

Article

Controlled-Release Iodine Fertilizer Improved Iodine Accumulation, Antioxidant Capacity, and Quality of Lettuce

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Abstract: To clarify the effects of newly developed controlled-release iodine fertilizer (CRIF) on enhancing lettuce (*Lactuca sativa* L.) iodine accumulation, improving the physiological traits, and reducing iodine leaching from soil, a greenhouse pot experiment was conducted. Polymer-coated iodate (PCIO), polymer-coated iodide (PCI), and two conventional iodine fertilizers—iodate (CIO) and iodide (CI)—were applied at a rate of 15 mg iodine per kg soil. The study found that the coating of iodine fertilizers had no significant effects on the biomass of lettuce. The iodine concentration in lettuce leaves subjected to PCIO treatment was elevated by 50.1% and 45.5%, respectively, in comparison to leaves treated with CIO and PCI. The soil-to-leaf transfer factor (TF_{leaf} , dry weight basis) for plants treated with PCIO was significantly higher than that of PCI-treated plants. PCIO also significantly reduced iodine leaching by 46.3% compared to CIO. In lettuce leaves with PCIO treatment, the enzymatic activities of superoxide dismutase (SOD) and catalase (CAT) significantly increased by 50.8% and 27.6%, respectively. Likewise, malonaldehyde (MDA) levels decreased by 23.2% compared to the control samples. PCIO also demonstrated advantages in enhancing the quality of the lettuce. In conclusion, the application of controlled-release iodine fertilizer could be a highly effective and eco-friendly approach to cultivating iodine-rich vegetables.

Keywords: iodized fertilizer; iodine biofortification; leaching loss; iodine concentration; iodine partition; physiological characteristics



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1. Introduction

Iodine deficiency disorder (IDD) is considered one of the most prevalent nutrient deficiency health issues affecting humans worldwide. Insufficient iodine intake can lead to various health problems, including goiter, perinatal mortality, stunted growth, intellectual disability, and even endemic cretinism [1]. It is estimated that close to 2.2 billion people worldwide are at risk of IDD, primarily due to the low iodine content in food products. In China, moderate-to-severe IDD continues to be a concern, resulting in nearly 10 billion instances of brain damage among adolescent and adult populations. Iodine deficiency is not only a nutritional and public health concern but also a significant barrier to human and socioeconomic progress. The only viable solution to eliminate IDD is to ensure iodine availability to the populations affected by the deficiency.

Iodized salt is acknowledged as an affordable, convenient, and efficient method for preventing IDD. Nonetheless, the implementation of this dietary approach is not universally accepted due to regional population characteristics and cultural preferences. The World Health Organization (WHO) has indicated that iodine can be lost during cooking and food preparation [2], with a potential 20% reduction in iodine content. Consequently, it has been proposed that additional strategies beyond salt iodination are needed to enhance iodine nutrition in certain regions [3].

Agriculture serves as the principal source of all essential micronutrients for human consumption. Approximately 80% of the iodine intake for most people comes from plant-based foods. Research suggests that the organic iodine present in plant foods can help maintain balanced iodine nutrition in the diet [4,5]. Consequently, the supplementation of iodine through agricultural biofortification is considered a cost-effective approach to enhancing human micronutrition and aiding the reduction of the global incidence of IDD.

Vegetables are essential components of human nutrition. Previous research has indicated that increased iodine application can lead to higher iodine accumulation in vegetables [6,7]. However, cooking vegetables at high temperatures may cause iodine to be lost through volatilization; therefore, it is recommended that consuming fresh vegetables may be more effective for iodine supplementation. Additionally, iodine is a species characterized by its high mobility, which leads to its transformation, transportation, and accumulation from soil into groundwater [8]. Iodine is lost through runoff water at a significant rate [9], as well as through volatilization. Previous studies have also indicated that iodide is more susceptible to loss and volatilization in soil compared to iodate [6,10]. To cultivate crops enriched with iodine through the application of iodine in soil, it is essential to assess the effectiveness of iodine in soil.

Although the literature contains numerous accounts of enhancing iodine intake in plants through soil application of iodine, there is limited information on the development of iodine fertilizers. Furthermore, there is limited data on the impact of these fertilizers on the nutritional quality of plants, particularly their antioxidant capacity. Controlled-release fertilizers (CRFs) hold significant promise for improving fertilizer efficiency and mitigating environmental risks, ensuring high crop yields and quality. Although CRFs have been extensively developed for macronutrients, they have been used to enhance nutrient use efficiency in various production systems over the past 50 years. However, their application for micronutrients has been relatively less explored.

A novel controlled-release iodine fertilizer has been introduced, which can achieve a gradual release of iodine and essential nutrients into the soil. We hypothesized that the application of CRIFs could boost the iodine enrichment efficiency of crops. The objectives of this study were as follows: (i) to investigate the potential of CRIFs to mitigate the leaching loss of applied iodine from the soil; (ii) to assess whether CRIFs enhance iodine accumulation in lettuce leaves compared to conventional iodine fertilizers; and (iii) to evaluate the impact of different CRIFs on biomass yield, quality attributes, chlorophyll content, and antioxidant capacity. Lettuce was selected as the primary crop for this research due to its status as a crucial horticultural crop and its widespread consumption as a fresh salad globally.

2. Materials and Methods

2.1. Preparation of Fertilizers

The CRIFs, which encompassed iodine and nitrogen, were enveloped in a thermoplastic resin coating. This coating facilitated a gradual release of iodine and promoted its absorption by plants. These CRIFs (containing 42% N and 8% iodine with a release longevity of approximately 60 days in water at 25 °C) were manufactured by the National Engineering Research Center for Efficient Utilization of Soil and Fertilizer Resources at Shandong Agricultural University (SDAU). The basal fertilizers consisted of polymer-coated urea (42% N) and calcium superphosphate (16% P₂O₅). They also included polymer-coated potassium sulfate (50% K₂O), with a release longevity of 60 days.

2.2. Plant Growth Experiment

The experiment was carried out in a greenhouse at the Yantai Academy of Agricultural Sciences in China, located at 121°29' E and 37°5' N, between 15 May and 5 September 2023. The greenhouse maintained an average temperature of 25 °C during the day and 18 °C at night, with a 15 h light and 9 h dark regime. Soil samples were collected from the top layer (0–20 cm) of the field at the SDAU farm, air-dried, then passed through a 2 mm mesh

sieve for the pot experiment. A sub-sample was further ground to pass through a 1 mm sieve for laboratory analysis. The soil was classified as Typic-Hapli-Udic Argosols (US Soil Taxonomy) [11] and had the following properties: texture—sandy loam; pH—6.41; electrical conductivity (EC)— $138.83 \mu\text{S cm}^{-1}$; organic matter— 9.45 g kg^{-1} ; total nitrogen (N)— 0.97 g kg^{-1} ; available phosphorus (P)— 68.92 mg kg^{-1} ; and available potassium (K)— $117.16 \text{ mg kg}^{-1}$. Additionally, the total iodine content was 0.92 mg kg^{-1} , with a composition of sand—55.14%; silt—31.19%; and clay—13.67%.

The seeds of lettuce (*Lactuca sativa* L. var Hongkong) were surface sterilized with a 5% (v/v) solution of H_2O_2 for a duration of 30 min and were then followed by four successive washes with distilled water. Subsequently, the seeds were germinated on a bed of moist filter paper within petri dishes, and maintained in darkness at a temperature of 25°C . The experimental design comprised five distinct treatments: (1) control (no iodine added), (2) conventional iodide (CI), (3) conventional iodate (CIO), (4) polymer-coated iodide (PCI), and (5) polymer-coated iodate (PCIO). Iodine was applied to the soil at a rate of 15 mg per kg of soil. Nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O) were added to each pot at respective rates of 105, 80, and 100 mg kg^{-1} of soil. These fertilizers were thoroughly mixed with the soil before planting. The potted soil was kept at field capacity moisture, and was allowed to equilibrate for one day before the seeds were sown. Three days post-emergence, 10 uniformly pre-germinated seeds were planted in plastic growing pots (with an upper diameter of 17 cm, lower diameter of 11 cm, and a height of 15 cm), with 1 kg of soil per pot. Seven days after sowing, thinning was carried out, leaving two seedlings per pot until harvest. The experiment was conducted using a completely randomized design with four replicates, leading to a total of 20 pots. Throughout the growth period, water loss was systematically replenished by adding water in equal amounts as needed.

The leachate from the soil was collected at 5, 10, 28, 56, and 70 days after planting (DAP). Following a 70-day growth period, the plants were detached, with the roots and leaves being separated. These were then carefully washed with deionized water, gently blotted to remove excess moisture, and their fresh weights were immediately determined. For biochemical and physiological analyses, three newly expanded leaves were sampled from each plant in each pot. These included assessments of chlorophyll concentration, ascorbic acid levels, and nitrogen compounds such as nitrate. Additionally, the enzyme activities of superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT), and the levels of malondialdehyde (MDA), an indicator of membrane lipid peroxidation, were measured. Subsequently, the plant materials were dried to a constant weight at 50°C in an oven, and the dry weight was determined. The tissue samples were then finely ground through a 0.25 mm mesh sieve, in preparation for iodine analysis.

2.3. Soil and Plant Analyses

Soil pH was assessed through a 1:2.5 soil-to-water suspension method. The content of organic matter was determined after dichromate oxidation. The procedures used to measure soil properties adhered to the standard methods recommended by the Chinese Society of Soil Science [12]. The total iodine content in the soil and the iodine concentration in the leachate fractions collected within 24 h, without the inclusion of a preservative or the need for freezing, were measured employing the method developed by Duborská et al. [13]. The quantity of iodine leached from the soil was then calculated based on the iodine concentrations and the volumes of the respective leachate fractions.

The soil-to-leaf transfer factor (TF_{leaf}) was calculated as [iodine concentration in dry leaves/initial iodine concentration in corresponding soil]. The leaching rate was calculated as $[100\% \times \text{total iodine leaching content}/\text{initial total iodine content in corresponding soil}]$.

For the measurement of SOD, POD, CAT, and MDA, approximately 0.5 g of fresh leaves were homogenized with 5 mL of a $50 \text{ mmol L}^{-1} \text{ Na}_2\text{HPO}_4\text{--NaH}_2\text{PO}_4$ buffer solution (pH 7.8). The mixture was then crushed on ice using a mortar and pestle and centrifuged at $10,500 \times g$ for 20 min at 4°C . The resulting supernatant was transferred to a separate container for the assessment of enzyme activities.

SOD activity was determined by its capacity to inhibit the photochemical reduction of nitro blue tetrazolium (NBT), following the method of Giannopolitis and Ries [14]. The reaction mixture (3 mL) contained $1.3 \mu\text{mol L}^{-1}$ riboflavin, $63 \mu\text{mol L}^{-1}$ NBT, 13 mmol L^{-1} methionine, 0.1 mmol L^{-1} EDTA- Na_2 , 50 mmol L^{-1} phosphate buffer (pH 7.8), and $20 \mu\text{L}$ of enzyme extract. The glass tubes containing the mixture were exposed to light at 4000 lx for 25 min, and the absorbance of each reaction mixture at 560 nm was recorded. A control reaction mixture without light exposure served as the blank, and its absorbance was subtracted from the A_{560} of the light-exposed reaction solution. One unit of SOD activity was defined as the amount of enzyme required to cause a 50% inhibition of the NBT reduction rate at 560 nm.

The activities of CAT and POD were analyzed using the procedure of Chance and Maehly [15]. For CAT assay, a 3 mL reaction mixture contained 50 mmol L^{-1} phosphate buffer (pH 7.0), 15 mmol L^{-1} of 30% H_2O_2 , and $100 \mu\text{L}$ of enzyme extract to initiate the reaction. The decomposition of H_2O_2 was monitored by measuring the decline in absorbance at 240 nm over 1 min. For POD, the oxidation of guaiacol was measured by the increase in absorbance at 470 nm over 1 min. The reaction mixture included $50 \mu\text{L}$ of 20 mmol L^{-1} guaiacol, 2.8 mL of 10 mmol L^{-1} phosphate buffer (pH 7.0), and $100 \mu\text{L}$ of enzyme extract, with the reaction initiated by the addition of $20 \mu\text{L}$ of 40 mmol L^{-1} H_2O_2 . POD activity was expressed as units per gram of fresh weight.

The MDA concentration was determined using the method of Buege and Aust [16]. Leaf chlorophyll content was assessed via the method of Lichtenthaler [17]. Ascorbic acid and nitrate content in the lettuce were determined according to the method of Cintya et al. [18].

2.4. Statistical Analysis

All instrumental analyses were conducted at least in triplicate. The data are presented as means $\pm$ standard deviation. All data were processed using Microsoft Excel 365 (Microsoft 365 software package) and the SAS 8.1 software package (SAS Institute, Cary, NC, USA). The significant differences between the mean values of each treatment were evaluated using ANOVA and Duncan's test ($p < 0.05$). Graphs were generated using SigmaPlot 12.5 software (MMIV Systat Software, Inc., San Jose, CA, USA).

3. Results

Biomass Production

This study provides a detailed analysis of iodine nutrition in lettuce plants cultivated under pot conditions. The application of iodine was found to enhance plant biomass compared to the control, as shown in Table 1. Notably, the fresh weight of lettuce leaves inoculated with iodate was approximately 1.1 times greater than that of the iodide-treated plants. The application of PCIO significantly increased leaf fresh weight, with the PCIO-treated plants showing a 13.2% advantage over the CIO-treated plants. Treatment with PCI led to a significant increase in root biomass, whereas no significant differences were observed in leaf biomass compared to the control. The results of this study indicated that the positive effects of iodate fertilization on biomass production were further enhanced by the application of PCIO, suggesting that PCIO fertilizer improves iodate availability to the plant in this soil system, thereby accelerating plant growth.

Data on iodine concentration and iodine partitioning were employed to assess the partitioning of total plant iodine between leaves and roots, as depicted in Figure 1. The data indicated that iodine fertilization positively influenced the iodine concentration in various plant tissues, resulting in a significant increase compared to the control. In the case of iodide, the increase of iodine concentration in the tissues of plants treated with CI was less substantial than that of the plants treated with PCI. The application of PCIO resulted in a significant increase in the total iodine concentration, with approximately 67.0% and 86.8% enhancements in the iodine concentration of the leaves and roots, respectively, when compared to the CIO treatment. No significant differences were observed in plants treated

with CI and PCI. When considering the distribution of iodine across different tissues, it was observed that the iodine concentration in the roots was significantly higher than in the leaves, regardless of whether iodate or iodide was used.

Table 1. Effects of different iodine treatments on biomass production of lettuce.

Treatment	Leaf (g Plant ^{−1})		Root (g Plant ^{−1})	
	Fresh Weight	Dry Weight	Fresh Weight	Dry Weight
Control	50.23 ± 2.15 ^b	5.88 ± 0.13 ^b	2.87 ± 0.14 ^c	0.29 ± 0.01 ^c
CI	51.88 ± 1.46 ^b	6.07 ± 0.14 ^b	4.02 ± 0.21 ^{ab}	0.36 ± 0.02 ^{bc}
CIO	54.96 ± 3.19 ^{ab}	6.18 ± 0.21 ^b	3.97 ± 0.19 ^b	0.37 ± 0.02 ^{abc}
PCI	58.94 ± 3.72 ^{ab}	6.31 ± 0.15 ^{ab}	4.43 ± 0.15 ^{ab}	0.41 ± 0.02 ^{ab}
PCIO	62.23 ± 2.43 ^a	6.77 ± 0.12 ^a	4.71 ± 0.26 ^a	0.47 ± 0.04 ^a

Means in the same vertical column with the same letter do not differ significantly at the $p < 0.05$ level.

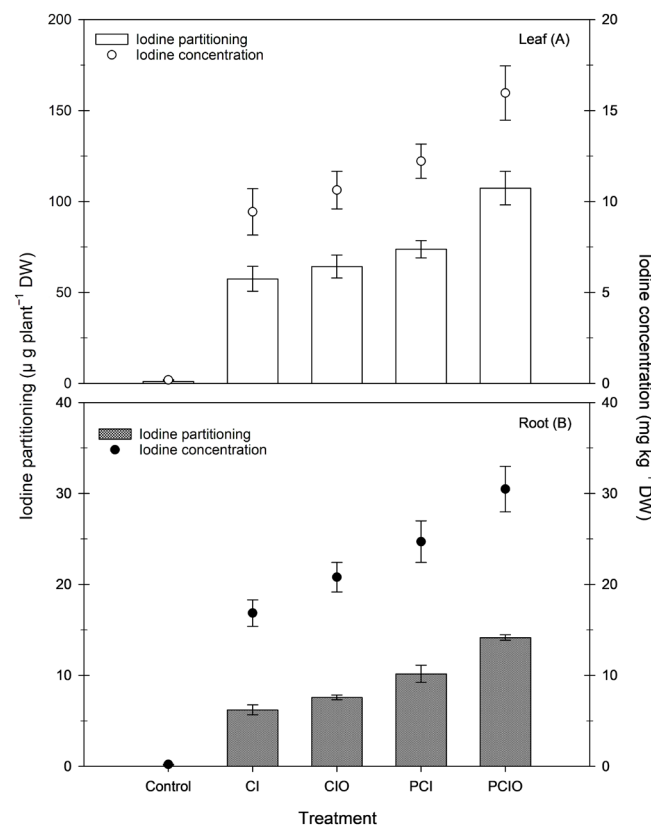


Figure 1. Effects of different iodine treatments on iodine concentration and iodine partitioning between leaves and roots.

The leaching of iodine was employed to assess the bioavailability of CRIFs in this experiment. From days 1 to 28 after planting, the iodine content in the leachate for traditional iodine fertilizers spiked significantly, far exceeding levels at other time points, before plummeting (Table 2). Concurrently, the leaching of iodine from traditional treatments was notably higher than that of the polymer-coated iodine. By day 28 DAP, the total iodine leached from CIO and CI treatments was 26.2% and 15.7%, respectively, whereas the total leached rate for PCIO and PCI was only 7.6% and 5.5%, respectively. In traditional iodine treatments, soil iodine concentrations peaked in the short term. Under irrigation, a substantial amount of soluble iodine was lost through leaching. The maximum leaching of controlled-release iodine treatments occurred from days 29 to 56 DAP, about a month later than traditional treatments. By day 70 DAP, a considerable induction for leached rate

was observed in the PCI and PCIO treatments, at 46.7% and 46.3% below the CI and CIO treatments, respectively.

Table 2. Iodine content in leachate fractions in relation to different iodine treatments.

Treatment	Iodine Leaching (μg)					Leached Rate (%)
	1–5 Days	6–10 Days	11–28 Days	29–56 Days	57–70 Days	
Control	21.82 ± 2.85^d	40.32 ± 3.29^d	18.40 ± 2.00^d	16.30 ± 1.91^c	4.68 ± 0.81^d	-
CI	155.48 ± 11.46^b	574.64 ± 20.14^b	1698.22 ± 28.49^b	616.18 ± 56.71^a	329.35 ± 24.12^b	21.82 ± 0.50^b
CIO	442.42 ± 30.91^a	1018.63 ± 90.55^a	2548.54 ± 250.31^a	202.57 ± 23.46^b	90.31 ± 6.47^c	28.00 ± 2.07^a
PCI	75.78 ± 1.65^c	218.41 ± 4.96^c	604.76 ± 28.44^c	639.40 ± 24.48^a	307.72 ± 20.91^b	11.63 ± 0.39^c
PCIO	105.65 ± 5.87^{bc}	328.90 ± 20.11^c	780.58 ± 38.28^c	699.76 ± 33.48^a	442.66 ± 7.70^a	15.04 ± 0.34^c

Means in the same vertical column with the same letter do not differ significantly at the $p < 0.05$ level.

The soil-to-leaf transfer factor (TF_{leaf}) was utilized as a metric to evaluate the translocation of iodine from the soil to the leaves of the plant. The analytical data revealed considerable TF_{leaf} for all treatments containing iodine, with the highest value observed following the application of PCIO (Figure 2). For plants treated with PCI, the TF_{leaf} increased by approximately 29.6% when compared to CI. The TF_{leaf} for the PCIO treatment showed a 50.1% increase over that of CIO.

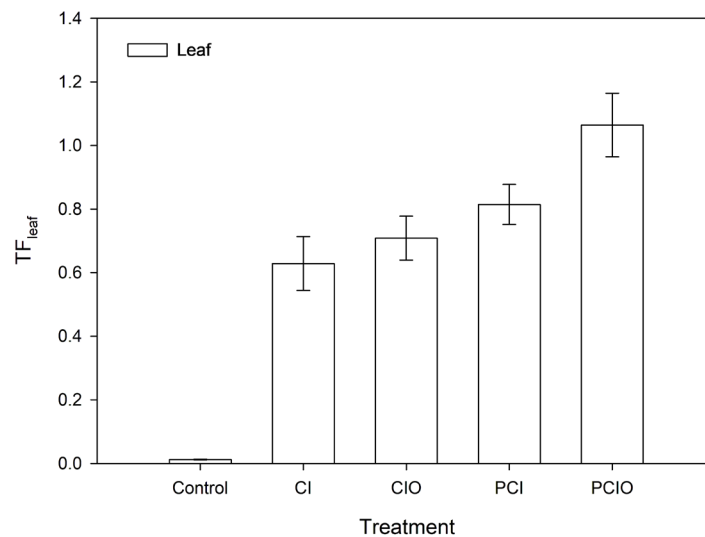


Figure 2. Effects of different iodine treatments on soil-to-leaf transfer factor (TF_{leaf}).

As evidenced in Table 3, the chlorophyll content in leaves subjected to PCIO exhibited a significant increase of 28.1% and 17.5%, respectively, in comparison to the control and CIO treatments. Likewise, leaves treated with PCI showed a notable elevation in chlorophyll content by 19.7% and 28.3%, respectively, compared to the control and CI treatments. The application of traditional iodine fertilizers did not elicit notable alterations in chlorophyll content. Furthermore, there was no significant difference between the CIO and CI treatments.

Table 3. Effects of different iodine treatments on chlorophyll content, ascorbic acid, and NO_3^- -N concentrations in lettuce leaves.

Treatment	Chlorophyll (mg g^{-1} FW)	Ascorbic Acid (mg kg^{-1} FW)	NO_3^- -N (mg g^{-1} FW)
Control	1.78 ± 0.09^c	209.31 ± 11.42^b	2.05 ± 0.12^b
CI	1.66 ± 0.10^c	250.00 ± 8.40^b	1.87 ± 0.15^{bc}
CIO	1.94 ± 0.14^{bc}	218.20 ± 10.99^b	2.66 ± 0.20^a
PCI	2.13 ± 0.07^{ab}	199.33 ± 7.25^b	1.44 ± 0.15^c
PCIO	2.28 ± 0.04^a	273.12 ± 7.29^a	1.63 ± 0.06^{bc}

Means in the same vertical column with the same letter do not differ significantly at the $p < 0.05$ level.

Ascorbic acid (vitamin C), a powerful antioxidant, is known for its ability to generate non-toxic by-products and is the most abundant water-soluble antioxidant in plants. Our analysis revealed an increase in vitamin C levels following the application of traditional iodine fertilizers or higher concentrations of PCIO, with the latter being the most effective in boosting vitamin C levels, suggesting a potential beneficial effect of iodine on plants (Table 3). Specifically, the concentration of vitamin C in lettuce leaves treated with PCIO increased by 30.5% compared to the control treatment, while the presence of PCI had a negative impact on vitamin C levels. Compared to the control and CI treatments, the vitamin C concentration in lettuce leaves treated with PCI decreased by 4.77% and 20.3%, respectively. The concentration of NO_3^- -N in lettuce leaves treated with CIO was notably higher than in the control. Treatment with PCI yielded the lowest concentration, with a decrease of 29.8% compared to control. The application of PCIO also reduced NO_3^- -N concentration by 20.5% in the leaves.

The levels of antioxidant enzymes such as SOD, POD, and CAT may determine the sensitivity of plants to lipid peroxidation [19]. As shown in Table 4, the highest SOD activity was observed in the leaves of plants treated with PCIO, with a similar enhancement noted in plants treated with PCI, although to a lesser degree. The application of traditional iodine fertilizers resulted in higher enzyme levels than the control, but these levels were lower than those achieved with CRIFs. The POD activity levels were enhanced in all iodine treatments compared to the control, with the PCI treatment generating the highest POD activity, which was about 6.0% higher than that of the PCIO treatment. After the application of PCIO, there was a significant improvement in CAT activity, with an increase of 0.90 units above the control level. In contrast, the PCI treatment showed a decrease of 0.78 units compared to the PCIO treatment. Traditional iodine fertilizers also resulted in increased enzyme levels, albeit to a lesser extent.

Table 4. Effects of different iodine treatments on SOD, POD, and CAT activities, and the MDA concentration of lettuce leaves.

Treatment	SOD Activity (U g^{-1} FW)	POD Activity (U g^{-1} FW min^{-1})	CAT Activity (U g^{-1} FW min^{-1})	MDA Concentration (n mol g^{-1} FW)
Control	140.40 ± 7.81^c	3.15 ± 0.12^{bc}	3.26 ± 0.28^b	4.48 ± 0.13^a
CI	167.83 ± 10.35^{bc}	2.71 ± 0.17^c	3.74 ± 0.11^{ab}	4.01 ± 0.15^{ab}
CIO	151.92 ± 9.36^{bc}	3.17 ± 0.19^{bc}	3.63 ± 0.17^{ab}	3.80 ± 0.09^{bc}
PCI	178.41 ± 7.39^b	3.92 ± 0.25^a	3.38 ± 0.16^b	4.08 ± 0.14^{ab}
PCIO	211.78 ± 11.39^a	3.70 ± 0.16^{ab}	4.16 ± 0.12^a	3.44 ± 0.19^c

Means in the same vertical column with the same letter do not differ significantly at the $p < 0.05$ level.

MDA is an oxidized product of membrane lipids, and higher concentrations of MDA indicate greater cell membrane damage. Compared to the control, the MDA content in lettuce leaves subjected to PCIO and CIO treatments decreased significantly by 23.2% and 15.2%, respectively (Table 4). Additionally, lettuce leaves treated with PCIO exhibited a notable 15.7% reduction in MDA content compared to those treated with PCI.

4. Discussion

Through a synthesis of recent research [20–22], it has become evident that both iodate and iodide can positively influence lettuce growth in solution culture. Compared to PCI and CI, both PCIO and CIO demonstrated higher fresh weights of lettuce leaves. This finding is corroborated by the work of Dávila Rangel et al. [21], who observed higher biomass production in potted lettuce treated with iodate compared to iodide. Similarly, Lawson et al. [6] reported reduced plant biomass in field-grown kohlrabi after iodide application, whereas iodate application did not result in such a significant reduction, although this effect was observed at higher concentrations. These data suggest that the impact of iodine on plant growth is largely dependent on its chemical form. Ekdahl [23] reported that iodide can weaken the cell membranes of root hairs to such an extent that they may burst at the tip, thereby retarding growth.

A review of the literature has suggested that biofortification of lettuce with iodate is an effective method for achieving an adequate accumulation of iodine [22,24]. In our research, the total iodine concentration in tissues treated with iodate was generally higher than that in tissues treated with iodide. Furthermore, the iodine concentration in lettuce leaves treated with PCIO was significantly higher than that in other treatments. However, Blasco et al. [25] and Voogt et al. [26] have shown that the iodine concentration in plants is higher when hydroponically grown lettuce is treated with iodide, making iodate treatments less effective for plant supplementation. Similarly, Zhu et al. [27], who studied spinach plants in solution culture, found that the iodine levels in treatments with $100 \mu\text{mol L}^{-1}$ of iodide were approximately 5.0 times higher than those in plants treated with iodate. These research results may be associated with the cultivation medium, environmental factors, or the variety of lettuce. Additionally, the enrichment of iodine in plants was found to be significantly greater with iodate than with iodide, aligning with the observations reported by Dai et al. [28].

Regarding the mobility of iodine within plants, the transport of iodine is influenced by both its concentration and form within the environment. The data also demonstrated that the concentration of iodine in leaves was contingent upon the amount of iodine retained in the roots. Roots are the initial organs to be affected by the nutrient solution. An increase in the iodine concentration in the roots may allow plants to maintain a relatively stable rate of nutrient acquisition. Iodine that is more water soluble when present in the roots possesses a greater capacity to mobilize iodine to the leaves. These findings align with research conducted by Humphrey et al. [29], who reported similar results when studying various plant species under hydroponic conditions. On the other hand, the lower iodine concentration observed in lettuce leaves treated with iodide could be attributed to iodide volatilization from the soil. Muramatsu et al. [30] have shown that iodide in the soil can volatilize as organic iodide, escaping from the soil–plant system into the atmosphere. Moreover, the extent of iodide volatilization from the soil is thought to be ultimately dependent on the amounts of iodide present in the soil.

Iodine exists in soil solution primarily as an anion, which is susceptible to leaching with water. Our research showed that traditional iodine fertilizers exhibited a shorter nutrient-release duration and retained less iodine in the soil during the later growth stages, whereas the release of iodine from controlled-release iodine was slow and steady, significantly reducing iodine leaching losses. Therefore, adequate iodine availability is essential for plant growth and iodine uptake. Mackowiak and Grossl [31] also have reported that the issue of iodine leaching from soil must be addressed, even with the development of more efficient iodine transport cultivars.

An increase in the TF_{leaf} value suggests an enhanced capacity for the plant to absorb and retain iodine within its leaves. After the application of PCIO, the TF_{leaf} value was notably elevated in comparison to those of other iodine fertilizer treatments. Furthermore, when contrasted with the application of CI, the use of PCIO resulted in an increase in the TF_{leaf} value. These findings are consistent with those of Dai et al. [28], who reported that the TF_{leaf} for iodide was more constrained than that of iodate. Conversely, Mackowiak and

Grossl [31] found that iodate uptake was consistently more limited than iodide. The TF_{leaf} values observed in this study were higher than those reported by Cakmak et al. [32] in their research on wheat grown under field conditions.

Leaf chlorophyll content is a critical indicator of plant nutritional status and reflects the potential for photosynthetic capacity. The impact of iodine fertilization with PCIO or PCI was notably more pronounced, as evidenced in Table 3. Traditional iodine fertilizers did not result in significant changes to the chlorophyll content. The enhanced chlorophyll content may also be linked to reduced photo-oxidation, as indicated by the rise in antioxidant enzyme activities and the decrease in lipid peroxidation, as will be discussed later. It can be inferred that the application of polymer-coated iodine fertilizers to soil significantly enhances the active Fe^{2+} form in lettuce leaves, contributing to higher chlorophyll content and robust plant growth.

Despite numerous efforts to enhance iodine uptake in plants through various iodine applications, none of these studies have conclusively determined whether this trace element can affect the fundamental plant quality within the soil–plant system, including ascorbic acid and nitrate (NO_3^- -N) levels in edible plant parts. In our research, the CI treatment was superior to the CIO treatment in improving the vitamin C concentration of lettuce leaves. However, the PCI treatment resulted in a decrease in the vitamin C concentration of lettuce leaves. This may be related to the fact that after the application of PCI, the iodide concentration in the soil remained relatively high during the mid-to-late growth stages of the lettuce. Similarly, Li et al. [33] observed a significant increase in vitamin C in strawberries cultivated in a solution culture following the application of low-level exogenous iodine. However, when iodide or iodate concentrations reached 1.0 mg L^{-1} or higher, exogenous iodine reduced the vitamin C concentration in strawberries. In *Opuntia ficus-indica* grown in soil, both iodate and iodide induced higher vitamin C levels [34]. Weng et al. [35] found that the concentration of vitamin C in hydroponic spinach treated with iodide increased, while iodate application decreased vitamin C levels. Iodine has been shown to induce the conversion of carbohydrates into polysaccharides and to promote the synthesis of cellulose, which can enhance the vitamin C concentration in plants.

Lettuce accumulates higher levels of nitrate (NO_3^- -N) compared to other vegetables. Nitrate itself is not toxic; however, during digestion, it can be reduced to nitrite, which can then oxidize hemoglobin to methemoglobin, potentially leading to methemoglobinemia [36]. Blasco et al. [37] demonstrated that the application of iodide reduced the leaf levels of nitrates. In a previous study, Li et al. [33] also noted that the concentration of NO_3^- -N in strawberry fruits was reduced when the iodide concentration in the hydroponic solution ranged from 0.25 to 2.5 mg L^{-1} . In our research, compared to the CIO and PCIO treatments, the levels of NO_3^- -N in lettuce leaves decreased after the application of CI and PCI, potentially due to the distinct absorption mechanisms of various iodine forms, warranting further discussion and investigation.

The antioxidant capacity of the food we consume is vital as it has been associated with a reduction in the incidence of cardiovascular diseases, cancer, degenerative eye disorders, and chronic neurodegenerative diseases such as Parkinson's and Alzheimer's [26]. Therefore, the antioxidant properties of vegetables are crucial for human health. The results indicated that the utilization of iodine fertilizer could boost the activity of antioxidant enzymes in lettuce leaves, particularly when employing CRIF. Similarly, in soybean, an increase in SOD enzyme activities was reported with the application of iodate at concentrations of 20 , 40 , and $80 \text{ } \mu\text{mol L}^{-1}$ [38]. Blasco et al. [39] reported that the application of iodate and iodide to lettuce plants increased CAT enzyme activities but reduced SOD activity. It was reported that the increase in POD activity can be explained by the possibility that the ascorbate cycle was operating at a high rate to detoxify reactive oxygen species formed in the leaves [40]. This is consistent with the conclusions drawn from this research on the ascorbic acid concentration in lettuce leaves. The concentration of MDA in lettuce grown in pots is not well-documented, studies under soil solution culture have shown that moderate iodine application can reduce MDA levels in lettuce [25]. In our research, the

concentration of MDA was significantly decreased under iodine treatments. This reduction was particularly pronounced with the application of PCIO, which could be attributed to the maintenance of high activities of certain antioxidant enzymes, particularly SOD activity.

Accordingly, the findings indicate that the application of CRIFs has a substantial impact on these enzymes, with the fertilizer that induced the most significant leaf biomass and iodine accumulation also showing the greatest influence. Enhanced activities of scavenging antioxidant enzymes may play a crucial role in safeguarding plants against oxidative stress.

WHO recommends a daily intake of 150 µg of iodine for adults. Assuming that the leaf iodine concentration in mature plants is typically the highest, an individual would need to consume approximately 86 g of fresh lettuce each day to meet the recommended daily iodine intake, without considering iodine changes during post-harvest and the absorption percentage during digestion.

5. Conclusions

The results indicate that the application of CRIFs aligns well with the iodine requirements during the growth stages of lettuce grown in pots, and that it has a beneficial effect on plant biomass production. Compared to traditional iodine fertilization methods, the use of CRIFs led to an increase in plant iodine concentration and a reduction in iodine leaching losses, thereby enhancing iodine use efficiency. There was also an increase in the concentrations of chlorophyll and the main enzymes responsible for detoxifying reactive oxygen species (ROS), such as SOD, POD, and CAT. These findings affirm that CRIFs do not result in lipid peroxidation or degradation of quality. Based on our results, the ability of PCIO to induce significantly higher iodine accumulation in edible plant parts and to enhance the antioxidant system suggests that the application of PCIO could be an effective strategy for improving iodine enrichment in plants, given its long-term efficiency and environmental safety. The application of CRIFs not only boosts the iodine content in the edible parts of crops, but it also diminishes the contamination of groundwater due to iodine leaching from the soil. Moreover, this approach also reduces the manual labor required for foliar spraying of iodine fertilizer.

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