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Influence of gibberellic acid on vegetable crop and weed emergence

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Research Article

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Abstract

Small-seeded vegetable crop production is challenged by poor emergence, stand establishment and canopy development, as well as a lack of effective weed control options. The potential use of plant growth regulators such as gibberellic acid (GA) could enhance early emergence and growth rates while potentially synchronizing weed germination with control tactics. In response, a controlled environment study was conducted to investigate the effects of GA on garden beet, cabbage, carrot, and onion. At 7 d after seeding (DAS) carrot emergence was greater when carrot seeds were treated with 2, 4, 8, 16, or 64 ppm GA compared with nontreated seeds. Total carrot emergence over the study period was 14% greater when seeds were treated with 4 ppm GA compared with nontreated seeds. Treatment of cabbage with as low as 2 to 4 ppm GA increased cabbage emergence rate and total plant emergence over the study period relative to nontreated seeds. Onion response to GA treatment was variable and unremarkable and was hypothesized to be influenced by seed dormancy because emergence was also low with the nontreated seeds. The GA rates that stimulated vegetable crop seed germination and emergence were then explored with three common weed species to determine whether a similar response was observed. If so, GA could be used to stimulate weed emergence in synchrony with management tactics. Palmer amaranth emergence was strongly affected by GA treatment, whereby the total number of emerged plants was 48% greater when 4 ppm GA was applied than in the nontreated check. Velvetleaf emergence at 3 DAS with the 4 and 8 ppm GA was 2.9 and 3.0 plants pot^{-1}, respectively, compared to no emergence in the nontreated pots. Redroot pigweed emergence was not affected by GA treatment at any rate.

Introduction

Small-seeded vegetable crop production is challenged by poor emergence, stand establishment, canopy development, and a lack of effective weed management options. For example, carrot often emerges inconsistently over a period of 21 d or longer, resulting in poor competition with weeds, and leading to stunted growth and severe yield loss (Colquhoun et al. 2017). Similarly, onion is a long-season crop that does not form a canopy that can compete with weeds, and in the absence of weed management yield reduction can be up to 77% (Bond et al. 1998). Weed control options in these poorly competitive crops are limited because the crops are sensitive to damage from mechanical cultivation, particularly during the early season when weeds are emerging. Hand-weeding is not practical given labor limitations, and few herbicides are registered for use with these crops (Colquhoun et al. 2022).

The potential use of plant growth regulators integrated with other management strategies could add to the limited weed management options available in vegetable crops by enhancing early emergence and growth rates while potentially synchronizing weed germination with control tactics. Gibberellic acid (GA) is a natural plant growth regulator that influences plant life processes such as seed germination, root and shoot elongation, flowering, and fruiting (Harms and Oplinger 1991). Gibberellic acid released during seed germination triggers seed cover weakening and stimulates cell expansion. More specifically, a seed that is mechanically constrained by the endosperm in the radicle tip germinates slowly, and the weakening of the endosperm by applied GA results in a faster seed germination rate (Andreoli and Khan 1999). Plant response to GA varies by growth stage and concentration, such as in carrot, when foliar application can promote leaf growth, inhibit root growth, stimulate bolting and decrease soil lead uptake (Ghani et al. 2021).

The influence of GA on crop growth has largely focused on foliar applications to influence desired crop production traits, such as to overcome plant disease, assist in drought tolerance or increase crop yield and quality. For example, Devi et al. (2018) reported that foliar GA applications increased onion leaf number, length and weight, bulb diameter and scale number, and overall bulb yield. Limited research has been reported on the influence of plant growth regulators on weed growth, and while preliminary results from laboratory studies were promising, the advent of effective synthetic herbicides appears to have stymied further developments. In the early 1970s, Holm and Miller (1972) reported that GA increased germination of 9 out of 11 tested weed species. The authors reported that "clearly more research into the endogenous promoters and inhibitors is needed to determine what roles they play in controlling dormancy and germination in weed seeds" but reports of continued work in this area are minimal. Since then, only sporadic research in laboratory studies has documented the use of plant growth regulators such as GA to break weed seed dormancy, but minimal research has occurred in agricultural settings (Wei et al. 2010).

Heavy reliance on synthetic herbicides for the majority of weed control and subsequent widespread herbicide resistance among weed species has stimulated renewed interest in the role of plant growth regulators in integrated weed management systems (Heap 2022; Oliveira et al. 2020). Several potential uses for plant growth regulators are envisioned. Crop seed treatment that enhances emergence rates and early season growth could allow for earlier cultivation, and less hand-weeding and postemergence herbicide use, and thus less injury risk. Furthermore, broadcast soil application and incorporation of plant growth regulators into the weed germination zone with irrigation, precipitation, or light tillage could break weed seed dormancy and promote germination either before crop planting in a false seedbed technique, or at the time of preemergence herbicide application when residual herbicides are most active. Das and Das (2018) demonstrated the potential of such a system in wheat and soybean: weed control was greater when KNO_3 or GA was applied with a residual herbicide than when the herbicide was used alone. Similar efforts have not been reported in vegetable crops.

The research presented here focuses specifically on small-seeded vegetable crops that are poor competitors with weeds largely because they germinate and emerge slowly and incompletely. Therefore, we evaluated whether GA applied to seed could improve crop emergence rate and uniformity. The GA rates that were found to improve crop emergence were then investigated with common weed species.

Materials and Methods

Controlled environment studies were conducted in 2020 through 2022 at the University of Wisconsin-Madison Arlington Agricultural Research Station in Arlington, WI (43.18947°N, 89.204332°W). All seeds were stored at 4 C in dark conditions. Growth chamber conditions were chosen to mimic a typical air temperature in the Midwestern United States during early season vegetable crop seed germination and emergence. The growth chamber was unlit (dark), and the temperature was set at a constant 16 C. Crop and weed studies were each conducted twice.

Studies were arranged in a completely randomized design with three (weed species) or four (vegetable species) replications. The crop seed study used four vegetable crops: garden beet, cabbage, carrot, and onion. The seeding rate for 'Patterson' F_1 hybrid yellow onion (Johnny's Selected Seeds, Winslow, ME), 'Bolero' F_1 hybrid storage carrot (Johnny's Selected Seeds), and 'Tendersweet' F_1 hybrid fresh market green cabbage (Johnny's Selected Seeds) was 0.1 g of seed on top of commercial potting mix (Grower Select M1 Professional Mix; BFG Supply Co., Burton, OH) in 10-cm diameter pots. The seeding rate for 'Red Ace' F_1 hybrid round garden beet (Johnny's Selected Seeds) was 0.4 g seed pot $^{-1}$. Each vegetable crop was subjected to eight concentrations of GA (ProGibb 40; Valent BioSciences, Libertyville, IL): 0, 2, 4, 8, 16, 32, 64, and 128 ppm active ingredient vol/vol) mixed in distilled water. The vegetable crop seeds for each treatment and replicate were placed in individual paper bags, GA was sprayed into the bag in the same amount for each treatment (2 ml bag^{-1}), and each bag was hand-mixed for 10 s. The nontreated seeds were similarly sprayed with distilled water. The seeds remained in the bags for 24 h to dry in ambient air, after which they were spread on the surface of the commercial potting mix and covered with 1 cm of additional potting mix. Emerged plants were counted and removed from the pots every 1 to 3 d over a 2-wk period.

The weed species studies were conducted with the same methodology outlined above for the vegetable crop studies except for the treatment method. Weed species included Palmer amaranth, redroot pigweed, and velvetleaf. Weed seeds were collected from field populations in Wisconsin. The seeding rate for Palmer amaranth and redroot pigweed was 0.1 g pot^{-1}, and it was 0.3 g seed pot^{-1} for velvetleaf. The GA rates that were most effective at stimulating vegetable crop germination and emergence were investigated for the weed species (2, 4, 8, and 16 ppm). Weed seeds were placed on the surface of commercial potting mix and GA was broadcast applied over the surface using a backpack air pressure sprayer calibrated to deliver 187 L ha^{-1} at 186 kPa with Teejet® XR8003VS nozzle tips (Spraying Systems Co., Wheaton, IL). Seeds were then covered with an additional 1 cm of commercial potting mix to aid in moisture retention. Emergence data collection was the same as outlined in the vegetable crop studies.

Studies were analyzed independently by species. Crop and weed seed data were subjected to ANOVA using the GLM procedure with SAS software (version 9.4; SAS Institute Inc., Cary, NC). Additionally, crop species proportion of total emergence at each evaluation timing was calculated as the percentage of emerged plants at the evaluation time relative to total emergence over the study period. The repeated studies were combined for analysis. Emergence and proportion of total emergence means were separated using Tukey's honestly significant difference test at $P = 0.05$.

Results and Discussion

Garden Beet

There were no statistical differences between GA rate and plant emergence or proportion of total emergence 7 and 10 d after seeding (DAS; Table 1). Similarly, at 13 DAS the only difference in emergence was between 2 ppm GA, which had the greatest emergence rate of 1.1 plants per pot, and 128 ppm GA, which had the lowest emergence rate of 0.1 beet plants. The greatest overall plant emergence occurred in the 2 ppm GA treatment, which resulted in 46.8 total emerged plants pot^{-1} over the study period, compared to the 16 ppm and 128 ppm GA treatments, which had the lowest total emergence. Overall, the influence of GA seed treatment on garden beet was rather minimal.

Cabbage

As early as 4 DAS, cabbage plant emergence was greater when 2 ppm GA was applied compared with seeds that were treated with 32, 64, or 128 ppm GA (Table 2). However, plant emergence in all GA seed treatments was similar to that of the nontreated seeds

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Table 1. 'Red Ace' garden beet plant emergence after seed treatment with gibberellic acid.[a,b]

	7 DAS		10 DAS		13 DAS		
Gibberellic acid rate	Emergence	Proportion of total emergence	Emergence	Proportion of total emergence	Emergence	Proportion of total emergence	Total
ppm ai	plants pot^{-1}	%	plants pot^{-1}	%	plants pot^{-1}	%	plants pot^{-1}
0	37.9	86.3	6.0	12.6	0.5 b[c]	1.0	44.4 ab
2	39.5	84.9	5.9	12.6	1.1 a	2.3	46.8 a
4	38.3	90.5	2.8	6.6	0.6 ab	1.7	42 ab
8	39.5	88.8	4.3	9.2	0.8 ab	1.7	44.6 ab
16	32.4	87.0	3.7	8.6	0.4 ab	0.9	37.6 b
32	34.5	85.5	3.4	8.2	0.3 ab	0.6	40 ab
64	34.9	86.6	4.5	10.4	0.8 ab	1.8	40.5 ab
128	34.5	89.6	3.6	8.4	0.1 b	0.2	38.9 b

[a]Studies were conducted in a dark growth chamber set at 16 C. Emerged plants were removed at each evaluation date.
[b]Abbreviation: DAS, d after seeding.
[c]Means followed by the same letter are not different according to Tukey's honestly significant difference test at P = 0.05. If no letters are included for a column, then there were no statistical differences noted.

at that evaluation timing. By 7 DAS, cabbage plant emergence was 43% greater after the 4 ppm GA treatment than that of the nontreated control. Seeds that had been treated with 2 ppm GA exhibited the greatest emergence 10 DAS, and more than double that of the nontreated control. No differences among treatments were noted at 13 DAS. Total cabbage plant emergence over the study period was greater when 2 ppm GA was applied compared with that of the nontreated seeds and seeds that had been treated with 32, 64, or 128 ppm GA. Treatment of cabbage with as low as 2 to 4 ppm GA increased both cabbage emergence rate and overall total plant emergence, suggesting this option would be affordable and practical to adopt in commercial production.

Carrot

Gibberellic acid had a strong and early influence on carrot plant emergence. At 7 DAS carrot emergence was greater than that of the nontreated control when carrot seeds were treated with all GA rates except 32 and 128 ppm (Table 3). Carrot emergence was greatest when 8 or 16 ppm GA was applied. After the 8 ppm GA treatment 40.5% of the total emergence during the study period occurred in the first 7 d compared with just 17.9% of total emergence from the nontreated seeds. By 10 and 13 DAS, in general carrot emergence and the proportion of total emergence were greatest in the treatments that had the least plant emergence at 7 DAS, indicating that 8 and 16 ppm GA were effective at hastening emergence time. By 13 DAS carrot emergence ranged from 4.8% to 11.3% across all treatments, suggesting faster emergence in controlled environment conditions than in field conditions as noted above. Total carrot emergence over the study period was 14% greater when seeds were treated with 4 ppm GA compared with nontreated seeds. Total plant emergence over the study period was similar among all GA treatments. These observations suggest that treating carrot seeds with between 4 and 16 ppm GA can sharply increase early emergence, and lower rates in that range can also improve overall plant emergence compared with nontreated seeds.

Onion

Overall, onion plant emergence was variable among treatments, but at 10 DAS emergence was greater when seeds were treated with 16 or 64 ppm GA, particularly compared with seeds that were treated with 128 ppm GA (Table 4). The proportion of total emergence at 10 DAS was between 42% and 59% when onion seeds were treated with 4, 8, 16, or 64 ppm GA compared to 34% of the nontreated control seeds. Like observations with carrot, by 13 DAS onion plant emergence and the proportion of total study emergence were generally lowest in treatments when emergence was greatest 10 DAS. No differences were observed in total onion plant emergence over the study period. Overall emergence did not differ among treatments and total emergence was low in all cases, including the nontreated seeds, suggesting that seed dormancy may have been a stronger influence on germination and emergence than GA as hypothesized by Karimmojeni et al. (2014).

Weed Emergence

Breaking weed seed dormancy and enhancing weed emergence with GA would be beneficial in a false seedbed approach prior to crop planting or at the time of residual preemergent herbicide application such that susceptible weeds would germinate when herbicides are most efficacious. Velvetleaf emergence began within 2 DAS, and at 3 DAS the 4 and 8 ppm GA treatments stimulated 2.9 and 3.0 plants pot^{-1}, respectively, compared with no emergence in the nontreated pots (Table 5). There were no differences in velvetleaf emergence among GA treatments 5 or 7 DAS. Total emergence was also not statistically significant ($P = 0.06$).

In contrast, Palmer amaranth emergence was strongly affected by GA treatment (Table 6). As early as 3 DAS, 23.9 and 12.6 Palmer amaranth plants pot^{-1} were observed when 4 and 8 ppm GA was applied, compared with only 1.9 plants pot^{-1} when no GA was applied. No difference in emergence among treatments were noted 5 and 7 DAS. The early germination stimulation increased total Palmer amaranth germination over the study period, with more total emerged plants noted when 2 and 4 ppm GA was applied compared with emergence in the nontreated plants. The 4 ppm GA treatment was particularly effective at increasing overall Palmer amaranth emergence in that the total number of emerged plants was 48% greater than that of the nontreated check.

Redroot pigweed emergence was not affected by GA treatment at any rate (data not shown). However, overall redroot pigweed

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Table 2. 'Tendersweet' cabbage plant emergence after seed treatment with gibberellic acid.[a,b]

Gibberellic acid rate	4 DAS		7 DAS		10 DAS		13 DAS		Total
	Emergence	Proportion of total emergence	Emergence	Proportion of total emergence	Emergence	Proportion of total emergence	Emergence	Proportion of total emergence	
ppm ai	plants pot^{-1}	%	plants pot^{-1}	%	plants pot^{-1}	%	plants pot^{-1}	%	plants pot^{-1}
0	12.3 abc[c]	63.3	5.4 b	28.1	0.9 bc	4.6	0.6	4.0	19.1 bc
2	15.0 a	59.7	7.8 ab	30.5	2.0 a	8.2	0.4	1.6	25.1 a
4	10.9 abc	50.4	9.5 a	44.8	0.9 bc	4.1	0.1	0.7	21.4 abc
8	14.0 ab	62.3	6.8 ab	32.4	0.5 c	2.0	0.8	3.3	22 abc
16	12.5 abc	53.6	8.1 ab	37.9	1.8 ab	8.0	0.1	0.5	22.5 ab
32	9.8 c	53.0	8.4 ab	38.9	1.4 abc	6.7	0.3	1.4	19.8 bc
64	10.5 c	54.7	8.0 ab	37.4	1.4 abc	6.8	0.3	1.1	20.1 bc
128	10.5 c	56.3	6.3 ab	33.8	1.5 abc	8.4	0.3	1.4	18.5 c

[a]Studies were conducted in a dark growth chamber set at 16 C. Emerged plants were removed at each evaluation date.
[b]Abbreviation: DAS, d after seeding.
[c]Means followed by the same letter are not different according to Tukey's honestly significant difference test at P = 0.05. If no letters are included for a column, then there were no statistical differences noted.

germination across all treatments was lower than anticipated and may account for the lack of observed differences, again suggesting that strong dormancy may be a factor that was not overcome by GA treatment.

The research presented here suggests a role for plant growth regulators to increase small-seeded vegetable crop competitiveness with weeds in several ways, although the response varied by species. Typically, carrot emergence can take up to 3 wk after seeding (Que et al. 2019), whereas in this study carrot plants emerged mostly between 7 and 10 DAS. The proportion of total emergence within the first week after seeding was among the lowest from nontreated seeds. Carrot emergence at low GA concentrations was greater than at the highest GA rate (128 ppm) and greater than the nontreated seed. Given that conventional carrot seed is almost always treated with fungicide and the GA concentrations that were found to be useful here were very low, this would be a very affordable way to improve carrot plant stand development and uniformity.

Early emergence and total emergence of cabbage over the study period was enhanced by GA treatments as low as 2 to 4 ppm compared with emergence from the nontreated seeds. In garden beet, emergence in all treatments was slow as is typically observed in the field. Garden beet "seed" is a seedball composed of one to several seed and covered by a mucilaginous layer (Taylor et al. 2003). We hypothesize that GA uptake may have been inhibited by this layer. Enhancing vegetable crop emergence would improve competitiveness with weeds and get the crop to a growth stage at which early cultivation, hand-weeding, and postemergence herbicide applications are less injurious. For example, few effective preemergence herbicides are labeled for use in onion, and postemergence herbicides can't be used until at least the 2-leaf onion growth stage if not later, leaving the crop without comprehensive weed control options for about 4 wk after seeding (Colquhoun et al. 2022).

Weed response to GA application varied by species but offered opportunities to improve control of challenging weeds such as Palmer amaranth, which is often resistant to multiple herbicide modes of action (Heap 2022) and evades control tactics by emerging over a long period during the growing season. For example, in California, Palmer amaranth emergence occurs from May to October (Mohler et al. 2022). In this case, a very low rate of GA could be applied to stimulate Palmer amaranth germination in a stale seedbed prior to crop planting, alongside application of an effective preemergence residual herbicide, or prior to cultivation or postemergence herbicide application.

Although the GA rates explored here formed a quantitative series, preliminary regression analyses were not significant (data not shown). The lack of quantitative relationship between GA rate and crop or weed emergence response is not unique to these studies. Karimmojeni et al. (2014) investigated herb sophia (*Descurainia sophia* L.), field pennycress (*Thlaspi arvense* L.), and African mustard (*Malcolmia africana* L.) response to GA rates ranging from 0 to 200 ppm. African mustard seed germination was greatest when seeds stored at 20 C were treated with 10 ppm, whereas fresh seed germination was greatest when seeds were treated with 150 ppm. Herb sophia also did not respond to GA rates in a quantitative fashion in that fresh seed germination was greater when seeds were treated with 50 ppm GA compared to all other GA rates and nontreated seeds. The authors concluded that seed germination did not necessarily increase with increasing GA rate, but at some rates GA resulted in increased germination, and that rate varied depending on pretreatment conditions that can affect inherent dormancy such as storage

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Table 3. 'Bolero' carrot plant emergence after seed treatment with gibberellic acid.[a,b]

Gibberellic acid rate	7 DAS		10 DAS		13 DAS		Total
	Emergence	Proportion of total emergence	Emergence	Proportion of total emergence	Emergence	Proportion of total emergence	
ppm ai	plants pot^{-1}	%	plants pot^{-1}	%	plants pot^{-1}	%	plants pot^{-1}
0	7.3 de[c]	17.9 cd	29.5 ab	72.2 ab	4.1 ab	9.9	40.9 b
2	13.5 bc	31.4 ab	25.6 b	59.8 bc	3.8 ab	8.8	42.9 ab
4	13.0 bc	28.0 abc	31.0 ab	65.3 abc	3.3 ab	6.7	47.3 a
8	17.5 a	40.5 a	25.6 b	54.7 c	2.5 b	4.8	45.6 ab
16	15.0 ab	34.1 ab	26.8 b	58.8 bc	3.5 ab	7.1	45.3 ab
32	5.8 e	12.9 d	34.9 a	78.7 a	3.8 ab	8.3	44.4 ab
64	13.8 b	30.8 abc	27.3 b	62.2 bc	3.1 ab	7.0	44.1 ab
128	10 cd	23.8 bcd	28.3 b	64.8 abc	4.9 a	11.3	43.1 ab

[a]Studies were conducted in a dark growth chamber set at 16 C. Emerged plants were removed at each evaluation date.
[b]Abbreviation: DAS, d after seeding.
[c]Means followed by the same letter are not different according to Tukey's honestly significant difference test at P = 0.05. If no letters are included for a column, then there were no statistical differences noted.

Table 4. 'Patterson' onion plant emergence after seed treatment with gibberellic acid.[a,b]

Gibberellic acid rate	10 DAS		13 DAS		17 DAS		Total
	Emergence	Proportion of total emergence	Emergence	Proportion of total emergence	Emergence	Proportion of total emergence	
ppm ai	plants pot^{-1}	%	plants pot^{-1}	%	plants pot^{-1}	%	plants pot^{-1}
0	2.9 abc[c]	34.1 ab	3.5 ab	44.4 ab	2 a	21.5	8.4
2	2.8 abc	37 ab	3.5 ab	42.7 ab	1.5 ab	20.2	7.8
4	3.3 ab	50.6 ab	2 b	25.2 b	1.5 ab	24.2	6.8
8	3.3 ab	42.2 ab	2.8 ab	30.8 ab	2.1 a	27	8.1
16	3.8 a	46.9 ab	3 ab	36.6 ab	1.4 ab	16.5	8.1
32	2.1 bc	34.6 ab	4.1 a	52.7 ab	1.1 ab	12.7	7.4
64	3.8 a	59.3 a	2.3 b	30.6 ab	0.8 b	10.1	6.8
128	1.6 c	26.7 b	3.5 ab	57.8 a	1 ab	15.5	6.1

[a]Studies were conducted in a dark growth chamber set at 16 C. Emerged plants were removed at each evaluation date.
[b]Abbreviation: DAS, d after seeding.
[c]Means followed by the same letter are not different according to Tukey's honestly significant difference test at P = 0.05. If no letters are included for a column, then there were no statistical differences noted.

Table 5. Velvetleaf plant emergence after gibberellic acid application.[a,b]

Gibberellic acid rate	2 DAS	3 DAS	5 DAS	7 DAS	Total
ppm ai	plants pot^{-1}				
0	0	0 b[c]	18.2	0.1	18.7
2	1.0	0.3 ab	18.5	0.4	21.3
4	0.3	2.9 a	14.8	0.1	19.2
8	1.3	3.1 a	15.8	0	21.3
16	0.5	2.0 ab	13.8	0.3	17.8

[a]Studies were conducted in a dark growth chamber set at 16 C. Emerged plants were removed at each evaluation date.
[b]Abbreviation: DAS, d after seeding.
[c]Means followed by the same letter are not different according to Tukey's honestly significant difference test at P = 0.05. If no letters are included for a column, then there were no statistical differences noted.

Table 6. Palmer amaranth plant emergence after gibberellic acid application.[a,b]

Gibberellic acid rate	3 DAS	5 DAS	7 DAS	Total
ppm ai	plants pot^{-1}			
0	1.9 b[c]	48.8	0.1	51.8 b
2	6.3 b	59.8	1.1	69.5 a
4	23.9 a	51.5	0	76.5 a
8	12.6 ab	50.8	0	65.8 ab
16	6.9 b	56.0	0.3	64.7 ab

[a]Studies were conducted in a dark growth chamber set at 16 C. Emerged plants were removed at each evaluation date.
[b]Abbreviation: DAS, d after seeding.
[c]Means followed by the same letter are not different according to Tukey's honestly significant difference test at P = 0.05. If no letters are included for a column, then there were no statistical differences noted.

temperature and burial depth (Karimmojeni et al. 2014). Similar observations in this study support the need for additional research to explore GA rate response in varying seed and field conditions.

Further research is also warranted to broaden the preliminary exploration to additional weed species and plant growth regulators. For example, abscisic acid might be used to enforce weed seed dormancy, allowing less competitive crops such as those studied here to become established and more competitive prior to widespread weed emergence (Leung and Giraudat 1998).

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References

Andreoli C, Khan AA (1999) Matriconditioning integrated with gibberellic acid to hasten seed germination and improve stand establishment of pepper and tomato. Presqui Agropecu Bras 34:1953–1958

Bond W, Burton S, Bevan JR, Lennartsson ME (1998) Optimum weed removal timing in drilled salad onions and transplanted bulb onions grown in organic and conventional systems. Biol Agric Hortic 16:191–201

Colquhoun JB, Chapman SA, Gevens AJ, Groves RL, Heider DJ, Jensen BM, Nice GR, Raurk MD, Wang Y (2022) Commercial Vegetable Production in Wisconsin – 2022. Madison: University of Wisconsin-Madison Extension publication. https://cdn.shopify.com/s/files/1/0145/8808/4272/files/A3422-2022.pdf. Accessed: March 2022

Colquhoun JB, Rittmeyer RA, Heider DJ (2017) Tolerance and suppression of weeds varies among carrot varieties. Weed Technol 31:897–902

Das TK, Das DK (2018) Using chemical seed dormancy breakers with herbicides for weed management in soyabean and wheat. Weed Res 58:188–199

Devi J, Singh D, Walia I (2018) Effect of foliar GA3 and NAA on onion – a review. Plant Arch 18:1209–1214

Ghani MA, Abbas MM, Ali B, Aziz R, Qadri RW, Noor A, Azam M, Bahzad S, Saleem MH, Abualreesh MH, Alatawi A, Ali S (2021) Alleviating role of gibberellic acid in enhancing plant growth and stimulating phenolic compounds in carrot (*Daucus carota* L.) under lead stress. Sustainability 13:123–129

Harms CL, Oplinger ES (1991) Plant growth regulators: Their use in crop production. North Central Region Ext Pub 303:1–6

Heap I (2022) The International Herbicide-Resistant Weed Database. www.weedscience.org. Accessed: March 7, 2022

Holm RE, Miller MR (1972) Weed seed germination responses to chemical and physical treatments. Weed Sci 20:150–153

Karimmojeni H, Taab A, Rashidi B, Hossein Bazrafshan A (2014) Dormancy breaking and seed germination of annual weeds *Thlaspi arvense*, *Descurainia sophia* and *Malcolmia Africana* (Brassicaceae). J Plant Prot Res 54:179–187

Leung J, Giraudat J (1998) Abscisic acid signal transduction. Annu Rev Plant Physiol Plant Mol Biol 49:199–222

Mohler C, Teasdale J, DiTomasso A (2022) Manage weeds on your farm: a guide to ecological strategies. College Park, MD: SARE Handbook Series 16, 416 p

Oliveira MC, Osipitan A, Begcy K, Werle R (2020) Cover crops, hormones and herbicides: Priming an integrated weed management strategy. Plant Sci 301:1–5

Que F, Hou XL, Wang GL, Xu ZS, Tan GF, Li T, Wang YH, Khadr A, Xiong AS (2019) Advances in research on the carrot, an important root vegetable in the Apiaceae family. Hortic Res 6:1–15

Taylor AG, Goffinet MC, Pikuz SA, Shelkovenko TA, Mitchell MD, Chandler KM, Hammer DA (2003) Physico-chemical factors influence beet (*Beta vulgaris* L.) seed germination. Pages 433–440 *in* Nicolás G, Bradford KJ, Côme D, Pritchard HW, eds., The Biology of Seeds: Recent Research Advances, Based on a Workshop held in Salamanca, Spain, May 2002. Wallingford, UK and Cambridge, MA: CABI Publishing

Wei S, Zhang C, Xuezheng C, Li X, Sui B, Huang H, Cui H, Liu Y, Zhang M, Guo F (2010) Rapid and effective methods for breaking seed dormancy in buffalobur (*Solanum rostratum*). Weed Sci 58:141–146