction of nitrate to nitrite. Its activity directly reflects the plant's ability to convert nitrate into utilizable nitrogen (Figure 3F). As shown in Figure 3I, Treatments B and D significantly enhanced NR activity in asparagus spears. In spears, NR activity in groups B, C, and D increased by 19.1%, 1.7%, and 10.6%, respectively, with groups B and D showing significant enhancement. In main stems, NR activity in groups B, C, and D decreased by 13.1%, 39.9%, and 26.7%, respectively, with groups C and D showing significant reduction. In cladodes, NR activity significantly decreased across all treatment groups, with Group C showing the lowest activity. The reduction in Group B was significantly less pronounced than in groups C and D. The overall trend of NR activity across tissues was consistent: B > D > C.

Ascorbic acid (vitamin C, AsA), as a core component of the plant antioxidant system, not only serves as a key substrate for ascorbate peroxidase (APX) but also plays multiple regulatory roles in plant growth and development by synergistically scavenging reactive oxygen species (ROS), maintaining redox homeostasis, and protecting photosynthetic machinery [53,54]. As shown in Figure 3G, Treatments B, C, and D exhibited differential effects on AsA accumulation in different organs of asparagus. In spears, Group C increased AsA content by 7.8% compared to the control group (A), while groups B and D increased by 4.0% and 0.95%, respectively, although these changes were not statistically significant; however, Group C still showed the highest accumulation trend. In main stems, Group B exhibited the highest AsA content, significantly increasing by 14.9% compared to Group A and surpassing groups C and D. This is consistent with a previous report of a 13% increase

in AsA content in celery under high CO_2 treatment [55], suggesting that Treatment B may preferentially enhance stem antioxidant capacity by activating the ascorbate regeneration pathway (e.g., monodehydroascorbate reductase, MDHAR). In cladodes, the AsA content in Group C increased by 45.3% compared to Group A, significantly exceeding that of Groups B and D. This confirms the synergistic effect of electric field and CO_2 interaction on AsA synthesis.

Flavonoids are a class of naturally occurring compounds widely present in plants, known for their diverse physiological functions and health benefits [56,57]. This study found (Figure 3H) that Treatments B, C, and D significantly increased total flavonoid content in both spears and main stems of asparagus. Specifically, in spears, Treatment D exhibited the highest total flavonoid content (0.70 $mg \cdot g^{-1}$ DW), representing a significant increase of 34.6% compared to the control group (A), while Treatments B and C increased by 19.5% and 22.9%, respectively, compared to Group A. In main stems, Treatments D and B significantly increased total flavonoid content by 47.8% and 46.2%, respectively, compared to Group A, whereas Treatment C showed a lower increase of 20.4%. In cladodes, Treatments B and C significantly increased total flavonoid content by 14.7% and 13.6%, respectively, compared to Group A, while Treatment D showed a decrease of 3.2%, though this difference was not statistically significant compared to Group A. We observed that Treatment D promoted the accumulation of total flavonoid content in spears and main stems but exhibited an inhibitory effect in cladodes.

Total phenolics are important antioxidant compounds in plants, capable of scavenging free radicals and playing a crucial role in plant growth and development. As shown in Figure 3I, different treatments had significant effects on total phenolic content across various organs of asparagus. In spears, Treatment C exhibited the highest total phenolic content (28.92 $mg \cdot g^{-1}$ DW), representing a significant increase of 41.3% compared to the control group (A), while Treatments B and D increased by 27.9% and 12.3%, respectively, compared to Group A. In main stems, Treatments C and D increased total phenolic content by 48.9% and 34.4%, respectively, compared to Group A, whereas Treatment B showed a non-significant increase of 1.9%. In cladodes, all treatment groups showed significantly higher total phenolic content compared to the control, with Treatments B, C, and D increasing by 12.3%, 10.6%, and 9.2%, respectively. In both spears and main stems, Treatment C exhibited a clear advantage in promoting the increase of total phenolic content, while its increase in cladodes was relatively moderate.

Cellulose is a natural dietary fiber widely present in plant cell walls. This study measured cellulose content in different organs of asparagus and found that in spears, Treatments B, C, and D reduced cellulose content by 2.1%, 20.1%, and 6.6%, respectively, compared to the control Group A, with Treatment C showing the lowest cellulose content (7.16 $mg \cdot g^{-1}$ DW). In main stems, Treatment B exhibited the highest cellulose content (47.08 $mg \cdot g^{-1}$ DW), representing a significant increase of 48.6% compared to Group A. In cladodes, the control group (A) showed the highest cellulose content (51.16 $mg \cdot g^{-1}$ DW), while Treatments B, C, and D reduced cellulose content by 29.7%, 17.5%, and 20.4%, respectively. This mechanism provides a critical theoretical foundation for optimizing asparagus cultivation practices.

3.5. Correlation Analysis

Correlation analysis revealed significant interrelationships among asparagus growth parameters, antioxidant capacity, nutritional indices, and metabolic markers (Figure 4). Total asparagus yield showed positive correlations with tender stem count, total chlorophyll, polyphenol oxidase (PPO) activity, soluble sugars, reducing sugars, ascorbic acid (AsA), total phenols, and cellulose content ($p < 0.05$), but a negative correlation with nitrate

($p < 0.05$). Concurrently, tender stem diameter correlated positively with ascorbate peroxidase (APX) activity and total flavonoids ($p < 0.05$), while exhibiting a negative correlation with tender stem count ($p < 0.05$). The tender stem count demonstrated positive correlations with total chlorophyll, PPO activity, soluble sugars, and total phenols ($p < 0.05$), along with a stronger positive correlation with reducing sugars ($p < 0.01$). Tender stem weight was positively associated with superoxide dismutase (SOD) activity, APX activity, PPO activity, soluble sugars, reducing sugars, total flavonoids, and total phenols ($p < 0.05$), but negatively correlated with malondialdehyde (MDA) and nitrate ($p < 0.01$). Further analysis identified tight linkages between growth parameters and four key metabolites: total chlorophyll correlated positively with total phenols ($p < 0.001$), soluble sugars ($p < 0.01$), and PPO activity ($p < 0.05$), yet negatively with MDA ($p < 0.05$); antioxidant indices showed significant correlations with nitrate, nitrate reductase (NR), and soluble sugars, suggesting involvement in carbon–nitrogen metabolic regulation.

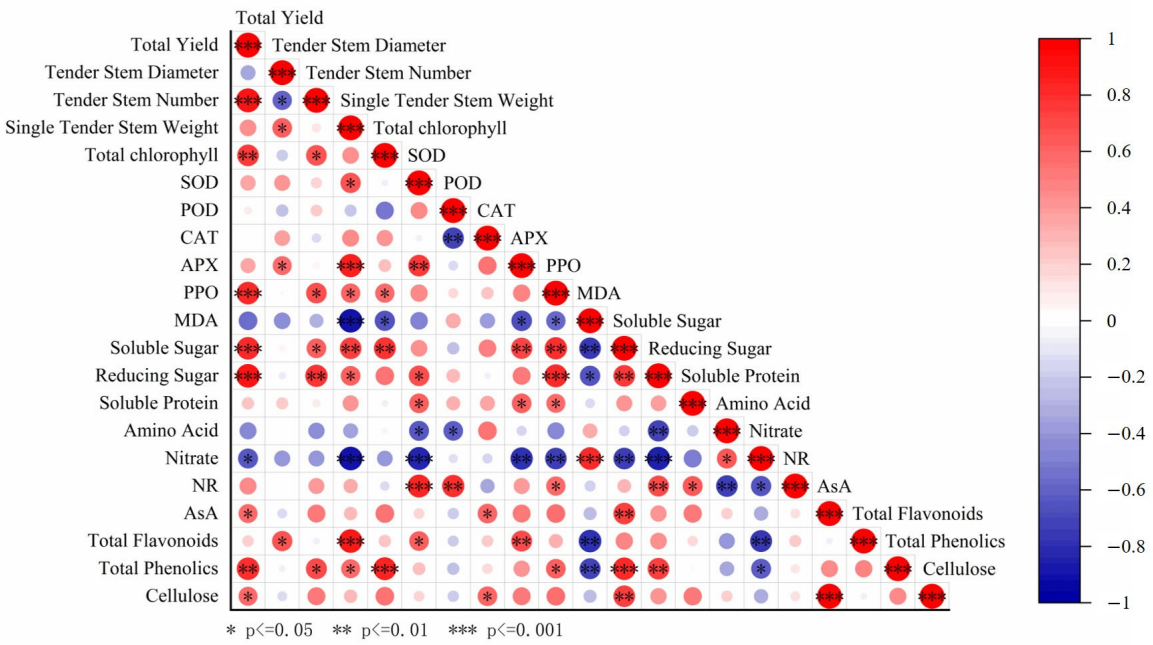


Figure 4. Correlation analysis of the effects of the interaction between electrostatic field and carbon dioxide on the growth and physiological indicators of asparagus. * indicates significant differences at 0.05 level; ** indicates significant differences at 0.01 level; *** indicates significant differences at 0.001 level.

3.6. Comprehensive Evaluation Based on Fuzzy Membership Function Analysis

Fuzzy membership function analysis of asparagus growth and physiological indicators under different treatments revealed that Treatment C exhibited the highest membership function values for growth indicators, nutritional components, and metabolic indicators (Tables 3 and 4), while Treatment D showed the highest membership function values for antioxidant indicators (Table 5). The comprehensive evaluation of all indicators (Table 6) demonstrated that the interaction between electrostatic fields and carbon dioxide had the most significant improvement on asparagus growth and physiological characteristics.

Table 3. Membership function values for the effects of the interaction between electrostatic field and CO_2 on asparagus growth.

	A	B	C	D
Total Yield	0.00	1.00	0.97	0.12
Tender Stem Diameter	0.00	0.09	0.22	1.00
Tender Stem Number	0.25	1.00	0.86	0.00
Tender Stem Weight	0.00	0.71	1.00	0.88
Average Membership Function Value	0.06	0.70	0.73	0.53
Comprehensive Ranking	4	2	1	3

A–D in the first row of the table indicate different experimental treatments. A: Control group without electric field and carbon dioxide. B: Treatment group with elevated carbon dioxide but without electric field. C: Treatment group with both elevated electric field and carbon dioxide. D: Treatment group with electric field but without elevated carbon dioxide.

Table 4. Membership function values for the effects of the interaction between electrostatic field and CO_2 on nutritional components and metabolism in asparagus.

	A	B	C	D
Soluble Sugar	0.00	0.68	1.00	0.50
Reducing Sugar	0.00	1.00	0.71	0.40
Soluble Protein	0.00	1.00	0.43	0.88
Amino Acid	1.00	0.00	0.83	0.63
Nitrate	0.00	1.00	0.79	0.88
NR	0.00	1.00	0.07	0.50
AsA	0.00	0.49	1.00	0.11
Total Flavonoids	0.00	0.56	0.66	1.00
Total Phenolics	0.00	0.68	1.00	0.30
Cellulose	0.00	0.10	1.00	0.33
Average Membership Function Value	0.10	0.65	0.75	0.55
Comprehensive Ranking	4	2	1	3

A–D in the first row of the table indicate different experimental treatments. A: Control group without electric field and carbon dioxide. B: Treatment group with elevated carbon dioxide but without electric field. C: Treatment group with both elevated electric field and carbon dioxide. D: Treatment group with electric field but without elevated carbon dioxide.

Table 5. Membership function values for the effects of the interaction between electrostatic field and CO_2 on antioxidant capacity in asparagus.

	A	B	C	D
SOD	0.00	1.00	0.38	0.86
POD	0.55	1.00	0.00	0.37
CAT	0.00	0.35	1.00	0.66
APX	0.00	0.69	0.79	1.00
PPO	1.00	0.00	0.14	0.41
MDA	0.00	0.64	1.00	0.80
Average Membership Function Value	0.26	0.61	0.55	0.68
Comprehensive Ranking	4	2	3	1

A–D in the first row of the table indicate different experimental treatments. A: Control group without electric field and carbon dioxide. B: Treatment group with elevated carbon dioxide but without electric field. C: Treatment group with both elevated electric field and carbon dioxide. D: Treatment group with electric field but without elevated carbon dioxide.

Table 6. Membership function values and comprehensive evaluation for the effects of the interaction between electrostatic field and CO_2 on growth and physiological characteristics in asparagus.

	A	B	C	D
Total Yield	0.00	1.00	0.97	0.12
Tender Stem Diameter	0.00	0.09	0.22	1.00
Tender Stem Number	0.25	1.00	0.86	0.00
Tender Stem Weight	0.00	0.71	1.00	0.88
Total chlorophyll	0.00	0.33	1.00	0.07
SOD	0.00	1.00	0.38	0.86
POD	0.55	1.00	0.00	0.37
CAT	0.00	0.35	1.00	0.66
APX	0.00	0.69	0.79	1.00
PPO	1.00	0.00	0.14	0.41
MDA	0.00	0.64	1.00	0.80
Soluble Sugar	0.00	0.68	1.00	0.50
Reducing Sugar	0.00	1.00	0.71	0.40
Soluble Protein	0.00	1.00	0.43	0.88
Amino Acid	1.00	0.00	0.83	0.63
Nitrate	0.00	1.00	0.79	0.88
NR	0.00	1.00	0.07	0.50
AsA	0.00	0.49	1.00	0.11
Total Flavonoids	0.00	0.56	0.66	1.00
Total Phenolics	0.00	0.68	1.00	0.30
Cellulose	0.00	0.10	1.00	0.33
Average Membership Function Value	0.13	0.63	0.70	0.56
Comprehensive Ranking	4	2	1	3

A–D in the first row of the table indicate different experimental treatments. A: Control group without electric field and carbon dioxide. B: Treatment group with elevated carbon dioxide but without electric field. C: Treatment group with both elevated electric field and carbon dioxide. D: Treatment group with electric field but without elevated carbon dioxide.

4. Discussion

4.1. Effects of the Interaction Between Electrostatic Field and Carbon Dioxide on Harvest Time Reduction and Yield Enhancement in Asparagus

Both electrostatic field and CO_2 enrichment as individual treatments significantly promote plant growth [13]. In this study, asparagus under CO_2 enrichment reached the marketable height (25 cm) in fewer days compared to the control and electrostatic field treatment alone. The harvest time distribution pattern under combined electrostatic field and CO_2 treatment aligned with that of CO_2 enrichment alone, yet the number of spears meeting harvest standards within 4 days was slightly higher in the combined treatment. According to previous studies, the average time for asparagus to reach 25 cm under greenhouse cultivation is approximately 3 days [58]. In our study, the control group exhibited a lower harvest proportion by day 3 and a prolonged harvest window, likely due to reduced nutrient availability in potted cultivation compared to greenhouse systems.

Earlier research has demonstrated that CO_2 enrichment substantially enhances crop biomass [55], consistent with our findings of increased total yield, harvested spear count, and individual spear weight in the CO_2-enriched group (Group B). For instance, Jin [27] reported that CO_2 enrichment significantly improved yield in stem-leaf vegetables such as celery, lettuce, and spinach. Song et al. [59] also observed that under CO_2 enrichment conditions, the plant height, stem diameter, and fresh weight per plant of celery were significantly increased, with a yield improvement of up to 25.33%. Electrostatic field treatment notably increased individual spear weight, mirroring observations in rice seedlings [60] where electric fields stimulated plant height and biomass accumulation. However, electrostatic treatment alone showed limited efficacy in improving spear yield quantity. Notably, the combined electrostatic field and CO_2 treatment outperformed individual treatments in

enhancing total yield, spear diameter, and individual spear weight, indicating a synergistic interaction between these two factors.

4.2. Effects of the Interaction Between Electrostatic Field and Carbon Dioxide on Chlorophyll Content in Asparagus

The combined application of electrostatic field and CO_2 enrichment significantly increased the contents of chlorophyll a, chlorophyll b, and total chlorophyll in asparagus leaves, a result consistent with the findings of Niu et al. [61]. Individual treatments of electrostatic field and CO_2 enrichment notably enhanced chlorophyll a content but had limited effects on chlorophyll b content. Specifically, CO_2 enrichment resulted in significantly higher chlorophyll a content compared to the electrostatic field treatment, alongside a marked increase in total chlorophyll content. This aligns with the research of Song et al. [62], who demonstrated that CO_2 enrichment promotes chlorophyll biosynthesis, upregulates chlorophyll-binding protein expression, and enhances chloroplast development, thereby increasing chlorophyll content and photosynthetic efficiency. However, Dong's study [63] reported that elevated CO_2 levels might increase chlorophyll b concentration while reducing chlorophyll a concentration in root and stem vegetables, which partially contrasts with our findings.

On the other hand, the electrostatic field treatment alone did not significantly increase total chlorophyll content. Studies by Kim [64] and Sora [65] also indicated that while chlorophyll content in broccoli and lettuce increased under electric field treatment, the differences were not statistically significant. Therefore, individual treatments of electrostatic field and CO_2 enrichment primarily increased total chlorophyll content by elevating chlorophyll a level, whereas their combined application further amplified the positive effects on both chlorophyll a and b, leading to a significant enhancement in photosynthetic activity.

4.3. Effects of the Interaction Between Electrostatic Field and Carbon Dioxide on Enhancing Antioxidant Enzyme Activity and Reducing Oxidative Damage in Asparagus

Under normal physiological conditions, plants maintain a dynamic equilibrium between reactive oxygen species (ROS) and the antioxidant enzyme system [66]. This study found that CO_2 enrichment significantly enhanced the activities of superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT) in asparagus spears, consistent with the findings of Wang et al. [67] in rice seedlings. However, in branches, the activities of CAT and ascorbate peroxidase (APX) were significantly reduced, aligning with observations in coffee leaves under high CO_2 conditions [68].

In spears, the activities of SOD, CAT, and APX showed a pronounced response to the electrostatic field, which was consistent with the results of César et al. [69] The combined electrostatic field and CO_2 treatment promoted SOD activity, though the extent of enhancement was lower than that of individual treatments. POD activity was significantly reduced in both spears and main stems, diverging from the effects of individual treatments, while in branches, POD activity was suppressed across all three treatments. The expression patterns of CAT and APX in spears and branches aligned with those of individual treatments, with the combined treatment exhibiting more pronounced enhancement.

Malondialdehyde (MDA) content is closely linked to the antioxidant system. Stronger antioxidant system activity (e.g., SOD, CAT, APX) correlates with higher ROS scavenging efficiency and lower MDA accumulation, consistent with the results of this study. Therefore, changes in MDA content under combined electrostatic field and CO_2 treatment can indirectly reflect the plant's antioxidant capacity [70,71]. Under the stimulation of electrostatic field and elevated CO_2, enhanced metabolic activities (particularly photosynthesis) increase ROS production in the electron transport chains of photosystem II (PSII) and photosystem I

(PSI) [72], thereby stimulating the synthesis of antioxidants to maintain redox homeostasis and mitigate oxidative damage.

4.4. Effects of the Interaction Between Electrostatic Field and Carbon Dioxide on Metabolic Activity Enhancement and Nutrient Composition in Asparagus

Carbohydrates serve as the primary energy source for vegetables, regulating cellular osmotic pressure and directly influencing taste [73], flavor, and nutritional value. The effects of CO_2 enrichment on sugar content vary among vegetables [27,74]. In this study, CO_2 enrichment significantly increased the levels of soluble sugars and reducing sugars in asparagus spears, consistent with the response observed in potatoes [75], thereby enhancing the taste and flavor of asparagus. Under electrostatic field treatment, the carbohydrate content in asparagus also increased significantly. This may be attributed to two factors: (1) enhanced ion exchange between roots and soil, providing sufficient nutrients for physiological metabolism [76]; and (2) increased photosynthetic activity in branches, leading to active sugar synthesis [77]. The combined electrostatic field and CO_2 treatment resulted in the highest levels of soluble and reducing sugars in branches, demonstrating a synergistic effect. The accumulation of carbohydrates positively impacts the growth and development of asparagus.

Nitrogen-containing compounds are indispensable for vital biological processes. In this study, we investigated the responses of nitrate, amino acids, proteins, and nitrate reductase (NR) to the interaction between electrostatic field and CO_2 enrichment. The results revealed that Treatments B, C, and D significantly reduced nitrate content in asparagus spears. Specifically, the reduction in nitrate observed in Group B aligned with findings in celery [55] under high CO_2 conditions, and this decrease was closely associated with enhanced NR activity. Additionally, the amino acid content in both spears and main stems of Group B was significantly lower than that of the control group. While this result contrasts with the findings of Miyagi et al. [78], it is consistent with previous studies on potatoes [75] and bell peppers [79], which reported a negative correlation between CO_2 treatment and certain amino acid concentrations. Overall, all three treatments exhibited a consistent trend: reduced nitrate content, enhanced NR activity, decreased amino acid levels, and increased soluble protein content. These findings suggest that under these treatments, nitrate is rapidly absorbed and converted into amino acids, improving nitrogen use efficiency and thereby promoting spear growth and optimizing edible quality. The high NR activity and elevated soluble protein levels indicate that the spears are in a rapid growth phase with vigorous metabolic activity. Furthermore, the low amino acid content coupled with high soluble protein levels implies efficient utilization of amino acids for protein synthesis, supporting cell division and elongation, and enhancing the growth potential of the spears. Among the treatments, Group D significantly improved nitrogen use efficiency, consistent with the findings of Zhang et al. [60]. Wu et al. [80] proposed that HVEF contributes to the affinity for nitrate in all treatment groups due to feedback adjustment in nitrogen assimilation. Notably, CO_2 enrichment alone induced higher metabolic activity compared to the electrostatic field treatment, while the combined treatment exhibited a relatively weaker effect. This subadditive interaction may be attributed to competition for energy resources or crosstalk between signaling pathways.

Phenolic compounds are essential antioxidants and key nutritional components in plants [81], which interact with other nutrients [82] and play a vital role in plant growth and overall nutritional value. This study found that the accumulation of phenolic compounds in Group B was consistent with the findings of Levine [83], indicating that elevated CO_2 levels contribute to the accumulation of phenolic compounds. Additionally, electrostatic field stimulation significantly increased the total phenolic and flavonoid content in asparagus, aligning with its effects observed in tomato [84] and Baikal skullcap [85] species.

Ascorbic acid (AsA), a multifunctional antioxidant, also exhibited a positive response to the interaction between the electrostatic field and CO_2 enrichment. Compared to Groups B and D, where APX enzyme activity decreased, AsA content in the leaves and branches of Group C increased significantly. This change, independent of APX enzyme activity, suggests that AsA biosynthesis may be regulated through alternative metabolic pathways [85].

5. Conclusions

This study demonstrates that the combined application of electrostatic field and CO_2 enrichment exhibits optimal effects in enhancing asparagus yield. The interaction treatment significantly increased chlorophyll content, thereby enhancing metabolic activity and promoting plant growth. Simultaneously, the treatment improved the antioxidant capacity of asparagus, as evidenced by elevated activities of superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), and ascorbate peroxidase (APX), along with reduced malondialdehyde (MDA) content. These physiological changes synergistically maintained the redox homeostasis of asparagus spears and minimized oxidative damage. Furthermore, the treatment promoted the accumulation of key nutritional components, including soluble sugars, reducing sugars, soluble proteins, total phenolics, total flavonoids, and ascorbic acid (AsA), thereby significantly enhancing the nutritional quality of asparagus. This conclusion highlights the effectiveness of the combined treatment and provides valuable insights for optimizing asparagus cultivation practices.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture15131416/s1, Figure S1. Physical pictures of the experimental equipment. A: electrostatic device. B: Electrostatic device timer. C: Carbon dioxide concentration detector. D: CO_2 gas cylinder.

Author Contributions: Conceptualization, W.L. and Y.Z.; methodology, M.L.; software, X.H.; validation, T.P., K.O., Z.L. and C.Q.; formal analysis, T.P., X.L. and K.G.; investigation, X.L. and L.L.; resources, Y.Z.; data curation, W.P.; writing—original draft preparation, X.L.; writing—review and editing, W.L., C.J. and T.P.; visualization, T.P. and P.C.; supervision, Y.Z. and M.L.; project administration, C.J.; funding acquisition, W.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Foreign Experts Program (H20240506); the Sichuan Haiju High-Level Talents Introduction Project (2025HJRC0048); the National Agricultural Science and Technology Innovation System Sichuan Characteristic Vegetable Innovation Team Project (SCCXTD-2024-22); and the Key R&D Program Project of Xinjiang Province (grant number: 2023B02020).

Data Availability Statement: Data are contained within the article or Supplementary Material. The original contributions presented in this study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

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

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