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Onion Peel Waste Has the Potential to Be Converted into a Useful Agricultural Product to Improve Vegetable Crop Growth

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Abstract. **The onion processing industry produces hundreds of thousands of tons of onion waste annually. Normally, onion peel waste is dumped in landfills, which creates additional sources of greenhouse gases. Research has validated that onion peel is a concentrated source of bioactive compounds; therefore, it can be turned into useful agricultural products such as soil amendments and possibly biostimulants. This study conducted three experiments to investigate the plant growth-promoting potential of an onion juice concentrate (OJC). The first experiment explored whether the application of OJC could increase plant growth of Bermuda grass, lettuce, and bok choy. The second experiment evaluated the effects of foliar and subsurface drench applications of OJC on bok choy and lettuce growth. The third experiment investigated the interaction between OJC application methods and fertilizer type on bok choy and radish growth. The results indicated that foliar applications of OJC of 1% to 2% concentrations increased the yield of bok choy and its overall growth. Subirrigation with OJC, however, enhanced the root growth of bok choy, lettuce, and radish. Notably, the combined approach of foliar and subirrigation applications further promoted the growth of both bok choy and radish. Comparing across experiments, longer OJC application periods emerged as a promising strategy for amplifying its growth-promoting benefits. Overall, our findings suggest that OJC holds promise for promoting sustainable agriculture. This potential comes from its ability to enhance both the growth and yield of vegetable crops like bok choy, lettuce, and radish while simultaneously reducing waste.**

Onion (*Allium cepa*) is one of the most essential vegetable crops, ranking third after tomato and potato (Teshika et al. 2019). Onion production has increased significantly in the past decades. The worldwide production of onion is approximately 3.7 million hectares in 175 countries (Orden et al. 2021). China, India, the United States, Egypt, and Turkey are the leading onion-growing countries, accounting for 80% of the total world onion production (FAOSTAT 2023). Although onion is a routinely used ingredient in many types of cooking, processed onion products have increased, especially in many industrial countries, such as the United States, and European countries (Osojnik Črnivec et al. 2021). When onions are processed on an industrial scale to produce flakes, powders, and pickles, and as "ready-to-use" or "ready-to-eat" onion products, approximately 37% of fresh onions are discarded during the processing as waste (Sharma et al. 2016). The processed onion waste mainly consists of onion peel and skin (Celano et al. 2021). The total onion waste generated in European countries, such as Spain, the Netherlands, and the United Kingdom, where onion production is significant, is as high as 500,000 tons per year (Sharma et al. 2016). In the United States, 3.2 million tons of onions were produced in 2022; of those onions, 1.03 million tons were used for processing, generating 381,100 tons of onion waste (USDA-NASS 2023). Therefore, onion waste disposal is a serious concern and needs to follow local regulations. Disposing of onion waste in landfills is costly and has adverse environmental effects, creating additional sources of greenhouse gases such as CO_2 and methane (CH_4) (Zhang et al. 2019). Thus, onion producers and processors are interested in alternative means of disposing of onion waste without negative environmental effects or methods of turning onion waste into useful and high-value by-products in terms of economic profit.

Previous research has indicated that onion skins or peels are a concentrated source of bioactive compounds (Kumar et al. 2022; Osojnik Črnivec et al. 2021). Onion waste may have potential applications in agricultural, industrial, nutraceutical, and cosmetic sectors (Celano et al. 2021). For example, as a functional food ingredient, onion waste can be turned into useful by-products with good antioxidant properties (Roldán et al. 2008) and a functional food product containing both flavonoids and probiotics (Kimoto-Nira et al. 2020). By optimizing the extraction parameters such as the solid-to-solvent ratio, temperature, and time, onion peel can be derived as a biostimulant that could promote the proliferation of microalgae farming (Suparmaniam et al. 2023). To sustainably use the onion processing waste, different biorefinery strategies such as enzymatic hydrolysis, fermentation, and hydrothermal carbonization have been widely investigated to produce organic acid, polyphenols, polysaccharides, biofuels, and pigment (Sagar et al. 2022).

Onion waste can be composted and used as an organic fertilizer or soil amendment for growers and gardeners (Orden et al. 2021; Pellejero et al. 2017). Composing onion waste into useful agricultural products can not only reduce the burden of synthetic fertilizers but also act as a good soil conditioner and source of plant nutrients (Pellejero et al. 2020). In general, fresh or green plant residues are decomposed quickly by soil microbes (Chowdhury et al. 2021). Applying composted onion wastes may increase soil fertility and improve the soil microbiome in soil-based culture either in controlled environments (greenhouses and high tunnels) or in open fields, including commercial farming fields, urban community gardens, city farms, and backyard gardens. To increase the value of onion waste and use bioactive compounds, high-value by-products should be developed.

One option is to turn the onion waste into a concentrated liquid product such as onion juice concentrate (OJC). Diamond Onions, Inc. (Dallas, TX, USA) is the largest onion fresh-cut processor (peeling, cleaning, and packaging) in the country, with more than 100,000 ft^2 dedicated to year-round processing of nearly 4 million pounds of onions every week. Diamond Onions, Inc. buys onions from shippers (contracted) year-round, processes them, and ships them to contracted customers. Thus, Diamond Onions, Inc. produces a huge amount of onion waste daily. Instead of dumping it in landfills, the huge amount of onion peel waste from onion processing can be turned into useful products for specialty crop production as soil conditioners or amendments. Since 2019, Diamond Onions, Inc., in collaboration with Water Is Alive (a nonprofit organization based in Dallas, TX,

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USA), has manufactured this onion juice product, which was applied to a number of local landscape sites, community vegetable gardens, and residential gardens. Based on anecdotal observations, OJC seems to have the potential to reduce fertilizer application, improve soil health, and ward off insects (personal communication with Water Is Alive). These potential benefits might be attributed to the bioactive ingredient contained in onion peels and skin.

Despite promising observations of the potential of OJC, there is a lack of solid data from scientific experiments to validate its effectiveness. We were contacted by Diamond Onions, Inc. and Water Is Alive to formally conduct research to investigate the potential benefits of this agricultural by-product. Therefore, the primary goal of this study was to determine whether OJC has the potential to enhance plant growth and yield when applied at different concentrations to several specialty crops.

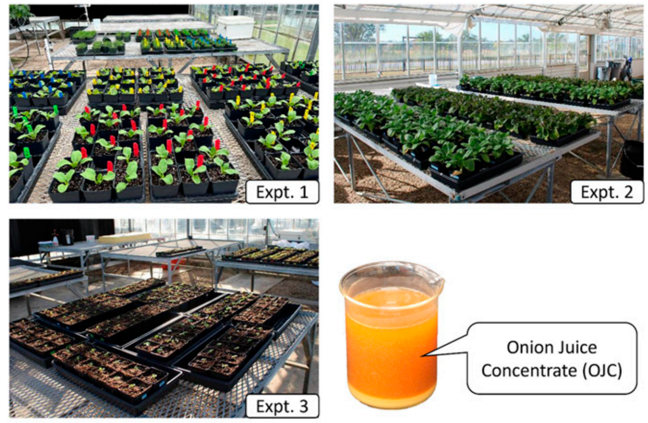

Fig. 1. Greenhouse set-up during Expts. 1, 2, and 3, and an image of onion juice concentrate.

Materials and Methods

In this study, three separate experiments were conducted in a greenhouse with two leafy vegetables (lettuce and bok choy), one turfgrass (Bermuda grass), and one root crop (radish). The first experiment was conducted based on the recommended concentrations of OJC on lettuce (*Lactuca sativa*), bok choy (*Brassica rapa* subsp. *Chinensis*), and Bermuda grass (*Cynodon dactylon*). The results indicated that the application rates might have been too high. Thus, in the second experiment, a lower concentration of OJC based on the results of the first experiment and two different application methods, foliar application and subsurface drench, were used for lettuce and bok choy, and the results were compared. The third experiment was designed based on the results of the previous two experiments, which showed that OJC might have positive effects on root growth. Therefore, radish (*Raphanus sativus*), which is a root crop, was included. The setup of each experiment is shown in Fig. 1.

Effects of the OJC application rate on lettuce, bok choy, and Bermuda grass (Expt. 1)

Plant materials and culture conditions. The first experiment included two leafy green crops, lettuce 'Cegolaine' (Osborne quality seeds, Mount Vernon, WA, USA) and bok choy 'Petite Star' (Kitazawa Seed Co., Salt Lake City, UT, USA), and Bermuda grass 'Tifway 419' (Tri-Tex Grass, Tioga, TX, USA) in a greenhouse at the Texas A&M AgriLife Research Center in Dallas, TX, USA, from Spring to Summer 2022. For lettuce and bok choy, seeds were sown in a germination media composed of fine-grade peat, perlite, vermiculite, limestone, and wetting agent (BM2; Berger, Saint-Modeste, Quebec City, Canada). Seedlings with two to three true leaves were transplanted to square pots (500 mL) filled with a soilless media composed of coarse-grade peat, perlite, limestone, and wetting agent (BM6; Berger). For Bermuda grass, the roots were washed and the rhizomes were transplanted into round pots filled with an all-purpose soilless media (BM6; Berger).

Treatments and experimental design. There were two treatment factors during the experiment. The first treatment factor was the applied concentration of OJC, including 0% (control without OJC), 2%, 4%, and 6.7% (volume/volume). The OJC was provided by Water Is Alive (nonprofit organization). The second treatment factor was the fertilizer application rate (50 or 100 mg N L^{-1}). The primary ingredients of OJC were composted and concentrated onion juice and a number of beneficial microbes consisting of lactic acid bacteria, photosynthesizing bacteria, yeasts, and fermenting fungi. However, the detailed ingredients and concentrations of the microorganisms were not available because of proprietary issues. The OJC is a brown to orange, nontransparent liquid with sediment at the bottom and a strong onion odor. The visual representation of OJC is provided in Fig. 1. The pH of OJC is 4; therefore, it requires adjustment before plant application. The fertilizer application rate treatment was used to determine whether applying OJC could alleviate a low fertilizer rate. Nutrient solutions were prepared by using Peters Professional Peat Lite Special 20–10–20 water-soluble fertilizer (Jr Peters Inc., Allentown, PA, USA). Treatments were initiated for the two leafy greens at 6 d after transplanting when plants had five to six true leaves. For Bermuda grasses, treatments were initiated 23 d after planting the rhizomes when the grasses covered the whole pot surface. Treatment solutions were prepared by diluting the OJC into the nutrient solutions (low or high) and applied to the plants through subirrigation weekly until harvest. Before diluting OJC in tap water, it was shaken vigorously to suspend any settled sediment. Then, the pH of the diluted OJC solutions was adjusted to between 5.8 and 6.0 for plant application. The eight treatment combinations (four OJC rates × two fertilizer rates) were arranged in a completely randomized design using each pot as one experiment unit. For each treatment combination, there were nine pots of lettuce, nine pots of bok choy, and eight pots of turfgrass. For the leafy greens, the trials were repeated twice. Bok choy and lettuce were harvested 21 d after OJC treatment in trial 1 and 14 d after OJC treatment in trial 2. For Bermuda grasses, the treatment period was from 5 May to 6 Jul 2022.

Data collection. For bok choy and lettuce, leaf greenness [Soil and Plant Analysis Development (SPAD) index] was measured on the top fully expanded leaves using a handheld SPAD-502 Plus meter (Konica Minolta, Osaka, Japan) 1 d before the harvest. The plant was severed at the substrate surface to separate the shoot from the root, and the shoot fresh weight (FW) was recorded. The total leaf area per plant was measured using an LI-3100C Leaf Area Meter (LI-COR, Lincoln, NE, USA). Roots were carefully separated from the substrate and washed. Plant shoots and roots were placed in separate paper bags and then placed in a drying oven (Thermo Fisher Scientific, Waltham, MA, USA) at 70 °C until constant weight to determine the dry weight (DW). For Bermuda grass, the grasses taller than 5 cm and those outside of the pots were clipped with scissors. The grasses were clipped weekly, and the cumulative FW and DW of the clipped grasses were recorded.

Effect of the OJC application rate and method on lettuce and bok choy (Expt. 2)

Plant materials and culture conditions. The second experiment was conducted from 8 Sep 8 to 1 Nov 2022, using the same plant materials ('Cegolaine' lettuce and 'Petite Star' bok choy) and culture conditions (BM2 for seedling growth, BM6 for plants after transplanting) as those used in Expt. 1.

Treatments and experiment design. Based on the results of Expt. 1, the OJC application rates may be too high, as evidenced by reduced shoot growth or no effect on shoot growth. Therefore, the objective of Expt. 2 was to evaluate the effect of the OJC applied as a sub-surface drench or foliar spray at lower rates (0%, 1%, 1.5%, and 2% volume/volume) on the growth and yield of bok choy and lettuce (similar to Expt. 1). For each crop, the experiment followed a randomized complete block design with factorial arrangement (four OJC rates × two OJC application methods). For each treatment combination of each crop, 12 plants were included and divided into two blocks of six plants each. The OJC treatments were initiated 6 d after transplanting. Plants were irrigated with only one level of nutrient solution at 150 mg/L N. The pH range of the diluted OJC treatment solution was adjusted to 5.8 to 6.0 before application (similar to Expt. 1). For foliar application, OJC treatment solutions were sprayed onto foliage until all leaves were fully covered with water drippings. For the sub-surface drench, treatment solutions were applied by drenching 100 mL of treatment solution per pot to the substrate surface. Control plants (OJC application rate at 0%) were either sub-surface-drenched or foliar-sprayed with the same amount of tap water. Both foliar spray and sub-surface drench methods were applied twice per week on plants until harvest (33 d after transplanting).

Data collection. Shoot FW and DW, root DW, leaf area, and leaf greenness (SPAD) were collected (similar to those of Expt. 1). For all parameters, three plants from each of the two blocks were collected, and the results were presented as the mean value of the six plants.

Effect of OJC on bok choy and radish (Expt. 3)

The results of Expt. 2 indicated that OJC increased shoot growth in bok choy, but not in lettuce. The results of both the first and the second experiments showed that OJC may increase root growth. Therefore, in this experiment, we included a root crop (radish) to perform comparisons with the leafy green crop (bok choy).

Plant materials and culture conditions. Two seeds of 'Rover' radish (*Raphanus sativus*) (Johnny's Selected Seeds, Winslow, ME, USA) and 'Petite Star' bok choy were sown on 13 Jan 2023 in square pots (500 mL) filled with the same BM6 soilless media as that used in previous experiments. After emergence, seedlings were thinned to one seedling per pot.

Treatments and experimental design. This experiment had a randomized complete block design with two experimental factors: OJC application method (no OJC, subirrigation at a low rate, subirrigation at a high rate, foliar spray at a low rate, foliar spray at a high rate, a combination of subirrigation and foliar spray at a low rate, or a combination of subirrigation and foliar spray at a high rate) and fertilizer type (conventional or organic). For foliar spray, the low OJC application rate was 0.5% (volume/volume), and the high rate was 1% (volume/volume). For subirrigation, the low OJC application rate was 1% (volume/volume), the high rate was 1.5% (volume/volume). For each treatment combination of each crop, 12 plants were included and divided into two blocks of six plants each. All OJC treatments were applied weekly starting from 1 d before sowing the seeds until harvest. Radish was harvested 41 d after sowing, whereas bok choy was harvested 51 d after sowing. That is, the OJC treatment durations were longer in this experiment compared with the previous two experiments. Plants were irrigated with tap water as needed. The conventional fertilizer used in this study was Osmocote 15–9–12 slow-release fertilizer (4–5 months) (The Scotts Company, Marysville, OH, USA), with 4 g incorporated into the substrate in each pot before sowing the seeds. The organic fertilizers used were slow-release fertilizer (Sustane 4–6–4; Sustane Corporate, Cannon Falls, MN, USA) and water-soluble fertilizer (Nature Safe 7–7–7; Nature Safe Fertilizers, Cold Spring, KY, USA) to ensure that sufficient nutrients were supplied. Sustane was applied twice at 7.5 g/pot; it was incorporated into the substrate before sowing and top-dressed 17 d after sowing. Nature Safe was drenched twice at 345 mg/pot: 21 d and 28 d after sowing. The pH of tap water-diluted OJC solutions was adjusted to 5.8 to 6.0 before applications.

Data collection. For bok choy, the leaf greenness (SPAD), leaf number, leaf area, compactness (leaf area divided by plant height), plant growth index, shoot FW and DW, root DW, and root-to-shoot DW ratio were collected. The plant growth index (GI) was calculated as the average of three measurements [plant height, the widest shoot width (width 1), and the width perpendicular to it (width 2)]. For radish, the SPAD, FW, and DW of the shoot and root and root average diameter were collected. The root of the radish refers to the swollen and fleshy portion of the root. For all parameters, three plants from each of the two blocks were collected, and the results are presented as the mean value of the six plants.

Statistical analysis

Because different crops responded to treatments differently, data were analyzed separately

Table 1. Expt. 1: Shoot fresh weight (FW), leaf area, shoot dry weight (DW), and root DW of bok choy and lettuce as affected by the onion juice concentrate (OJC) rate and fertilizer application rate and the probability of the analysis of variance (ANOVA) of the main factors [OJC and fertilizer (F) rate] and their interaction (OJC × F).

Crop	Treatment		Shoot FW (g)	Leaf area (cm^2)	Shoot DW (g)	Root DW (g)
Bok choy (pooled from different fertilizers)	OJC (%)	0	32.4 a	359.8 ab	2.78 ab	0.584 b
		2.0	32.2 a	376.8 a	2.85 a	0.762 a
		4.0	29.9 a	348.6 b	2.61 b	0.762 a
		6.7	29.9 a	348.5 b	2.63 b	0.681 a
Bok choy (pooled from different OJC concentrations)	Fertilizer rate	High	28.9 A	400.5 A	2.93 A	0.724 A
		Low	23.4 B	316.4 B	2.51 B	0.629 B
Lettuce (high fertilizer rate)	OJC (%)	0	38.8 a	871.6 a	3.184 a	0.688 b
		2.0	42.0 a	891.5 a	3.186 a	0.821 b
		4.0	41.0 a	878.8 a	3.294 a	1.039 a
		6.7	31.0 a	908.8 a	3.291 a	1.053 a
		Average	38.2 A	887.7 A	3.239 A	0.900 A
Lettuce (low fertilizer rate)	OJC (%)	0	30.9 a	677.6 a	2.839 a	0.770 b
		2.0	26.4 b	628.8 a	2.363 b	1.003 a
		4.0	30.4 a	668.1 a	2.566 ab	0.956 ab
		6.7	29.7 ab	696.4 a	2.655 ab	0.954 ab
		Average	29.3 B	667.7 B	2.606 B	0.921 A
ANOVA results						
Bok choy	Fertilizer (F)		***	***	***	***
	OJC		*	**	**	***
	F × OJC		NS	NS	NS	NS
Lettuce	Fertilizer (F)		***	***	***	NS
	OJC		***	NS	NS	***
	F × OJC		***	NS	NS	*

Different lowercase letters within a column of one category suggest significant differences among OJC rates. Different capitalized letters within column of one category suggest significant differences among fertilizer application rates. For bok choy, data were pooled from two fertilizer rates because no interaction between the OJC rate and fertilizer rate was found.

Level of significance: NS = not significant; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

Table 2. Expt. 1: Shoot fresh weight (FW), shoot dry weight (DW), root DW, root-to-shoot DW ratio (R/S), and cumulative clipped DW of Bermuda grass 'Tifway 419' as affected by onion juice concentrate (OJC) application and fertilizer rate and the probability of the analysis of variance (ANOVA) of the main factors [OJC and fertilizer (F) rate] and their interaction (OJC × F).

	Treatment	Shoot FW	Shoot DW	Root DW	R/S	Cumulative DW
OJC (%)	0.0	12.9 a	3.74 a	3.22 a	0.878 a	2.60 a
	2.0	11.5 b	3.43 ab	3.36 a	0.992 a	1.95 a
	4.0	11.0 b	3.18 b	3.42 a	1.089 a	1.83 a
	6.7	12.8 a	3.59 a	3.48 a	0.993 a	2.18 a
F rate	High F	13.1 A	3.77 A	3.31 A	0.898 B	2.69 A
	Low F	11.0 B	3.20 B	3.426 A	1.077 A	1.60 B
ANOVA results	F	***	***	NS	*	***
	OJC	***	***	NS	NS	NS
	F × OJC	NS	NS	NS	NS	NS

Different lowercase letters within a column of one category suggest significant differences among OJC rates. Different capitalized letters within column of one category suggest significant differences among fertilizer application rates. Data were pooled from two fertilizer rates because no interaction between OJC and fertilizer rate was found.

Level of significance: NS = not significant; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

for each crop. In Expt. 1, the two leafy greens trial was repeated twice. For each crop, a two-way analysis of variance (ANOVA) was used to determine the effects of the fertilizer level (F), concentration of the OJC, and their interactions on all growth traits. For Expt. 2, the effects of the application method, concentration of the OJC, and the application method × OJC interaction were tested using an ANOVA. Expt. 3 investigated the combined effects of the application method, fertilizer type, and their interactions on plant responses using an ANOVA. All experimental factors were analyzed using SAS for Windows (version 9.4; SAS Institute Inc., Cary, NC, USA). Mean values were compared and separated using Tukey's honestly significant difference (HSD) test at a significance level of $P \leq 0.05$.

Results

OJC effect on bok choy, lettuce, and Bermuda grass (Expt. 1)

For bok choy, both the concentration of the OJC and fertilizer level influenced shoot and root growth; however, no interaction between fertilizer and OJC was observed (Table 1). The OJC application concentration did not affect shoot FW. The OJC concentration of 2% resulted in the highest leaf area, although no statistical difference was found between the control and OJC of 2%. The higher OJC concentrations of 4% and 6.7% and the control resulted in statistically similar leaf areas. The shoot DW had a trend similar to that of the leaf area among treatments: the shoot DW with an OJC of 2% was higher than the shoot DWs with OJCs of 4% and 6.7%, whereas no differences were found among OJCs of 4%, 6.7%, and control and between the control and OJC of 2%. However, the OJC application enhanced root DW. These results indicated that OJC increased root growth in bok choy, however, high OJC concentrations may reduce the shoot growth of bok choy.

For lettuce plants at high fertilizer levels, the OJC did not affect shoot FW, shoot DW, and leaf area, whereas root DW was increased in plants treated with OJC of 4% and 6.7% compared with those treated with OJC of 2% and control (Table 1). At the low fertilizer rate, the OJC of 2% reduced shoot FW (by 14%) and shoot DW (by 7%), whereas the root DW increased by 23% compared with the control. No difference was observed in shoot DW among the control, OJCs of 4% and 6.7%, and among the plants treated with OJC. Similarly, for root DW, no differences were observed among the control, OJCs of 4% and 6.7%, and among the plants treated with OJC. These results indicated that OJC treatment may promote root growth in lettuce; however, the effect on shoot growth was not clear.

For Bermuda grass, the OJC application concentration only affected shoot growth; it did not affect root growth (Table 2). For shoot FW, the OJC of 6.7% had a value similar to that of the control, whereas the OJCs of 2% and 4% reduced shoot FW by 10% to 14%. No significant effect of OJC was observed in root DW, cumulative DW, and the root-to-shoot DW ratio. The shoot DW was the lowest in plants treated with the OJC of 4%; however, no differences were found between the OJCs of 4% and 2% and between the control and OJC of 2%. These results indicated that OJC application did not affect the root growth, but that the effect on shoot growth was not clear.

OJC effect on bok choy and lettuce (Expt. 2)

The ANOVA results indicated that the application method affected both shoot and root parameters in bok choy, but only root growth in lettuce (Table 3). The application concentration of OJC did not influence bok choy growth except for SPAD and leaf greenness. The interactive effect between the application method and OJC concentration was significant in the leaf area of both bok choy and lettuce and root DW of lettuce. Thus, multiple comparisons were conducted separately for each OJC application method.

For bok choy, OJC foliar spray improved plant growth, as reflected in an 11% increase in leaf area, 7% increase in shoot DW, and 13% increase in root DW compared with sub-surface drench (Fig. 2A–C). The OJC sub-surface drench did not affect the leaf area, shoot DW, and leaf greenness, regardless of the concentration. When applied as a foliar spray, the leaf area was increased by 15% at an OJC of 1.5%, whereas no statistical difference was found between plants treated with other OJC concentrations and control. Similar to the leaf area as affected by the OJC foliar spray, the shoot DW was increased by 15% by the OJC foliar spray at 1.5%. Leaf greenness or SPAD readings were higher in plants treated with the OJC foliar spray at 1.5% and 2% compared with control and OJC at 0.5%. Shoot FW and root DW were unaffected by the OJC, regardless of the application method (data not shown).

For lettuce crops, there was no significant difference between sub-surface drench and foliar spray, except for root DW, which was increased by 29% because of foliar spray with OJC (Fig. 2D–F). The leaf area was unaffected by the OJC foliar spray concentration. However, the sub-surface drench of OJC at 1.5% reduced the leaf area by 15% compared

Table 3. Expt. 2: Summary of the analysis of variance (ANOVA) results of leaf area, shoot fresh weight (FW), shoot dry weight (DW), root DW, and leaf greenness (SPAD) of bok choy and lettuce as affected by application rates at 0% (control), 1%, 1.5%, or 2% of onion juice concentrate (OJC) and application method (sub-surface drench or foliar spray).

	Leaf area	Shoot FW	Shoot DW	Root DW	SPAD
Bok choy					
OJC rate	NS	NS	NS	NS	*
OJC method	***	*	*	*	NS
Rate × method	*	NS	NS	NS	NS
Lettuce					
OJC rate	NS	*	*	NS	NS
OJC method	NS	NS	NS	***	NS
Rate × method	*	NS	NS	*	NS

Level of significance: NS = not significant; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

SPAD = Soil and Plant Analysis Development.

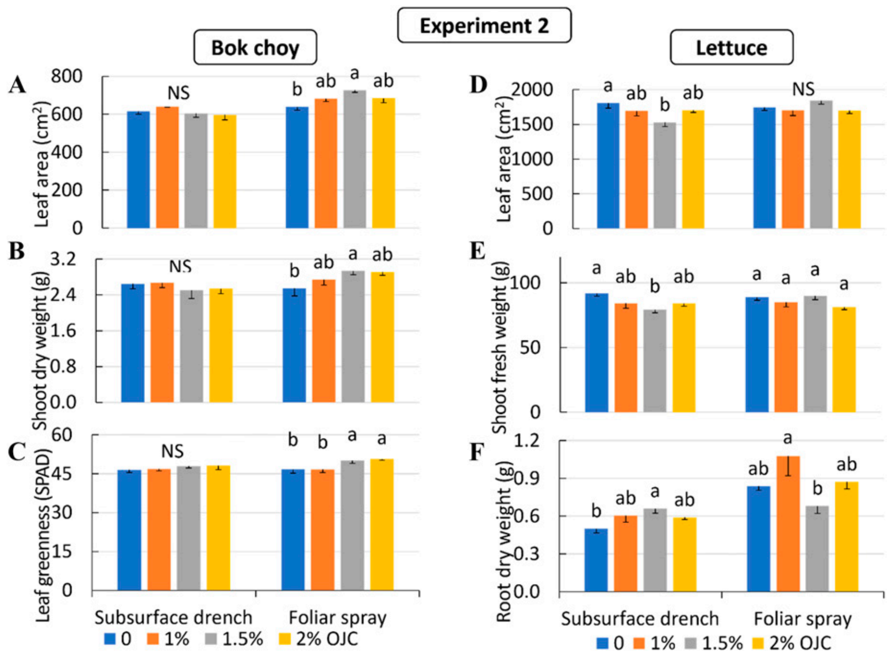

Fig. 2. Expt. 2: Plant growth parameters with different application concentrations (0%, 1%, 1.5%, or 2%) and application methods (sub-surface drench or foliar spray) of onion juice concentrate (OJC). (**A–C**) Bok choy. (**D–F**) Lettuce. No OJC (control) is indicated by 0. Different letters on top of the bars with the same OJC application method within a plot suggest significant differences among OJC application concentrations.

with the control, whereas no statistical differences were observed among plants treated with the control, OJC at 0.5%, and OJC at 2%. Leaf FW followed a similar pattern as leaf area in plants treated with sub-surface OJC drench. The OJC applied as a sub-surface drench tended to increase the root DW, as observed in this experiment, with an OJC of 1.5% resulting in the highest root DW. There was an unclear trend of the OJC concentration effect on the root DW of the lettuce crop. No effect of the OJC concentration on SPAD readings and shoot DW was found (data now shown).

OJC effect on bok choy and radish (Expt. 3)

OJC effect on bok choy. For bok choy, significant differences in all measured plant growth parameters (except root-to-shoot DW ratio) were observed among OJC application methods (Table 4). For all parameters except for leaf area, shoot FW, and shoot DW, there was no significant interaction between the type of fertilizer and OJC application method. Consequently, for those parameters that demonstrated significant interactions between the type of fertilizer and OJC application method, post hoc tests were conducted separately based on the different OJC application methods or the type of fertilizer (Table 5). Regarding the parameters with nonsignificant interactions, post hoc tests of pooled data, either averaged by fertilizer type or OJC application method, were conducted (Fig. 3, Table 6).

Figure 3 shows the effects of OJC application methods on bok choy shoot growth. The foliar spray of OJC at 0.5% and combined foliar spray at 1% and subirrigation at 1.5% increased the leaf greenness (SPAD) in bok choy leaves by 7% and 6% compared with the control, respectively. The foliar spray of OJC at 1% increased leaf number by 23% compared with the control. The compactness of bok choy, which was calculated as the leaf area × plant height, was highest for foliar spray at both 0.5% and 1% and subirrigation at 1%, and lowest for the control and subirrigation at 1.5%. The foliar spray of OJC at 1% resulted in the highest plant growth index (PGI), which increased by 16% compared with the control. Subirrigation of OJC at 1%, combined subirrigation at 1.5% and foliar spray at 1%, and combined subirrigation at 1% and foliar spray at 0.5% increased the PGI by 12%, 11%, and 9%, respectively, compared with the control. The OJC application did not change the root-to-shoot DW ratio of bok choy compared with that of the control. Foliar application with 1% OJC, a combination of subirrigation with 1.5% OJC and foliar application with 1% OJC, and subirrigation with 1% OJC increased root DW by 100%, 61%, and 57%, respectively, compared with that of the control.

The parameters demonstrating significant interactions between the fertilizer type and OJC application method are shown in Table 5. More significant differences between the OJC application and control were found in the conventional fertilizer (Osmocote) group than in the organic fertilizer (Sustane) group. For example, in the conventional fertilizer group, all OJC application methods except for foliar spray at 0.5% and combined subirrigation at 1% and foliar spray at 0.5% significantly increased the leaf area compared with the control. However, in the organic fertilizer group, only the foliar spray of OJC at 1% significantly increased the leaf area and single leaf area. When applied with conventional fertilizer, combined subirrigation at 1.5% and foliar spray at 1%, foliar spray of OJC of 1%, and subirrigation at 1% increased the shoot FW by 173%, 162%, and 130%, respectively, compared with the control. When applied with organic fertilizer, foliar spray at 1% increased the shoot FW by 54% compared with the control. Similar trends among fertilizer types and OJC application methods were observed in the shoot DW. Notably, all OJC applications increased the shoot water content compared with the control when applied with conventional fertilizer. However, the OJC application did not have any effect on the shoot water content when applied with organic fertilizer on bok choy plants. In most cases (Table 5), bok choy plants grown with organic fertilizer performed better than those grown with conventional fertilizer; in some cases, there was no significant difference between the two fertilizer types. Table 6 shows the effects of different fertilizers on bok choy plant growth. Organic fertilizer resulted in higher SPAD, plant compactness, root-to-shoot DW ratio, and root DW in bok choy plants.

Radish. The results of the two-way ANOVA for radish are shown in Table 4. Although both

Table 4. Expt. 3: Two-way analysis of variance (ANOVA) test results showing levels of significance of experimental factors [fertilizer type and onion juice concentrate (OJC) application method] for bok choy and radish.

	Parameters	Fertilizer	OJC	Fertilizer × OJC
Bok choy	SPAD	*	**	NS
	Leaf number	NS	**	NS
	Leaf area	NS	***	**
	Leaf area by height (compactness)	**	**	NS
	Plant growth index	NS	**	NS
	Shoot fresh weight	NS	***	**
	Shoot dry weight	*	***	*
	Root dry weight	**	**	NS
	Root-to-shoot dry weight ratio	**	NS	NS
Radish	SPAD	NS	*	**
	Shoot fresh weight	***	*	NS
	Shoot dry weight	***	*	*
	Root average diameter	***	*	NS
	Root fresh weight	***	*	NS
	Root dry weight	***	NS	NS

Level of significance: NS = not significant; $*P < 0.05$; $**P < 0.01$; $***P < 0.001$.
SPAD = Soil and Plant Analysis Development.

Table 5. Expt. 3: Leaf area, shoot fresh weight, and shoot dry weight of bok choy plants as affected by different fertilizers and onion juice application methods and rate. For foliar spray (foliar) application, the low (L) and high (H) onion juice concentrate (OJC) rates were 0.5% and 1%, respectively. For subirrigation (Sub) application, the L and H OJC rates were 1% and 1.5%, respectively.

	Control	Sub L	Sub H	Foliar L	Foliar H	Sub + Foliar L	Sub + Foliar H	Mean
Leaf area (cm^2)								
Conventional fertilizer	259 Bd	450 Aab	366 Abc	337 Bcd	487 Aa	352 Bcd	495 Aa	392
Organic fertilizer	389 Abc	400 Aabc	314 Ac	438 Aab	515 Aa	453 Aab	389 Abc	414
Mean	324	425	340	388	501	402	442	
Shoot fresh weight (g)								
Conventional fertilizer	16.8 Bc	38.6 Aab	28.3 Abc	22.8 Bc	44.0 Aa	26.2 Bc	45.9 Aa	31.8
Organic fertilizer	30.9 Ab	34.2 Ab	25.5 Ab	36.9 Aab	47.7 Aa	36.7 Aab	32.2 Ab	34.9
Mean	23.9	36.4	26.9	29.8	45.9	31.4	39.0	
Shoot dry weight (g)								
Conventional fertilizer	1.02 Bc	1.97 Aab	1.55 Abc	1.29 Bc	2.27 Aa	1.44 Bbc	2.28 Aa	1.69
Organic fertilizer	1.68 Ab	1.93 Aab	1.42 Ab	2.12 Aab	2.63 Aa	2.06 Aab	1.86 Ab	1.96
Mean	1.35	1.95	1.49	1.71	2.45	1.75	2.07	

Different uppercase letters within a column suggest significant differences between fertilizer treatments. Different lowercase letters within a row suggest significant differences between onion juice applications. Conventional fertilizer refers to Osmocote 15–9–12 slow-release fertilizer (4–5 months) (The Scotts Company, Marysville, OH, USA). Organic fertilizer refers to Sustane 4–6–4 slow-release fertilizer (Sustane Corporate, Cannon Falls, MN, USA).

fertilizer type and the OJC application method influenced the majority of plant growth parameters measured, the impact of fertilizer type was significantly greater. There were significant effects of fertilizer type and OJC application methods on SPAD and shoot DW of radish plants. Figure 4 shows the effects of OJC application methods on radish plant growth. Subirrigation of OJC at 1.5% resulted in the highest shoot FW among all OJC application methods. The combination of subirrigation of OJC at 1% and foliar spray at 0.5% increased the root average diameter and root FW of radish by 9% and 26%, respectively, compared with the control. Additionally, subirrigation of OJC at 1% increased the root average diameter by 7% compared with the control. The OJC application methods did not result in a significant difference in root DW compared with the control. Table 7 shows the parameters demonstrating significant interactions between the fertilizer type and OJC application method. For radish plants grown with conventional fertilizer, OJC application methods did not have a significant effect on leaf greenness (SPAD), whereas for organic fertilizer, the control showed the highest SPAD among different OJC application methods. The impact of the fertilizer type on the SPAD of radish plants varied across OJC application methods, and the overall trend of its effect remains unclear. For radish plants grown with conventional fertilizer, subirrigation of OJC at 1% increased the shoot FW by 24% compared with the control and resulted in the highest value among different OJC application methods. However, the OJC application did not result in a significant difference compared with the control in the shoot DW of organically fertilized radish plants. Table 6 presents the effects of the fertilizer type on radish plant growth parameters; conventional fertilizer resulted in significantly higher shoot and root FWs, root average diameter, and root DW compared with organic fertilizer.

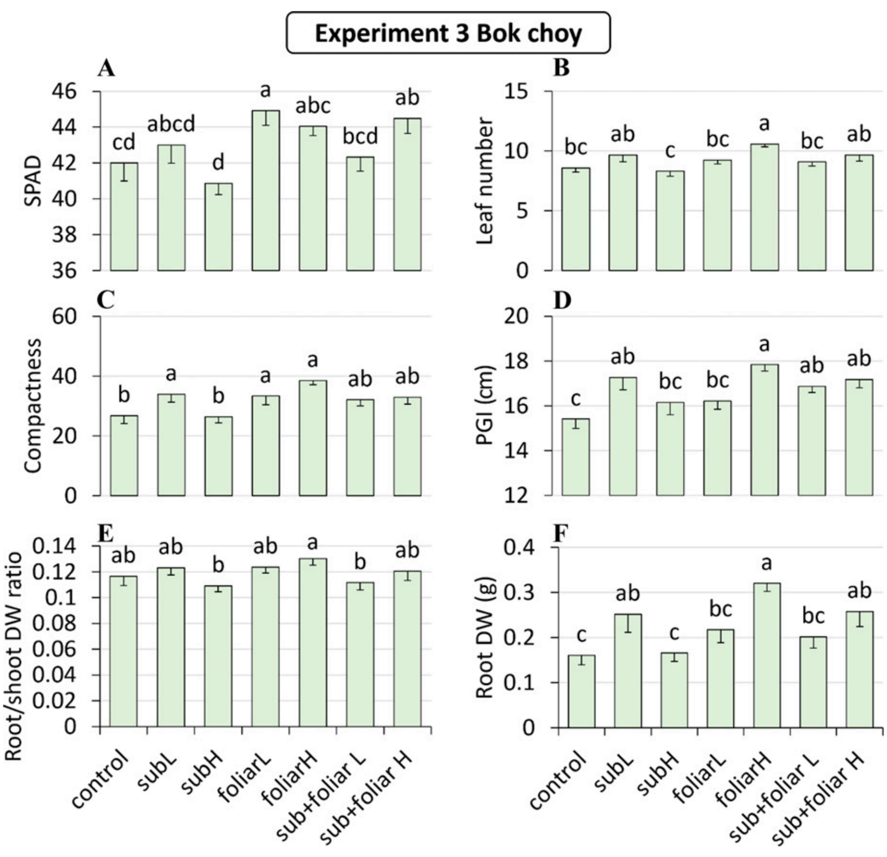

Fig. 3. Expt. 3: Bok choy plant growth parameters (**A–F**) with different onion juice concentrate (OJC) application methods. Different letters above bars indicate significant differences between OJC application methods. "Sub" refers to subirrigation, whereas "foliar" refers to foliar spray application. For foliar spray application, the low (L) and high (H) OJC concentrations were 0.5% and 1%, respectively. For subirrigation application, the L and H OJC concentrations were 1% and 1.5%, respectively. DW = dry weight; PGI = plant growth index.

Discussion

Turning onion peel waste into a useful plant biostimulant product would be beneficial for both onion processing industries and crop production. Onion peel waste is rich in carbohydrates and various bioactive metabolites, such as quercetin (Celano et al. 2021; Vojvodić Cebin et al. 2020); all of these have been shown to have beneficial effects on plant growth (Jańczak-Pieniążek et al. 2021; Trouvelot et al. 2014; Zenda et al. 2021). Therefore, this study investigated the effects of OJC on various vegetables and turfgrass to explore its potential as a beneficial product for plant growth. Through a series of step-by-step experiments of OJC application, we found that foliar application of OJC at 1% to 2% increased yield and benefited bok choy growth. Drench or subirrigation of OJC boosted the root growth of bok choy, lettuce, and radish. Combining subirrigation and foliar application of OJC also had a positive impact on bok choy and radish growth.

The positive effects of OJC on root growth were evident across all experiments. However, the OJC effect on shoot growth is not as significant as that on root growth. In

Table 6. Expt. 3: Comparison of bok choy and radish plant growth parameters and leaf SPAD readings (greenness) with conventional and organic fertilizers.

Crop	Conventional fertilizer	Organic fertilizer
Bok choy		
SPAD	42.4 b	43.8 a
Leaf number	9.3 a	9.3 a
Plant compactness	30.0 b	34.2 a
Plant growth index	16.5 a	16.9 a
Root-to-shoot dry weight ratio	0.11 b	0.13 a
Root dry weight	0.20 b	0.25 a
Radish		
Shoot fresh weight	7.27 a	6.05 b
Root average diameter	36.3 a	30.2 b
Root fresh weight	21.5 a	12.9 b
Root dry weight	1.03 a	0.58 b

Different letters within a row suggest significant differences between fertilizers.

SPAD = Soil and Plant Analysis Development.

Expt. 1, the OJC application did not increase the shoot FWs of bok choy and lettuce, but it increased their root DWs by 17% to 52%. The same trends were observed for lettuce in Expt. 2, which implied that roots were more responsive than shoots to OJC treatment. Similarly, a study of winter oilseed rape, another Brassica vegetable, found that although root DW increased significantly with plant-derived biostimulants, these same treatments did not produce significant effects on shoot DW (Billard et al. 2014). Increased substrate nutrient availability induced by beneficial bacteria, bioactive compounds that induce phytohormone synthesis in plants, and carbohydrates that trigger improved nitrogen assimilation are potential contributors to enhanced root growth (Zulfiqar et al. 2020). Many plant-derived substances promote plant growth and yield by exhibiting hormone-like effects, which can stimulate the root growth with more adventitious roots (Bulgari et al. 2015; Kim et al. 2019). However, the mechanism behind the plant-derived substances promoting plant growth is challenging to elucidate because of their complex compositions (Bulgari et al. 2019). Further studies are needed to unveil the chemical composition of OJC and investigate the specific compounds responsible for its beneficial effects on plant growth by, ideally, separating the onion juice with other added beneficial microorganisms. Understanding the molecular mechanisms of each microorganism behind these effects will help optimize the development of plant growth-promoting agricultural products using onion waste.

Application methods of biostimulants can be grouped into three categories based on the part of the plant they target [leaf (foliar spray), root (substrate application), and seed treatments] (Bulgari et al. 2019). In this study, we compared foliar spray, drench, and subirrigation application methods of OJC. In Expt. 2, foliar spray of OJC increased bok choy shoot growth, thus reflecting on the increased leaf area, shoot DW, and SPAD compared with the control, whereas drench application did not affect these parameters. In Expt. 3, the combined application of OJC through subirrigation and foliar spray further enhanced the total leaf area and shoot FW of bok choy and lettuce compared with the foliar application alone or subirrigation alone. For radishes, combining foliar spray with subirrigation of OJC boosted the average root diameter, root FW, and root DW compared with foliar spray application alone or subirrigation alone. Similar synergistic effects were also found with the application of plant-derived protein on lettuce (Lucini et al. 2015). However, from a cost–benefit perspective, deciding whether to solely implement substrate application or include foliar application of OJC requires further consideration. A comprehensive review of 180 biostimulant studies revealed that soil treatment is the most effective way to apply biostimulants, resulting in an 11% higher yield compared with foliar and seed applications (Li et al. 2022). Our radish results further support this finding because subirrigation of OJC increased yield by 31% compared with foliar application. Compared with foliar spray application, applying OJC directly to the substrate offers several advantages. Because OJC is a liquid, it can be easily incorporated in the irrigation systems, thus saving labor compared with foliar spray application. Additionally, OJC is brown to orange, especially when applied to leafy greens; therefore, OJC may leave brown stains on leaves, potentially raising concerns among consumers about the quality of the vegetable. Therefore, applying OJC directly to the substrate appears to be a more promising and practical option.

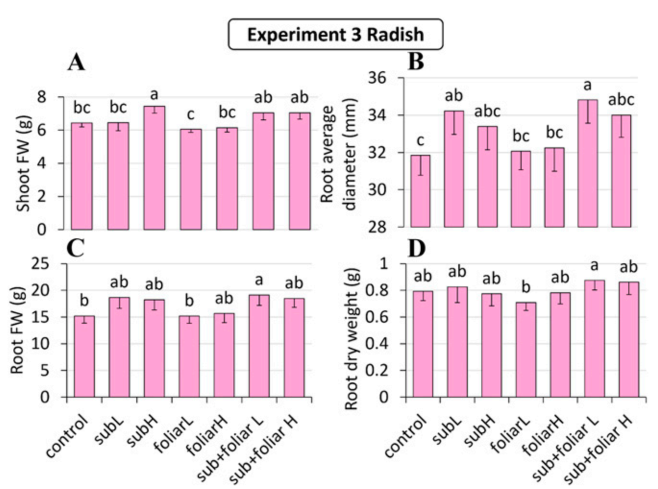

Fig. 4. Expt. 3: Radish plant growth parameters (**A–D**) with different onion juice concentrate (OJC) application methods. Different letters above bars indicate significant differences between OJC application methods. “Sub” refers to subirrigation, whereas “foliar” refers to foliar spray application. For foliar spray application, the low (L) and high (H) OJC concentrations were 0.5% and 1%, respectively. For subirrigation application, the L and H OJC concentrations were 1% and 1.5%, respectively. FW = fresh weight.

Despite limited OJC application durations (2–3 weeks in Expt. 1 and Expt. 2; 5–7 weeks in Expt. 3), OJC application led to increased growth, particularly root growth. For field crops, enhanced root growth will increase the use efficiency of both water and nutrients, leading to a gradual improvement in overall plant health and resilience, particularly in the aboveground parts (Hodge et al. 2009). Thus, our findings may have important implications for developing the OJC into a plant biostimulant for agriculture application, which has become a hot topic among scientists and related industry professionals worldwide. Plant biostimulants can be derived from a wide range of materials, including beneficial fungi (such as arbuscular mycorrhizal fungi) and beneficial bacteria (such as plant growth-promoting rhizobacteria, protein hydrolysate, humic substances, seaweed extract, and others) (Del Buono 2021; Shahrajabian et al. 2021). The abundance of onion waste in many countries and our positive results warrant further study and, potentially, development as a useful plant biostimulant product for agriculture. It is worth pointing out that our experiments were conducted in a greenhouse with soilless substrates. For future studies, OJC should be applied to field crops with longer production times or perennial crops to investigate its long-term benefits on overall plant performance, yield, and soil health.

Conclusions

As a new agricultural product, OJC has been proven to have beneficial effects on plant growth. Foliar application of OJC diluted at 1% to 2% in water increased the yield and overall growth of bok choy. Subirrigation with OJC applied at varying concentrations between 0.5% and 2% enhanced root growth

Table 7. Expt. 3: Radish plant leaf SPAD readings (greenness) and shoot dry weight among different fertilizers and onion juice applications.

	Control	Subirrigation L	Subirrigation H	Foliar L	Foliar H	Sub + Fol L	Sub + Fol H	Mean
SPAD								
Conventional fertilizer	44.7 Ba	44.8 Aa	45.3 Aa	46.2 Aa	44.5 Aa	44.0 Aa	44.0 Aa	44.8
Organic fertilizer	48.0 Aa	42.2 Ad	42.0 Bd	45.8 Aabc	46.8 Aab	44.4 Abcd	44.0 Acd	44.8
Mean	46.4	43.5	43.7	46.0	45.7	44.2	44.0	
Shoot dry weight (g)								
Conventional fertilizer	0.59 Abc	0.67 Aab	0.73 Aa	0.55 Ac	0.60 Abc	0.69 Aab	0.66 Aab	0.64
Organic fertilizer	0.53 Aab	0.42 Bb	0.51 Bab	0.50 Aab	0.48 Bab	0.52 Bab	0.54 Ba	0.50
Mean	0.56	0.55	0.62	0.53	0.54	0.61	0.60	

Different uppercase letters within a column suggest significant differences between fertilizer treatments. Different lowercase letters within a row suggest significant differences between onion juice applications.

Foliar = foliar spray; H = high; L = low; SPAD = Soil and Plant Analysis Development; Sub = subirrigation.

in bok choy, lettuce, and radish. Notably, the combined approach of foliar and subirrigation application further boosted the growth of both bok choy and radish. Across all experiments, longer OJC application periods emerged as a promising strategy for maximizing its growth-promoting benefits. Additionally, considering economic factors, substrate application of OJC may be more cost-effective than foliar spray application. Further research should explore the use of OJC on crops with extended growth periods to prolong the application time and optimize its effectiveness. Overall, the OJC appears to be a viable and sustainable agricultural product. By repurposing waste from the onion processing industry instead of disposing it in a landfill, OJC offers the dual benefits of enhancing crop production and protecting the environment. Although our experiments were conducted in a greenhouse and plants were cultured in containers with soilless substrate, real-world open field production is more complex; therefore, crop responses to OJC applications in open fields may be different because of the interaction of soil microorganisms and stressful growing conditions.

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