HortScience 52(3):371–376. 2017. doi: 10.21273/HORTSCI11388-16

Response of Vegetable Seedling Emergence to Mustard (*Sinapis alba* 'IdaGold' and *Brassica juncea* 'Pacific Gold') Seed Meal

Xi Wang
Department of Horticultural Sciences, Texas A&M University, 2134 TAMU, College Station, TX 77843

Genhua Niu[1]
Texas A&M AgriLife Research Center at El Paso, Texas A&M University, 1380 A&M Circle, El Paso, TX 79927

Mengmeng Gu
Department of Horticultural Sciences, Texas A&M AgriLife Extension Service, College Station, TX 77843

Paul A. Baumann
Department of Soil and Crop Sciences, Texas A&M AgriLife Extension Service, College Station, TX 77843

Joseph Masabni
Department of Horticultural Sciences, Texas A&M AgriLife Extension Service, Overton, TX 75684

Additional index words. allelopathy, bio-herbicide, mustard seed meal, organic farming

***Abstract*. Mustard Seed Meals (MSMs) are by-products of biodiesel and an alternative to conventional herbicides for organic farming. However, MSMs might also suppress the emergence of vegetable seedlings. The objective of this study was to determine the response of vegetable seedling emergence to different MSM types and rates applied as an alternative herbicide. Six types of vegetable seeds, onion (*Allium cepa*), two cultivars of lettuce (*Lactuca sativa* 'Black Seeded Simpson' and 'Buttercrunch'), mustard (*Brassica juncea*), kale (*Brassica oleracea*), and Mizuna (*Brassica rapa* var. *japonica*), were sowed in petri dishes containing germination mix. MSMs (*Sinapis alba* 'IdaGold' and *B. juncea* 'Pacific Gold') were incorporated into the germination mix at 0, 88, 176, or 265 g·m^{-2}. Petri dishes were sealed for 1, 3, 5, or 7 days after sowing. For onion, 'Pacific Gold' had a greater suppressive effect on seedling emergence than 'IdaGold'. For kale and mustard, 'IdaGold' and 'Pacific Gold' had similar suppressive effects on seedling emergence, but 'Pacific Gold' delayed emergence of kale at 88 g·m^{-2} when sealed for 3, 5, and 7 days. For Mizuna, 'IdaGold' had more suppressive effects than 'Pacific Gold' on seedling emergence, while sealing delayed but did not decrease emergence percentage (EP) at the lower rate (88 g·m^{-2}) compared with the control treatment. For 'Buttercrunch' lettuce, there were no differences in the suppressive effects between the two MSMs. For 'Black Seeded Simpson' lettuce, 'Pacific Gold' had more suppressive effects on seedling emergence than 'IdaGold' when sealed at the lower rate (88 g·m^{-2}) for longer durations (7 days) or at higher rates (176 and 265 g·m^{-2}) for shorter durations (1 and 3 days). These results suggest that MSMs might suppress vegetable seedling emergence when applied at high rates (176 and 265 g·m^{-2}), and sealing for more than 7 days after sowing may strengthen the suppressive effect. Extending sealing duration at the medium rates could achieve similar weed control results to high rates without sealing.**

Organic farming is rapidly increasing in U.S. agriculture. Weeds are listed as the number one problem for organic producers (Walz, 1999). Only a few organic herbicides are used in organic farming systems (Webber III et al., 2012). MSMs as by-products of biodiesel and industrial oil production are residues remaining after oil extraction. As an alternative method to chemical herbicides, utilization of MSM not only assists the biodiesel industry to be economically and environmentally viable but also offers a solution to organic agricultural production systems. Our previous study demonstrated the herbicidal efficacy of *S. alba* 'IdaGold' and *B. juncea* 'Pacific Gold', which varied with application rate and method and weed species (Wang et al., 2015).

The herbicidal activity of MSM is due to allelopathy induced by hydrolysis products of glucosinolates (GSLs) (Hoagland et al., 2008). Certain plants in the *Brassicaceae* family are known to possess allelopathic properties, and are used as cover crops in different cropping systems (Haramoto and Gallandt, 2005). There are about 20 GSLs in *Brassica* species, with concentrations varying among species and also within different plant tissues (Kirkegaard and Sarwar, 1998). *Sinapis alba* 'IdaGold' seed meal is dominated by 4-hydroxybenzyl GSL (glucosinalbin), whereas *B. juncea* seed meal is dominated by 2-propenyl GSL (sinigrin) (Hansson et al., 2008). GSLs hydrolyze or degrade quickly and volatiles may be released after incorporation of MSM in soil (Morra and Kirkegaard, 2002). For this reason, sealing after incorporating MSM into soil may increase the efficacy of MSM to suppress weed emergence. In our previous study using petri dishes, sealing did decrease weed emergence compared with the unsealed treatment (Wang et al., 2015). Plastic mulch, commonly used in commercial vegetable production, can provide a condition similar to sealing.

Early development of vegetable seedlings may be the most vulnerable part of the life cycle when exposed to allelopathic chemicals (Russo et al., 1997), and MSMs have been reported to have potential herbicidal, insecticidal, nematicidal, and fungicidal effects (Hansson et al., 2008). In a greenhouse experiment, onion was severely injured when MSM (*S. alba*) was applied at planting and at one-leaf stage at 110, 220, and 440 g·m^{-2}, whereas redroot pigweed (*Amaranthus retroflexus*) was mostly killed by 70 and 280 g·m^{-2} MSM when surface applied at cotyledon stage or one-leaf stage (Boydston et al., 2011). Canola (*Brassica napus*) and mustard (*S. alba*) seed meals were used as organic sources of fertilizer to increase essential nutrients in the strawberry (*Fragaria* ×*ananassa*) production, and greatly reduced summer annual weeds like large crabgrass (*Digitaria sanguinalis*), barnyardgrass (*Echinochloa crus-galli*), common purslane (*Portulaca oleracea*), and redroot pigweed at all rates of seed meals (Bañuelos and Hanson, 2010). In a field experiment, *B. juncea* 'Pacific Gold' and *S. alba* 'IdaGold' seed meal at 2,000 kg·ha^{-1} greatly reduced weed seedling emergence and biomass of Italian ryegrass (*Lolium perenne* spp. *multiflorum*), prickly lettuce (*Lactuca serriola*), redroot pigweed and wild oat (*Avena fatua*), which are major weeds in vegetable production systems (Handiseni and Brown, 2011). Rice et al. (2007) also demonstrated that 'Pacific Gold' and 'IdaGold' greatly reduced the emergence and biomass of redroot pigweed,

Received for publication 23 Sept. 2016. Accepted for publication 17 Jan. 2017.
This research is partially supported by U.S. Department of Agriculture National Institute of Food and Agriculture Hatch project TEX090450 and Texas AgriLife Research. The content is solely the responsibility of the authors and does not necessarily represent the official views of the funding agencies.
[1]Corresponding author. E-mail: gniu@ag.tamu.edu.

common chickweed (*Stellaria media*), lettuce, and beet (*Beta vulgaris*). However, tomato (*Lycopersicon esculentum*) and pepper (*Capsicum annuum*) seedling emergence in *Pythium ultimum* infested soils was improved by *B. napus* and *B. juncea* seed meals (Handiseni and Brown, 2011). 'Pacific Gold' and 'IdaGold' seed meals did not influence carrot (*Daucus carota* subsp. *sativus*) emergence when applied at 1 and 2 $t \cdot ha^{-1}$ 36 d before planting, whereas carrot emergence decreased 40% in *S. alba* treatments when applied 15 d before planting (Snyder et al., 2009).

On the basis of previous findings and the potential of MSM in organic farming, the objectives of this study were to determine the effects of two types of MSM at a range of rates on the emergence of six vegetable seedlings under laboratory conditions. The ultimate goal is to minimize the potential phytotoxicity to vegetable crops, especially at emergence stage, when applying MSM for weed control in organic production systems.

Materials and Methods

Emergence of vegetable seedlings in petri dish. Two MSMs, *S. alba* 'IdaGold' and *B. juncea* 'Pacific Gold' (Farm Fuel Inc., Freedom, CA), which were derived from cold press with no heat, were incorporated uniformly into 10 g of germination mix formulated with Canadian Sphagnum peatmoss, vermiculite, starter nutrient charge (with Gypsum) and dolomitic limestone (Sunshine Professional Growing Mix, BWI, Schulenburg, TX) at 0, 0.5, 1.0, or 1.5 g per petri dish (0%, 5%, 10%, or 15% w/w) and were evenly applied at the bottom of 10-cm petri dishes and 25 mL water was added. The above MSM rates were equivalent to 0, 88, 176, or 265 $g \cdot m^{-2}$ or 0, 785, 1570, or 2364 $lb \cdot acre^{-1}$. Onion 'Texas Grano 1015Y', two lettuce 'Black Seeded Simpson' and 'Buttercrunch', mustard 'Green Wave', kale 'Vates Blue Curled', green 'Mizuna' were purchased from Morgan County Seeds (Barnett, MO). Ten onion, 10 kale, and 10 'Buttercrunch' lettuce seeds were sowed in three separated parts of 1 petri dish, 10 mustard, 10 green and 10 'Black Seeded Simpson' lettuce seeds were sowed in three separated parts of another petri dish. Seeds were sowed 2 mm below the substrate surface in each petri dish. To simulate the sealing condition of plastic mulch, all petri dishes were covered and sealed with parafilm immediately after sowing. Each MSM rate and plant seed combination was sealed for 1, 3, 5, or 7 d before uncovering. All petri dishes were placed on a shelf in the laboratory. Supplemental lighting was provided by two 40-W fluorescent light tubes (50 $\mu mol \cdot m^{-2} \cdot s^{-1}$, 25-cm above shelf) using a 12-h photoperiod at an air temperature of 18 to 22 °C. The unsealed petri dishes (uncovered) were kept moist with a hand held sprayer. The number of emerged seedlings (vegetable seedlings with at least 5 mm radicle above substrate surface) was counted daily for 14 consecutive days after sowing.

Experimental design and statistical analysis. All experiments (all species) were conducted twice (Oct. to Nov. 2013 and Mar. to Apr. 2014) under the same conditions with the same experimental design. For each vegetable type, the petri dish experiment was arranged in a three-factor (MSM type, rate, and sealing duration) factorial design with two replications. The replication in time was treated as time block. For each species, the independent variables were analyzed with analysis of variance (ANOVA; Statistical Analysis System Version 9.3; SAS Institute, Cary, NC). For each type of vegetables, EP was calculated as: EP (%) = (no. of emerged seedlings/total no. of seeds) × 100%. In addition, emergence index (EI) was calculated as $EI = \sum_{i=1}^{n} (EP_i/T_i)$; where EP_i is EP on day i (i ≥2), and T_i is the number of days after sowing. Different from EP, EI reflects both number of seedlings emerged and their rates of emergence. Since each type of vegetables was treated as a separate experiment, results are presented for each type, grouped by genus. Only EI data are presented. The effects of MSMs on EP are presented in the ANOVA summary table. When effect of application rate and sealing duration was significant, Duncan's multiple range comparison was performed to distinguish the effects among application rates and sealing durations.

Results

The two experiments treated as a time block significantly affected the EI of all types of vegetables, except for Mustard. Therefore, results of EI from both experiments are presented in tables separately for all types of vegetables except for mustard. For mustard, results of Expt. 1 and Expt. 2 were pooled.

'Texas Grano 1015Y' onion. The effects of MSM type, rate, and sealing duration and the interaction between MSM type and rate on EP and EI were significant, while the effects of the interaction among three main factors (MSM type, rate, and sealing duration), the interaction between MSM type and sealing duration, and the interaction of MSM rate and sealing duration did not significantly affect EP or EI (Tables 1 and 2). When there was no MSM incorporated in the germination mix, sealing decreased EI when sealed for 5 and 7 d in Expt. 1 and for 7 d in Expt. 2 (Table 3). EI was zero or at a very low value when sealed with 176 $g \cdot m^{-2}$ or higher rate of 'Pacific Gold'. At all rates of MSM, EI values were lower in 'Pacific Gold' than 'IdaGold', regardless of sealing duration; and the differences were larger in Expt. 2. For 'IdaGold', with all sealing durations, there were no differences in EI between 176 $g \cdot m^{-2}$ and 265 $g \cdot m^{-2}$. For 'Pacific Gold', no differences in EI were observed either between 176 $g \cdot m^{-2}$ and 265 $g \cdot m^{-2}$, except for dealing duration of

Table 1. A summary of analysis of variance (ANOVA) of emergence percentage (EP) of six vegetable seedlings exposed to different types ('IdaGold' and 'Pacific Gold') and rates (0, 88, 175, and 265 $g \cdot m^{-2}$ per dish) of mustard seed meal (MSM) and sealing durations (1, 3, 5, and 7 d). Block: time block of the two experiments conducted at different time periods.

	ANOVA of EP					
	Pr > F					
Source	Onion	Kale	Mizuna	Mustard	'Buttercrunch' lettuce	'Black Seeded Simpson' lettuce
Block	<0.0001	NS	0.0065	NS	<0.0001	<0.0001
Rate	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Sealing duration	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Type	<0.0001	NS	0.0176	NS	0.0367	<0.0001
Type × rate	0.0248	0.0008	NS	0.014	NS	0.0256
Rate × sealing duration	NS	0.0009	<0.0001	0.0075	0.0055	0.0007
Type × sealing duration	NS	NS	NS	NS	NS	NS
Type × rate × sealing duration	NS	NS	NS	NS	NS	NS

Table 2. A summary of analysis of variance (ANOVA) of emergence index (EI) of six types of vegetables exposed to different types ('IdaGold' and 'Pacific Gold') and rates (0, 88, 175, and 265 $g \cdot m^{-2}$) of mustard seed meal and sealing durations (1, 3, 5, and 7 d). Block: time block of the two experiments conducted at different time periods.

	ANOVA of EI					
	Pr > F					
Source	Onion	Kale	Mizuna	Mustard	'Buttercrunch' lettuce	'Black Seeded Simpson' lettuce
Block	<0.0001	0.0018	0.0002	NS	<0.0001	<0.0001
Rate	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Sealing duration	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Type	<0.0001	NS	0.0263	NS	0.0261	<0.0001
Type × rate	0.0252	0.0087	NS	0.026	NS	0.0272
Rate × sealing duration	NS	0.0076	<0.0001	0.0071	0.0158	0.0014
Type × sealing duration	NS	NS	NS	NS	NS	NS
Type × rate × sealing duration	NS	NS	NS	NS	NS	NS

1 d in Expt. 1. For all sealing durations, 'Pacific Gold' at 88 g·m^{-2} did not impact EI in Expt. 1.

'Vates Blue Curled' kale. The effects of MSM rate, sealing duration, the interaction between MSM type and rate, and the interaction between MSM rate and sealing duration significantly impacted EP and EI of kale seedlings, while the effects of the interaction among the three main factors (MSM type, rate, and sealing duration), the interaction between MSM type and sealing duration, and MSM type did not significantly affect EP and EI of kale seedlings (Tables 1 and 2). When there was no MSM incorporated into the germination mix, sealing decreased EI when sealed for 7 d in both experiments (Table 4). For both 'IdaGold' and 'Pacific Gold', EI generally decreased as rate increased for all sealing durations. There was no difference in EI between 'IdaGold' and 'Pacific Gold' under the same rate and sealing duration (Tables 2 and 4).

Mizuna. The effects of MSM type, rate, sealing duration, and the interaction between MSM rate and sealing duration were significant on EP and EI of Mizuna seedlings, while the interaction among three main factors (MSM type, rate, and sealing duration), the interaction between MSM type and sealing duration were not significant on EP and EI (Tables 1 and 2). When there was no MSM incorporated into the germination mix, sealing reduced EI when sealed for 3 to 7 d in Expt. 2 but not in Expt. 1 (Table 5). For both 'IdaGold' and 'Pacific Gold', EI was significantly decreased when sealed with 88 to 265 g·m^{-2} of MSM from 1 to 7 d in both experiments except for 88 to 176 g·m^{-2} of 'Pacific Gold' sealed for 1 d in Expt. 1.

'Green Wave' mustard. The effects of MSM rate, sealing duration, the interaction between MSM type and rate, and the interaction between MSM rate and sealing duration were significant on EP and EI of mustard seedlings, while the interaction among the three main factors (MSM type, rate, and sealing duration), the interaction between type and sealing duration, and MSM type were not significant on EP and EI of mustard seedlings (Tables 1 and 2). When there was no MSM incorporated into the germination mix, sealing decreased EI of mustard seedlings when sealed from 3 to 7 d (Table 6). For 'IdaGold', EI significantly decreased when sealed with 176 g·m^{-2} for 1 and 5 d, and with 88 g·m^{-2} for 3 and 7 d. For 'Pacific Gold', EI was significantly reduced when sealed with 88 g·m^{-2} from 1 to 7 d. There was no difference in EI among all sealing durations. Type of MSM did not affect EI of mustard seedling.

'Buttercrunch' lettuce. The effects of MSM type, rate, sealing duration, and the interaction between MSM rate and sealing duration were significant on EP and EI of 'Buttercrunch' seedlings, while the effects of the interaction among three main factors (MSM type, rate, and sealing duration), the interaction between

Table 3. Effects of different types ('IdaGold' and 'Pacific Gold') and rates (0 to 265 g·m^{-2}) of mustard seed meal (MSM) and sealing durations (1, 3, 5, and 7 d) on emergence index (EI) of 'Texas Grano 1015Y' onion seedlings at 14 d after sowing.

		EI of onion seedlings (%)			
Expt. 1:	Rates	Sealing duration (d)			
MSM	(g·m^{-2})	1	3	5	7
IdaGold	0	89.00 A a	76.45 A ab	61.30 A b	63.15 A b
	88	78.00 AB a	58.05 AB ab	41.05 AB bc	21.90 B c
	176	50.00 AB a	25.80 B b	10.90 B c	1.50 B c
	265	20.15 B a	36.55 AB a	9.75 B a	1.50 B a
Pacific Gold	0	81.05 A a	72.90 A a	67.65 A a	78.50 A a
	88	77.65 A a	38.25 A b	14.30 A c	6.65 A c
	176	35.90 B a	10.80 A b	0.00 A b	7.00 A b
	265	3.00 C a	0.35 A a	0.00 A a	0.35 A a
		EI of Onion seedlings (%)			
Expt. 2:	Rates	Sealing duration (d)			
MSM	(g·m^{-2})	1	3	5	7
IdaGold	0	74.25 A^z a^y	67.95 A a	48.75 A ab	37.35 A b
	88	61.45 AB a	45.90 AB a	32.15 AB a	16.65 B a
	176	33.7 BC a	17.75 B ab	9.35 BC b	0.00 C b
	265	11.80 C a	8.10 B a	4.75 C a	3.00 BC a
Pacific Gold	0	75.95 A a	60.20 A ab	55.65 A b	28.70 A c
	88	12.40 B a	5.75 B a	7.05 B a	1.50 B a
	176	1.15 C a	0.00 B a	0.35 B a	0.00 B a
	265	0.00 C a	0.00 B a	0.00 B a	0.00 B a

^{z}Means followed by a different letter (upper case) within a column are significantly different at $P \leq 0.05$.
^{y}Means followed by a different letter (lower case) within a row are significantly different at $P \leq 0.05$.

Table 4. Effects of different types ('IdaGold' and 'Pacific Gold') and rates (g·m^{-2}) of mustard seed meal (MSM) and sealing durations (1, 3, 5, and 7 d) on emergence index (EI) of 'Vates Blue Curled' kale seedlings at 14 d after sowing.

		EI of kale seedlings (%)			
Expt. 1:	Rates	Sealing duration (d)			
MSM	(g·m^{-2})	1	3	5	7
IdaGold	0	156.35 A^z a^y	143.30 A ab	155.15 A a	107.85 A b
	88	133.25 A a	111.30 AB a	67.35 B b	35.45 B b
	176	68.80 B a	43.75 BC ab	30.10 C ab	7.40 C b
	265	13.30 C a	19.45 C a	10.55 C a	7.95 C a
Pacific Gold	0	166.00 A a	133.95 A a	127.10 A a	137.60 A a
	88	108.40 B a	45.25 B b	14.55 B b	6.30 B b
	176	54.55 BC a	19.70 B b	6.80 B b	1.45 B b
	265	8.30 C a	24.80 B a	8.55 B a	5.60 B a
		EI of kale seedlings (%)			
Expt. 2:	Rates	Sealing duration (d)			
MSM	(g·m^{-2})	1	3	5	7
IdaGold	0	144.90 A a	111.35 A a	105.90 A a	60.85 A b
	88	106.40 AB a	50.05 B b	42.35 B b	40.60 AB b
	176	51.35 BC a	19.65 C ab	10.75 BC b	1.50 AB b
	265	10.85 C a	2.65 C ab	1.90 C ab	0.75 B b
Pacific Gold	0	140.80 A a	107.00 A ab	97.90 A bc	61.70 A c
	88	83.55 B a	56.65 AB ab	22.90 B b	22.95 B b
	176	74.00 B a	36.75 B ab	14.10 B b	4.80 B b
	265	50.40 B a	24.70 B ab	10.90 B b	1.80 B b

^{z}Means followed by a different letter (upper case) within a column are significantly different at $P \leq 0.05$.
^{y}Means followed by a different letter (lower case) within a row are significantly different at $P \leq 0.05$.

MSM type and sealing duration, and the interaction between MSM type and rate were not significant on EP and EI of 'Buttercrunch' seedlings (Tables 1 and 2). When there was no MSM incorporated into the germination mix, sealing slightly reduced EI in Expt. 2 but not in Expt. 1 (Table 7). For 'Pacific Gold', EI was zero for all sealing durations in Expt. 2, regardless of MSM rate; in Expt. 1, EI was zero or at a very low value when sealed for 5 to 7 d. Similarly, 'IdaGold' at 176 g·m^{-2} and 265 g·m^{-2} also resulted in zero or very low values of EI. The three rates of 'IdaGold' and 'Pacific Gold' generally had similar impact on EI.

'Black Seeded Simpson' lettuce. The effects of MSM type, rate, sealing duration,

Table 5. Effects of different types (‘IdaGold’ and ‘Pacific Gold’) and rates (0 to 265 g·m^{-2}) of mustard seed meal (MSM) and sealing durations (1, 3, 5, and 7 d) on emergence index (EI) of ‘Mizuna’ green seedlings at 14 d after sowing.

		EI of Mizuna seedlings (%)			
Expt. 2:	Rates	Sealing duration (d)			
MSM	(g·m^{-2})	1	3	5	7
IdaGold	0	153.70 A[z] a[y]	134.85 A a	142.80 A a	127.35 A a
	88	111.25 B a	43.60 B ab	55.05 B b	19.55 B b
	176	24.20 C a	10.15 B ab	4.05 C b	1.85 B b
	265	0.00 C a	0.00 B a	0.00 C a	0.00 B a
Pacific Gold	0	152.05 A a	170.40 A a	161.65 A a	148.70 A a
	88	117.10 AB a	23.20 B b	8.00 B b	2.55 B b
	176	50.65 AB a	17.85 B a	21.30 B a	1.05 B a
	265	16.10 B a	10.60 B a	0.00 B a	0.00 B a
		EI of Mizuna seedlings (%)			
Expt. 2:	Rates	Sealing duration (d)			
MSM	(g·m^{-2})	1	3	5	7
IdaGold	0	152.90 A a	126.20 A b	126.25 A b	83.05 A c
	88	52.15 B a	10.70 B b	20.75 B ab	10.95 B b
	176	0.75 C a	2.30 B a	2.30 BC a	0.85 B a
	265	1.60 C a	0.00 B a	0.00 C a	0.00 B a
Pacific Gold	0	153.90 A a	122.15 A a	107.75 A a	124.75 A a
	88	93.60 B a	58.50 B ab	32.15 B b	20.90 B b
	176	19.65 C a	2.65 C ab	8.20 C ab	0.75 B b
	265	3.25 C a	0.00 C a	0.00 C a	0.00 B a

[z]Means followed by a different letter (upper case) within a column are significantly different at $P \leq 0.05$.
[y]Means followed by a different letter (lower case) within a row are significantly different at $P \leq 0.05$.

Table 6. Effects of different types (‘IdaGold’ and ‘Pacific Gold’) and rates (0 to 265 g·m^{-2}) of mustard seed meal (MSM) and sealing durations (1, 3, 5, and 7 d) on emergence index (EI) of ‘Green Wave’ mustard seedlings at 14 d after sowing.

		EI of mustard seedlings (%)			
	Rates	Sealing duration (d)			
MSM	(g·m^{-2})	1	3	5	7
IdaGold	0	138.9 A[z] a[y]	109.9 A b	94.1 A b	69.8 A c
	88	112.1 A a	52.1 B bc	66.7 A b	29.7 B c
	176	67.9 B a	26.8 C b	10.4 B bc	6.4 B c
	265	32.2 C a	12.7 C ab	1.9 B b	9.1 B b
Pacific Gold	0	125.5 A a	111.3 A ab	93.2 A b	95.3 A b
	88	115.2 AB a	21.3 B b	22.1 B b	13.1 B b
	176	87.7 B a	20.1 B b	19.5 B b	5.4 B b
	265	41.1 C a	6.7 B b	9.4 B b	1.7 B b

[z]Means followed by a different letter (upper case) within a column are significantly different at $P \leq 0.05$.
[y]Means followed by a different letter (lower case) within a row are significantly different at $P \leq 0.05$.

the interaction between MSM type and rate, and the interaction between MSM rate and sealing duration were significant on EP and EI of ‘Black Seeded Simpson’ seedlings, while the interaction among three main factors (MSM type, rate, and sealing duration) and the interaction between MSM type and sealing duration were not significant on EP and EI of ‘Black’ seedlings (Tables 1 and 2). When there was no MSM incorporated into the germination mix, sealing duration did not affect EI (Table 8). For both MSM, EI decreased as sealing duration and rates increased in Expt. 1. In Expt. 2, EI was zero when ‘Pacific Gold’ was incorporated into the germination mix. For ‘IdaGold’ at the two higher rates, EI was zero or close to zero for all sealing durations.

Discussion

The efficacy of MSM depends on several factors, type of seed meal, application rates, and target plant species. ‘Pacific Gold’ seed meal mainly contains sinigrin (2-propenyl GSL), whereas ‘IdaGold’ seed meal contains a large concentration of sinalbin (4-hydroxybenzyl GSL) (Borek and Morra, 2005; Hansson et al., 2008; Rice et al., 2007). 2-Propenyl-ITC was the dominant GSL hydrolysis product from ‘Pacific Gold’ seed meal, which is phytotoxic due to a nonspecific and irreversible reaction with sulfur-containing groups in proteins (Bending and Lincoln, 1999; Brown and Morra, 1997; Rice et al., 2007). Other studies have reported that SCN^- was more persistent in the soil compared with 2-propenyl-ITC (Borek et al., 1995; Brown and Morra, 1993). Also, ‘Pacific Gold’ produces volatile allyl-ITCs that are toxic on contact, with a half-life of 16 h after soil incorporation (Petersen et al., 2001). SCN^- produced by ‘IdaGold’ is translocated and accumulates in plant tissues, which might not kill seedlings at shorter sealing durations (Stiehl and Bible, 1989), but may affect plant growth. Different responses of vegetable seedlings to the type, rate, and sealing duration of MSM treatments observed in this experiment may also be due to different sensitivity to GSL breakdown products that have been observed among plant species (Vaughn et al., 2006).

As discussed above, due to the different GSLs in the two different MSMs, the responses of vegetable seedling emergence to these MSM applications differed among species. For onion seedlings, ‘Pacific Gold’ had greater suppressive effects on seedling emergence than ‘IdaGold’ (Table 3). For kale and mustard seedlings, ‘IdaGold’ and ‘Pacific Gold’ had similar suppressive effects; however, ‘Pacific Gold’ delayed emergence of kale seedlings at 88 g·m^{-2} when sealed for 3, 5, and 7 d (Tables 4 and 6). For Mizuna seedlings, ‘IdaGold’ had more suppressive effects than ‘Pacific Gold’ on seedling emergence, while sealing delayed but did not decrease emergence at a low rate (88 g·m^{-2}) of MSMs compared with the control (Table 5).

Lettuce is particularly sensitive to *Brassicaceae* seed meal-derived allelochemicals (Rice et al., 2007). For ‘Buttercrunch’ seedlings, sealing durations did not provide additional reduction of emergence, and there were also no different suppressive effects between ‘IdaGold’ and ‘Pacific Gold’ (Table 7). For ‘Black Seeded Simpson’ seedlings, ‘Pacific Gold’ had more suppressive effects on ‘Black Seeded Simpson’ seedlings emergence than ‘IdaGold’ when sealed using the lower rate (88 g·m^{-2}) of MSM for longer durations (7 d) or at higher rates (176 and 265 g·m^{-2}) of MSM for shorter durations (1 and 3 d) (Table 8). Meyer et al. (2011) found that 0.5% (w/w) ‘IdaGold’ seed meal did not reduce lettuce seed germination, but all seed meal treatments containing ‘Pacific Gold’ significantly reduced germination when applied immediately after planting. Although the MSM did not affect lettuce seed germination at 1–5 weeks after planting, hypocotyl growth was reduced. In a field experiment, lettuce emergence was lower with 3% ‘Pacific Gold’ than 3% ‘IdaGold’ or *B. napus* seed meal when planted 28 d after seed meal treatments (Rice et al., 2007).

On the basis of the results of this study, there might be suppressive effects of MSMs at higher rates (176 and 265 g·m^{-2}) on vegetable emergence. Suppressive efficacy of MSM would be enhanced by sealing the soil after application such as plastic mulches. MSM at medium rate with sealing may achieve similar efficacy to high rates

Table 7. Effects of different types ('IdaGold' and 'Pacific Gold') and rates (0 to 265 $g\cdot m^{-2}$) of mustard seed meal (MSM) and sealing durations (1, 3, 5, and 7 d) on emergence index (EI) of 'Buttercrunch' lettuce seedlings at 14 d after sowing.

Expt. 1: MSM	Rates ($g\cdot m^{-2}$)	EI of 'Buttercrunch' lettuce seedlings (%) Sealing duration (d) 1	3	5	7
IdaGold	0	141.65 A[z] a[y]	149.70 A a	137.85 A a	145.75 A a
	88	97.45 AB a	51.65 B ab	48.90 B ab	16.60 B b
	176	45.70 BC a	10.25 B b	8.10 B b	0.00 B b
	265	3.35 C a	4.90 B a	0.00 B a	1.15 B a
Pacific Gold	0	144.30 A a	150.30 A a	134.80 A a	119.70 A a
	88	99.20 B a	34.70 B ab	11.40 B b	6.20 B b
	176	17.85 C a	5.90 B ab	0.75 B b	0.00 B b
	265	0.00 C a	0.00 B a	0.00 B a	0.00 B a

Expt. 2: MSM	Rates ($g\cdot m^{-2}$)	EI of 'Buttercrunch' lettuce seedlings (%) Sealing duration (d) 1	3	5	7
IdaGold	0	135.15 A a	109.00 A bc	127.10 A ab	99.05 A c
	88	35.40 B a	29.20 B ab	5.00 B b	4.70 B b
	176	2.10 B a	1.15 B a	3.75 B a	0.00 B a
	265	0.00 B a	0.00 B a	0.00 B a	0.00 B a
Pacific Gold	0	138.85 A a	123.65 A a	116.05 A ab	87.55 A b
	88	0.00 B a	0.00 B a	0.00 B a	0.00 B a
	176	0.00 B a	0.00 B a	0.00 B a	0.00 B a
	265	0.00 B a	0.00 B a	0.00 B a	0.00 B a

[z]Means followed by a different letter (upper case) within a column are significantly different at $P \leq 0.05$.
[y]Means followed by a different letter (lower case) within a row are significantly different at $P \leq 0.05$.

Table 8. Effects of different types ('IdaGold' and 'Pacific Gold') and rates (0 to 265 $g\cdot m^{-2}$) of mustard seed meal (MSM) and sealing durations (1, 3, 5, and 7 d) on emergence index (EI) of 'Black Seeded Simpson' lettuce seedlings at 14 d after sowing.

Expt. 1: MSM	Rates ($g\cdot m^{-2}$)	EI of 'Black Seeded Simpson' lettuce seedlings (%) Sealing duration (d) 1	3	5	7
IdaGold	0	155.85 A[z] a[y]	147.30 A a	138.25 A a	141.90 A a
	88	125.75 AB a	44.85 B ab	79.90 AB ab	9.05 B b
	176	50.15 BC a	35.45 B ab	14.85 B ab	2.95 B b
	265	11.60 C a	8.80 B a	3.95 B a	1.60 B a
Pacific Gold	0	148.80 A a	125.55 A a	129.25 A a	140.20 A a
	88	101.35 A a	41.60 AB a	15.15 B a	23.15 B a
	176	12.15 B a	4.30 B a	1.50 B a	1.15 B a
	265	0.00 B a	0.00 B a	0.00 B a	0.00 B a

Expt. 2: MSM	Rates ($g\cdot m^{-2}$)	EI of 'Black Seeded Simpson' lettuce seedlings (%) Sealing duration (d) 1	3	5	7
IdaGold	0	138.50 A a	124.10 A a	139.75 A a	124.20 A a
	88	113.40 B a	41.15 B b	44.90 B b	16.30 B b
	176	19.05 C a	16.95 B a	13.45 C a	11.25 B a
	265	10.95 C a	5.40 B a	0.00 C a	1.10 B a
Pacific Gold	0	71.90 A a	94.15 A a	77.55 A a	89.75 A a
	88	0.00 B a	0.00 B a	0.00 B a	0.00 B a
	176	0.00 B a	0.00 B a	0.00 B a	0.00 B a
	265	0.00 B a	0.00 B a	0.00 B a	0.00 B a

[z]Means followed by a different letter (upper case) within a column are significantly different at $P \leq 0.05$.
[y]Means followed by a different letter (lower case) within a row are significantly different at $P \leq 0.05$.

of MSM without sealing. Also, MSMs are basically a nonselective type of weed control and its efficacy varies with crop species, application rate and method, and environmental conditions. Therefore, extensive field studies are needed to determine the rate and timing of applying MSM to suppress weed emergence for vegetable production with direct seeding or transplanting to avoid or minimize suppressive effects on seedling emergence of vegetable crops.

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