HERBICIDAL ACTIVITY OF MUSTARD SEED MEAL ON WEED AND VEGETABLE EMERGENCE

A Thesis

by

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ABSTRACT

Mustard seed meals (MSMs) are by-products resulting from crushing mustard seeds to provide biofuel. MSMs have been applied as bio-herbicides due to the release of active glucosinolates hydrolysis products. Four experiments were conducted to determine the herbicidal activity of MSMs (*Sinapis alba* 'IdaGold' and *Brassica juncea* 'Pacific Gold') on weed and vegetable emergence. In Expt. 1, MSMs were applied at 0, 50, 100, 200 or 300 g/m^2 to the bottom of petri dishes and covered with germination mix. Five of the ten reps were sealed with parafilm. In Expt. 2, MSMs were applied on the surface or incorporated with germination mix at 0, 1.5, 3.0 or 4.5 g/pot in the top layer of greenhouse containers. In Expt. 3, MSMs were incorporated with germination mix at 0, 1.5 or 3.0 g/pot in the top layer of outdoor containers. In Expt. 4, six types of vegetable seeds (onion *Allium cepa* 'Texas Grano 1015Y', lettuces *Lactuca sativa* 'Black Seeded Simpson' and 'Buttercrunch', mustard *Brassica juncea* 'Green Wave', kale *Brassica oleracea* 'Vates Blue Curled', green *Brassica rapa* 'Mizuna') and two types of weeds, large crabgrass (*Digitaria sanguinalis*) and Palmer amaranth (*Amaranthus palmeri*) were sowed in a germination mix incorporated with MSMs at 0, 88, 176 or 265 g/m^2 in petri dishes, and unsealed for 1, 3, 5 or 7 days after sowing. Results suggest that 'Pacific Gold' had better suppressive effects on large crabgrass and Palmer amaranth emergence than 'IdaGold' at 100 to 300 g/m^2 under all sealing conditions in petri dishes, while less emergence was exhibited under sealed than unsealed conditions at same rates. Surface applied MSMs had better suppressive effects on weed emergence than incorporated in greenhouse containers, 'IdaGold' exhibited better herbicidal efficacy on Palmer amaranth, whereas 'Pacific Gold' was more effective on large crabgrass. Besides, there was suppressive effects and phytotoxicity of MSMs at higher rates (176 and 265 g/m^2) on vegetable and weed emergence in petri dishes, and increased sealing durations strengthened the suppressive effect when sealed longer than 7 days after sowing. In conclusion, MSMs have potential to control weeds in nursery containers and organic farms.

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Weeds are a serious problem in container nursery production, due to competition for nutrients, and water in containers or producing chemicals to suppress plant growth, causing reductions in nursery plant growth or quality. The potential damage caused by weeds create a poor image for a nursery plants by reducing aesthetic and economic value (Case et al., 2005; Harpster et al., 2012). In a study by Mathers, the cost of weed control was higher than any other form of pest control. Nursery growers estimated it cost $500 to $4,000/acre for manual weed control, and all the losses caused by weeds have been estimated about $7,000/acre (Mathers, 2003). Thus, effective weeds control methods are very important in container nursery production.

Currently, weed control in container nursery production generally includes herbicides (preemergence and postemergence), physical methods (hand-weeding and mulches) and bioherbicides (e.g. dried distillers grains with soluble, corn gluten meal and mustard seed meal). Preemergent herbicides are applied before weed seed germination. When germinating seeds come in contact with the herbicide, the growth of emerging roots and/or shoots is inhibited, but preemergent herbicides may not be effective without good contact with germinated weed seeds (Altland, 2003). Postemergent herbicides are applied after weeds have emerged, ideally at the seedling stage, due to the relatively small amount of biomass. In order to provide complete weed control, hand weeding and spot treatment with postemergent herbicides are usually necessary after application of preemergent herbicides (Wilen, 2009; Harpster et al., 2012). Labeled postemergent herbicides for use in container nurseries were less effective than preemergent herbicides, and there were no good herbicides choices for postemergent broad leaf control in containers (Monaco et al., 2002).

Among preemergent herbicides, flumioxazin was used in nursery production and landscape maintenance industries, providing both PRE and POST weed control (Altland et al., 2003). Flumioxazin provided complete (100%) control on hairy bittercress (*Cardamine hirsuta*) and spotted spurge (*Euphorbia maculata*) in nursery containers (Wehtje et al., 2012). Among postemergent herbicides, glyphosate was widely used in the nursery and landscape maintenance industries as a nonselective herbicide against a wide range of weed species (Jaworski, 1972; Steinrücken and Amrhein, 1980). Dithiopyr, pendimethalin, and prodiamine applied at the maximum rate provided good weed control on spotted spurge (*Euphorbia maculata*) and yellow woodsorrel (*Oxalis stricta*) with little injury to black-eyed Susan *(Rudbeckia hirta*.), lanceleaf coreopsis (*Coreopsis lanceolata*), shasta daisy (*Chrysanthemum × superbum Bergmans*), purple coneflower (*Echinacea purpurea*), and blanket flower (*Gaillardia aristata*) (Jeffrey, 1994). There were also studies indicating that mulches can be used as barriers along with preemergent herbicides, reducing weed emergence by 35% to 74% as compared with direct spray applications of preemergent herbicides (Knight et al., 2001). In a study by Gilliam et al., a high percentage of herbicide did not fall into containers during application, and led to non-target loss contributing to groundwater pollution (Gilliam et al., 1992).

Physical methods employed in weed control include hand-pulling and mulches (including weed discs). Hand-pulling seems obsolete since it is labor intensive, time consuming and thus expensive, but it is still widely used. It was necessary to use hand-pulling in some high-value areas such as container nurseries, seedbeds, or highly visible landscape sites (Harpster et al., 2012). Mulching can suppress weed seed germination and weed growth. Wood chip mulches significantly inhibited germination of large crabgrass (*Digitaria sanguinalis*) and redroot pigweed (*Amaranthus retroflexus*), while rice hulls had a greater inhibitory effect on barnyardgrass (*Echinochloa crus-galli*) germination and seedling growth compared with the vermiculite mulch control (Ferguson et al., 2008; Ahn and Chung, 2000). Nurseries also used weed discs as mulching materials, such as fabric discs (Tex-R Geodisc), pressed peat moss discs (Biodisc), corrugated cardboard (Corrudisc), and plastic lids (Enviro LID). Both Tex-R Geodisc and Enviro LID were as effective as weekly hand-pulling and herbicide application in controlling weeds (Chong, 2003). Appleton and French (2000) found that Geodisc provided complete weed control in container-grown willow oak (*Quercus phellos*).

Dried distiller grains with solubles (DDGS) are a byproduct of ethanol production which is commonly used as cattle feed. As an organic N fertilizer source, DDGS have low C: N ratios and typical N content ranging between 3.8 and 4.8% (Moore, 2011). DDGS applied to the surface of potting mix at 800 to 1600 g/m^2 reduced the number of annual bluegrass (*Poa annua*) seedlings by 40% and 57%, and common chickweed (*Stellaria media*) by 33% and 58%, respectively (Boydston et al, 2008a). In another study, DDGS applied to the soil surface at 225 g/m^2 reduced the number of creeping woodsorrel (*Oxalis corniculata*) emerging by 25% (Boydston et al, 2008b).

Another byproduct of ethanol production showing herbicidal activity is corn gluten meal (CGM). Five dipeptides extracted from hydrolyzed corn gluten meal were shown to inhibit root growth of germinating weeds, whereas shoot growth was less affected (Liu and Christians, 1994). The CGM reduced plant survival, shoot length, and root development of black nightshade (*Solanum nigrum*), common lambsquarters (*Chenopodium album*), creeping bentgrass (*Agrostis palustris*), curly dock (*Rumex crispus*), purslane *(Portulaca oleracea*) and redroot pigweed (*Amaranthus retroflexus*) when applied at soil surface in greenhouse (Bingaman and Christians, 1995). As for kochia (*Kochia scoparia*) and barnyardgrass (*Echinochloa crus-galli*) in CGM amended soil, emergence rates were reduced more than 60%, and the aboveground dry biomass of green foxtail (*Setaria viridis*) was 40% of the nontreated control (Yu and Morishita, 2014).

Mustard seed meals (MSMs) are by-products of biodiesel and industrial oil production after oil extraction. The herbicidal activity of MSM is caused by allelopathy induced by glucosinolates (GSLs) (Hoagland et al., 2008). Certain plants in the *Brassicaceae* family are known to possess allelopathic properties, and they can be used as cover crops in many different cropping systems (Haramoto and Gallandt, 2005). There are approximately twenty GSLs in *Brassica* species, with concentrations varying among species and also within different plant tissues (Kirkegaard and Sarwar, 1998). *Sinapis alba* 'IdaGold' seed meal contains mainly 4-hydroxybenzyl GSL (glucosinalbin), whereas *Brassica juncea* 'Pacific Gold' seed meal contains 2-propenyl GSL (sinigrin) (Hansson et al., 2008). GSLs are enzymatically degraded by myrosinase, which is activated when tissues of GSL-containing plants are damaged (Gimsing and Kirkegaard, 2009). The endogenous enzyme myrosinase hydrolyses GSLs to several biologically active compounds, including isothiocyanates (ITCs), nitriles, thiocyanates (SCN-) and oxazolidinethione (OZT) among which ITCs are believed to be the most toxic to a wide range of organisms. The toxicity is due to a non-specific and irreversible reaction with sulphur containing groups in proteins. The chemical side chain structure of ITCs determines important chemical and physical properties like hydrophobicity and volatility (Brown and Morra, 1997).

The GSLs are hydrolyzed or degraded quickly, and volatiles are released after MSM is incorporated in soil (Morra and Kirkegaard, 2002). Since ITCs are relatively insoluble in water, their activity would be in the vapor phase as volatiles, including allyl isothiocyanate (allyl-ITC), 3-butenyl isothiocyanate (3-butenyl-ITC), benzyl isothiocyanate (benzyl-ITC), methyl-ITC (methyl-ITC) and 0-phenylethyl-ITC. Among these, allyl-ITC and methyl-ITC were the most inhibiting compounds to seed germination of several crop and weed species when applied as volatiles (Brown and Morra, 1997). Compared to GSLs, ITCs are hydrophobic with long side chains, while the ITCs are adsorbed mainly by the organic matter in the soil and leaching losses are likely to be lower than GSLs (Gimsing and Kirkegaard, 2009). In a study of *Brassica juncea* 'Pacific Gold' degradation, allyl-ITC was the primary volatiles, and the concentration of volatiles was affected by soil temperature, texture and soil microbes (Price et al., 2005). Studies showed that the activity of ITCs generally decreased with increasing time (Morra and Kirkegaard, 2002; Brown et al, 1991). SCN^- production in soils amended with *Sinapis alba* 'IdaGold' seed meal is also important for weed suppression. In *Sinapis alba* 'IdaGold' meal, 4-hydroxybenzyl-ITC produced by 4-hydroxybenzyl GSL is rapidly hydrolyzed to SCN^- in most soils (Borek and Morra, 2005).

ITCs concentration was related to soil texture. In studies of GSL transformations in soil, allyl-ITC disappeared most quickly in dry soils with a high concentration of organic carbon (Borek et al. 1995). Bending and Lincoln (1999) found that gas phase allyl-ITC concentrations in clay loam soil were lower than in a sandy loam soil which due to allyl-ITC may adsorb or react to higher organic carbon content of clay loam soil. So that, volatile allyl-ITC may be less effective when used as biofumigants in soils with high clay content compared with sandy soils. Also, soil adsorption of methyl-ITC was reported to increase with increasing organic matter (Matthiessen et al., 1996).

MSMs have been reported to have potential herbicidal, insecticidal, nematicidal, and fungicidal properties (Hansson et al., 2008). As a biofumigant, high rates of MSM shows suppression of annual bluegrass (*Poa annua*), large crabgrass (*Digitaria sanguinalis*), buckhorn plantain (*Plantago lanceolata*), white clover (*Trifolium repens*), and common chickweed (*Stellaria media*) in turfgrass renovated areas within 2 weeks. The optimum activity of MSM application can be realized by tarping treated soil after MSM application (Earlywine and Smeda, 2010). In a greenhouse study, MSM (*Sinapis alba* 'IdaGold') greatly decreased redroot pigweed (*Amaranthus retroflexus*) emergence while slightly reducing total yield of onion (Boydston et al., 2011). In strawberry production, after applying of canola (*Brassica napus*) and mustard (*Sinapis alba* 'IdaGold') seed meals, the weed biomass of shepherd's purse (*Capsella bursa-pastoris*), Italian ryegrass (*Lolium multiflorum*), desert rock purslane (*Calandrinia ciliata*) and annual bluegrass (*Poa annua*) was greatly reduced, and the emergence of addtional small-seeded broadleaf weeds was also reduced by all seed meal treatments. In addition, the seed meals could be used as organic fertilizer to increase essential nutrients in strawberry production in both growth chamber and field studies (Ban˜uelos and Hanson, 2010). In greenhouse containers, the emergence and growth of annual bluegrass (*Poa annua*), common chickweed (*Stellaria media*) and creeping woodsorrel (*Oxalis corniculata*) in soil amended with MSM (*Sinapis alba* 'IdaGold') were suppressed (Boydston et al., 2008). The *Brassica juncea* 'Pacific Gold' and *Sinapis alba* 'IdaGold' seed meals reduced weed seedling emergence and biomass of the broadleaf and grassy weeds in a vegetable field, while 'IdaGold' showed better herbicidal efficacy on broadleaf weeds and 'Pacific Gold' showed better herbicidal efficacy on grassy weeds (Handiseni and Brown, 2011). Rice et al. (2007) also proved that 'Pacific Gold' and 'IdaGold' seed meals reduced the emergence of redroot pigweed (*Amaranthus retroflexus*), common chickweed (*Stellaria media*), lettuce and beet seeds. However, tomato and pepper seedling emergence in *P. ultimum* infested soils have been improved by *Brassica napus* and *Brassica juncea* seed meals, while *Sinapis alba* seed meal caused low germination as a result of breakdown products from 4-hydroxybenzyl GSLs (Handiseni et al, 2012).

In addition to weed control benefits of GSL hydrolysis, MSMs (*Brassica juncea* 'Pacific Gold' and *Sinapis alba* 'IdaGold') contain between 5 and 6% N by weight (Rothlisberger et al., 2012), and represent an important nutrient source to crop plants.

Organic agriculture may thus benefit from the use of *Sinapis alba* 'IdaGold' meal as a soil amendment and for weed control (Snyder et al., 2009). MSMs have the potential to be used as an alternative to hand-pulling and other laborious methods of weed control in organic systems (Boydston et al., 2008). As an alternative method to hand-weeding for container growers, utilization of MSM not only assists the biofuel industry to be economically and environmentally viable but also offers a solution to some production issues in organic agricultural production systems.

CHAPTER II

HERBICIDAL ACTIVITY OF MUSTARD SEED MEAL (*Sinapis alba* 'IdaGold' and *Brassica juncea* 'Pacific Gold') ON WEED EMERGENCE

2.1 Synopsis

Mustard seed meals (MSMs) are by-products resulting from crushing mustard seeds to provide biofuel. MSMs have been applied as bio-herbicides due to the release of active glucosinolates hydrolysis products. Three experiments were conducted to determine the herbicidal activity of MSM (*Sinapis alba* 'IdaGold' and *Brassica juncea* 'Pacific Gold'). In petri dishes, MSMs were applied at 0, 50, 100, 200 or 300 g/m^2 to the bottom and covered with germination mix. Fifty seeds of each weed were placed in each dish. There were 10 replications per MSM rate and weed type combination, and 5 of the 10 dishes were sealed with parafilm. In greenhouse containers, MSMs were applied on the surface or incorporated with germination mix at 0, 1.5, 3.0 or 4.5 g/pot in the top layer. In outdoor containers, MSMs were incorporated with germination mix at 0, 1.5 or 3.0 g/pot in the top layer. Seeds of each weed were sown 2 mm deep. In petri dishes, emergence percentage (EP) and emergence index (EI) of large crabgrass (*Digitaria sanguinalis*) were lower in 'Pacific Gold' than 'IdaGold' under unsealed conditions, and EP and EI were lower under sealed than unsealed conditions at all rates. The EP and EI of Palmer amaranth (*Amaranthus palmeri*) were lower in 'Pacific Gold' than 'IdaGold' at 100 to 300 g/m^2 under all sealing conditions, while EP and EI were lower under sealed than unsealed conditions at 200 g/m^2. In greenhouse containers, the EP and EI of crabgrass were lower in ‘Pacific Gold’ than ‘IdaGold’ when applied on the surface at 3.0 and 4.5 g/pot, while EP and EI was lower in ‘Pacific Gold’ when applied on the surface than incorporated at 1.5 to 4.5 g/pot. The EP of amaranth was lower in ‘IdaGold’ than ‘Pacific Gold’ at 1.5 g/pot under both application methods, while EI was lower in ‘Pacific Gold’ when applied on the surface than incorporated. In outdoor containers, EP and EI of crabgrass were lower in ‘Pacific Gold’ than ‘IdaGold’ at 3.0 g/pot. These results demonstrated that ‘IdaGold’ might have better herbicidal efficacy on Palmer amaranth (broadleaf weeds), whereas ‘Pacific Gold’ was more effective on large crabgrass (grass weeds).

2.2 Introduction

Weeds are a serious problem in container nursery production, due to competition for nutrients, and water in containers or from producing chemicals to suppress plant growth, causing reductions in nursery plant growth or quality. The potential damage caused by weeds created a poor image for a nursery plants by reducing aesthetic and economic values (Case et al., 2005; Harpster et al., 2012). In a study by Mathers, the cost of weed control was higher than any other form of pest control. Nursery growers estimated it cost $500 to $4,000/acre for manual weed control, and all the losses caused by weeds have been estimated about $7,000/acre (Mathers, 2003). Thus, effective weeds control methods are very important in container nursery production.

Mustard seed meals (MSMs) as by-products of biodiesel production have been reported to have potential herbicidal, insecticidal, nematicidal, and fungicidal effects (Hansson et al., 2008). As a biofumigant, high rates (3,360 kg/ha) of MSM showed weed suppressive effects on annual bluegrass (*Poa annua*), large crabgrass (*Digitaria* *sanguinalis*), buckhorn plantain (*Plantago lanceolata*), white clover (*Trifolium repens*) and common chickweed (*Stellaria media*) in turfgrass within 2 weeks, and tarping after application provided the greatest suppressive effect from MSM (Earlywine and Smeda, 2010). In a container greenhouse experiment, emergence and growth of annual bluegrass (*Poa annua*), common chickweed (*Stellaria media*) and creeping woodsorrel (*Oxalis corniculata*) were suppressed, when MSM was applied on the substrate surface of containers at 113, 225, and 450 g/m^2 (Boydston et al., 2008). In a field experiment, *Brassica juncea* 'Pacific Gold' and *Sinapis alba* 'IdaGold' seed meal at rate of 2,000 kg/ha greatly reduced weed seedling emergence and biomass of Italian ryegrass (*Lolium perenne* spp. *multiflorum*), prickly lettuce (*Lactuca serriola*), redroot pigweed (*Amaranthus retroflexus*), and wild oat (*Avena fatua*) which are major weeds in vegetable production systems (Handiseni and Brown, 2011).

The herbicidal activity of MSM is due to glucosinolates induced allelopathy (Hoagland et al., 2008). Certain plants in the *Brassicaceae* family are known to possess allelopathic properties, and they can be used as cover crops in many different cropping systems (Haramoto and Gallandt, 2005). There are approximately twenty glucosinolates (GSLs) in *Brassica* species, with concentrations varying among species and also within different plant tissues (Kirkegaard and Sarwar, 1998). *S. alba* 'IdaGold' seed meal was dominated by 4-hydroxybenzyl GSL (glucosinalbin), whereas *B. juncea* seed meal was dominated by 2-propenyl GSL (sinigrin) (Hansson et al., 2008). GSLs were enzymatically degraded by myrosinase, which was activated when tissues of GSL-containing plants are damaged (Gimsing and Kirkegaard, 2009). The endogenous enzyme myrosinase hydrolize the GSLs into several biologically active compounds, including isothiocyanates (ITCs), nitriles, thiocyanates (SCN^-), and oxazolidinethione (OZT). Among them, ITCs are believed to be the most toxic to a wide range of organisms and the toxicity is due to a non-specific and irreversible reaction with sulphur containing groups in proteins. The chemical side chain structure of ITCs determines important chemical and physical properties like hydrophobicity and volatility (Brown and Morra, 1997). It is expected that GSLs would hydrolyze or degrade quickly and volatiles would be released after incorporation of MSM into the substrate (Morra and Kirkegaard, 2002). Since ITCs are relatively insoluble in water, their activities would be in the vapor phase as volatiles, including allyl isothiocyanate (allyl-ITC), 3-butenyl isothiocyanate (3-butenyl-ITC), benzyl isothiocyanate (benzyl-ITC), methyl-ITC (methyl-ITC) and 0-phenylethyl-ITC. Among these, allyl-ITC and methyl-ITC were the most inhibiting compounds to seed germination of several crops and weed species when applied as volatiles (Brown and Morra, 1997). Compared to GSLs, ITCs are hydrophobic with long side chains, while the ITCs are adsorbed mainly by the organic matter in the substrate and leaching losses are likely to be lower than GSLs (Gimsing and Kirkegaard, 2009). In *S. alba* seed meal, 4-hydroxybenzyl-ITC produced by 4-hydroxybenzyl GSL is rapidly hydrolyzed to SCN^- expected in most substrates (Borek and Morra, 2005).

Application of MSM can meet the needs for weed control in sustainable agricultural-production systems (Handiseni and Brown, 2011). In order to be useful for weed control in container nurseries, rates and application method and timing of MSM must be determined. Our objectives were to evaluate the response of weeds to *B. juncea*

‘Pacific Gold’ and *S. alba* ‘IdaGold’ seed meal applied to petri dishes and to containers in the greenhouse and outdoors to compare the herbicidal efficacy of two types of MSM applied at various rates and methods.

2.3 Materials and Methods

2.3.1 Effects of MSMs on Emergence of Large Crabgrass and Palmer Amaranth Seedlings in Petri Dishes

Mustard seed meal (MSM) flakes (*S. alba* ‘IdaGold’ and *B. juncea* ‘Pacific Gold’, Farm Fuel Inc. Freedom, CA) processed with a grinder to coarse powder were evenly applied at the bottom of 10-cm petri dishes at 0, 50, 100, 200 or 300 g/m^2 (0, 446, 892, 1784 or 2677 lb/acre) and 25 ml water was added before covering with 10 g of germination mix formulated with Canadian Sphagnum peat moss, vermiculite, starter nutrient charge (with Gypsum) and dolomitic limestone (Sunshine Professional Growing Mix, BWI, Schulenburg, TX), which was about 1 cm thick and saturated with MSM solution. Fifty seeds of large crabgrass (*Digitaria sanguinalis*) or Palmer amaranth (*Amaranthus palmeri*) obtained from Dr. Paul A. Baumann (Texas A&M AgriLife Extension Service, College Station, TX) were sown 2 mm below the substrate surface in each petri dish. For each weed, there were ten petri dishes per MSM rate and type combination with five dishes covered with lids and sealed with parafilm right after sowing and the other five dishes covered with lids without sealing. All petri dishes were placed on a shelf in a laboratory. Supplemental lighting was provided by two 40 W fluorescent light tubes (50 µmol/m^2·s, 25 cm above shelf) employing a 12-h photoperiod at room temperature of 18 to 22 ^{o}C. The number of emerged seedlings (seedlings with at least 3 mm above substrate surface) were counted daily for 6 consecutive days after sowing. Seedling height was measured 7 days after sowing.

2.3.2 Effects of MSMs on Emergence of Large Crabgrass and Palmer Amaranth Seedlings in Greenhouse Containers

Two types of MSM (‘IdaGold’ and ‘Pacific Gold’) were applied to the substrate surface at 0, 113, 226 or 339 g/m^2 (0, 1.5, 3.0 or 4.5 g/pot or 0, 1008, 2016, 3024 lb/acre) or incorporated thoroughly into 30 g (out of the total of 100 g in a pot) of germination mix at 0, 5, 10 or 15% w/w (by weight) in the top 2.5 cm layer in each pot (15 cm diameter). Thirty large crabgrass and thirty Palmer amaranth seeds were sown 2 mm below the substrate surface in two separated parts of one pot. Pots were sub-irrigated to container capacity (or field capacity) to avoid disturbing the thin MSM layer and the small seeds. Containers were placed on greenhouse benches exposed to a natural photoperiod and temperatures of 18 to 25^o C from 23 Feb. to 10 Mar. 2014, and sub-irrigated as needed. The numbers of emerged large crabgrass and Palmer amaranth seedlings (seedlings with at least 3 mm above the substrate surface) were counted daily for 12 consecutive days after sowing.

2.3.3 Effects of MSMs on Emergence of Large Crabgrass and Palmer Amaranth Seedlings in Outdoor Containers

Two types of MSM (‘IdaGold’ and ‘Pacific Gold’) were incorporated thoroughly into 30 g of germination mix and incorporated at 0, 5 or 10% w/w (by weight) (0, 1.5 or 3.0 g/pot) of ‘IdaGold’ and ‘Pacific Gold’ in the top 2.5 cm layer in 15 cm diameter pots with 100 g of germination mix. Fifty large crabgrass and fifty Palmer amaranth seeds were sown 2 mm below the substrate surface in two separated parts of each pot. Containers were placed on outdoor benches exposed to a natural photoperiod, temperatures of 6 to 28 ^{o}C from 27 Oct. to 10 Nov. 2013 and natural rainfall (Table 1). Pots were sub-irrigated to container capacity (or field capacity) as needed. The numbers of emerged large crabgrass and Palmer amaranth seedlings (seedlings with at least 3 mm above the substrate surface) were counted daily for 14 consecutive days after sowing.

Table 1. Temperature, humidity and precipitation during outdoor containers experiment (27 Oct. to 10 Nov. 2013).

2013	**Temp. (°F)**			**Humidity (%)**			**Precip. (inch)**
Oct	**high**	**avg**	**low**	**high**	**avg**	**low**	**sum**
27	71	66	61	100	89	78	1.4
28	83	74	64	93	78	62	0
29	84	77	69	97	78	58	0
30	84	78	71	100	85	69	0.5
31	81	69	57	100	62	23	1.5
2013	**Temp. (°F)**			**Humidity (%)**			**Precip. (inch)**
Nov	**high**	**avg**	**low**	**high**	**avg**	**low**	**sum**
1	79	65	51	96	69	42	0
2	72	61	49	83	55	27	0
3	69	58	46	80	59	37	0
4	69	63	56	100	86	72	0.31
5	72	68	63	100	97	93	0.37
6	72	61	49	100	89	77	0.19
7	66	55	43	86	60	34	0
8	65	58	51	77	57	37	0
9	66	60	54	93	80	66	0.05
10	72	63	54	86	63	40	0

2.3.4 Data Analysis and Statistics

In all experiments, emergence percentage (EP) was calculated as: EP= (No. of emerged seedlings/total No. of seeds) x 100%. In addition, emergence index (EI) was calculated as: $\mathrm{EI} = \sum_{i=1}^{n}(\mathrm{EP_i}/\mathrm{T_i})$; where $\mathrm{EP_i}$ is EP on day i ($i \geq 2$), and $\mathrm{T_i}$ is the number of days after sowing. Different from EP, EI was related with EP of everyday during emergence. The EI provides an evidence if emergence was delayed by MSM treatments.

Within each weed specie, the petri dish experiment was arranged in a three-factor (MSM type, rate and sealing condition) factorial design with five replications. Within each weed species, the greenhouse container experiment was in a three-factor (MSM type, rate and application method) factorial design with four replications. Within each weed species, the outdoor container experiment was in a two-factor (MSM type, rate) factorial design with five replications

In each experiment, the independent variables were analyzed with analysis of variance (ANOVA; Statistical Analysis System Version 9.3; SAS Institute, Cary, N.C.). Dependent variables (EP and EI for all three experiments, and in addition, seedling height for petri dish experiment) in response to MSM rates were subjected to regression analyses in all three experiments.

2.4 Results

2.4.1 Effects of MSMs on Emergence of Large Crabgrass Seedlings in Petri Dishes

The effects of MSM type and rate, sealing conditions (sealed and unsealed) and their interactions on EP, EI and the height of large crabgrass seedlings were significant, except for the effects of MSM type on the height of seedlings (Table 2). When there was no MSM in the petri dishes, sealing conditions did not affect EP at 6 days after sowing (DAS), EI or the height of large crabgrass seedlings (Tables 3 and 4, Figure 1). The EP at 6 DAS, EI and the height of large crabgrass seedlings were zero at 300 g/m^2 of ‘IdaGold’ and 100, 200 and 300 g/m^2 of ‘Pacific Gold’ in sealed petri dishes. The EP at 6 DAS was below 10% at 300 g/m^2 of ‘Pacific Gold’ under unsealed conditions, 50 g/m^2 of ‘Pacific Gold’ and 200 g/m^2 of ‘IdaGold’ under sealed conditions (Figure 1). The EI of large crabgrass seedlings was below 5% at 300 g/m^2 of ‘Pacific Gold’ under unsealed conditions, 50 g/m^2 of ‘Pacific Gold’ and 200 g/m^2 of ‘IdaGold’ under sealed conditions (Table 3). At 50, 100, 200 and 300 g/m^2, EP at 6 DAS and EI of large crabgrass seedlings was up to 49.6 percentage points lower in ‘Pacific Gold’ than ‘IdaGold’ in unsealed petri dishes (Table 3 and Figure 1). For both types of MSM at 50, 100, 200 and 300 g/m^2, EP at 6 DAS and EI of large crabgrass seedlings were up to 60.6 percentage points lower in sealed petri dishes than unsealed dishes. The EP at 2 and 4 DAS showed similar trends as the EP at 6 DAS (Figure 1).

At 200 g/m^2 of ‘IdaGold’, the height of large crabgrass seedlings was almost zero in sealed petri dishes (Table 4). At 50, 100, 200 and 300 g/m^2, the height of large crabgrass was 0.7 to 4.7 mm (18.4 to 83.9%) higher in ‘Pacific Gold’ than ‘IdaGold’ in unsealed petri dishes, although the EP at 6 DAS and EI were lower (Tables 3 and 4, Figure 1). Also, at 50 and 100 g/m^2 of ‘IdaGold’, seedlings in unsealed petri dishes were 1.9 and 3.1 mm (25.3 and 38.3%) shorter than those in sealed dishes, although EP at 6 DAS and EI were higher.

Table 2. ANOVA of emergence percentage (EP), emergence index (EI) and the height of large crabgrass seedlings exposed to different types ('IdaGold' and 'Pacific Gold') and rates (0 to 300 g/m^2) of mustard seed meal and sealing conditions (sealed and unsealed) in petri dishes.

Source	***P*-value**		
	EP	**EI**	**Height**
Rate	<.0001	<.0001	<.0001
Sealing Condition	<.0001	<.0001	<.0001
Type	<.0001	<.0001	0.7337
Type*Sealing Condition	0.0069	0.0033	<.0001
Type*Rate	<.0001	<.0001	<.0001
Rate*Sealing Condition	<.0001	<.0001	<.0001
Type*Rate*Sealing Condition	<.0001	<.0001	<.0001

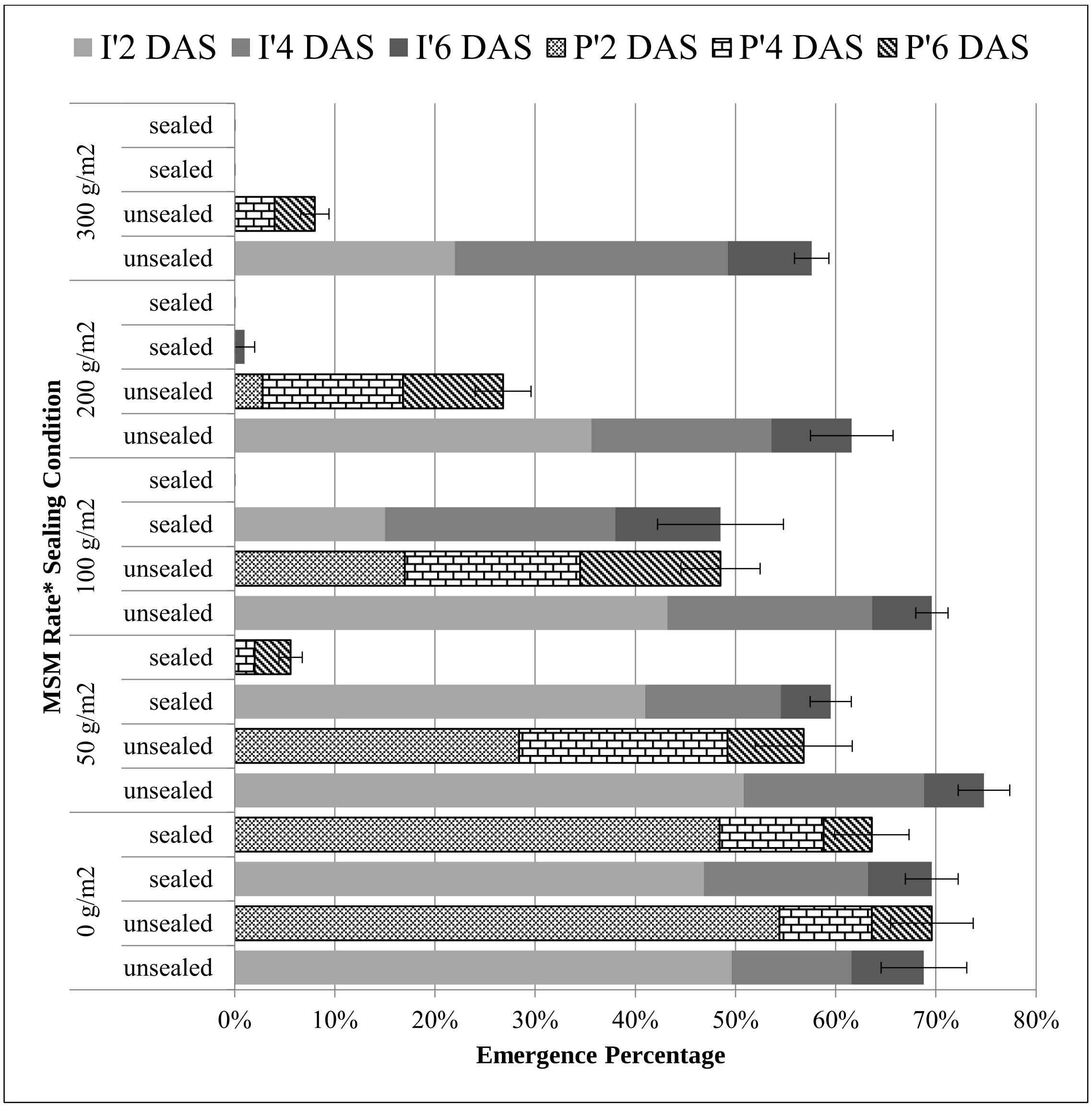
Table 3. Effects of different types ('IdaGold' and 'Pacific Gold') and rates (0 to 300 g/m^2) of mustard seed meal (MSM) and sealing conditions (sealed and unsealed) on emergence index (± standard error) of large crabgrass seedlings in petri dishes.

MSM Rates	Emergence Index (%) of Large Crabgrass Seedlings			
	IdaGold		Pacific Gold	
	Unsealed	Sealed	Unsealed	Sealed
0 g/m^2	76.9 ± 5.3	75.8 ± 6.1	82.7 ± 4.6	73.6 ± 4.1
50 g/m^2	77.8 ± 1.7	63.6 ± 4.4	48.5 ± 5.3	1.9 ± 0.5
100 g/m^2	70.8 ± 1.5	35.7 ± 7.4	33.2 ± 2.0	0.0
200 g/m^2	56.7 ± 3.7	0.2 ± 0.2	14.6 ± 1.3	0.0
300 g/m^2	45.4 ± 2.6	0.0	3.1 ± 0.4	0.0

Table 4. Effects of different types ('IdaGold' and 'Pacific Gold') and rates (0 to 300 g/m^2) of mustard seed meal (MSM) and sealing conditions (sealed and unsealed) on the height (± standard error) of large crabgrass seedlings in petri dishes.

MSM Rates	Height (mm) of Large Crabgrass Seedlings			
	IdaGold		Pacific Gold	
	Unsealed	Sealed	Unsealed	Sealed
0 g/m^2	13.9 ± 0.8	17.0 ± 0.5	14.3 ± 0.4	15.2 ± 0.2
50 g/m^2	5.6 ± 0.3	7.5 ± 0.4	10.3 ± 0.6	4.3 ± 0.8
100 g/m^2	5.0 ± 0.3	8.1 ± 0.9	9.6 ± 0.7	0.0
200 g/m^2	4.7 ± 0.3	0.3 ± 0.3	8.7 ± 0.6	0.0
300 g/m^2	3.8 ± 0.3	0.0	4.5 ± 0.7	0.0

Figure 1. Effects of different types (I'- 'IdaGold' and P'- 'Pacific Gold') and rates (0 to 300 g/m^2) of mustard seed meal (MSM) and sealing conditions (sealed and unsealed) on emergence percentage (EP) of large crabgrass seedlings at 2, 4 and 6 days after sowing (DAS) in petri dishes. Bars represent standard error of EP at 6 DAS.



The EP at 6 DAS, the EI and the height of large crabgrass seedlings were significantly correlated ($P < 0.01$) with MSM rate under each combination of MSM type and sealing condition (Tables 5, 6 and 7). The significant linear, quadratic and cubic correlation indicated that increasing MSM rate under each combination of MSM type and sealing condition decreased the EP at 6 DAS, EI and the height of large crabgrass seedlings.

Table 5. Regression analysis of emergence percentage (EP) at 6 days after sowing (DAS) of large crabgrass seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealed or unsealed conditions in petri dishes.

Regression Analysis of Emergence Percentage at 6 DAS				
	Model		***P*-value**	**R-Square**
IdaGold Unsealed	**Linear**	$Y=0.73-5.02*10^{-4}X$	0.0009	0.3884
	Quadratic	$Y=0.71-6.11*10^{-5}X-1.45*10^{-6}X^2$	0.0030	0.4111
	Cubic	$Y=0.69+1.43*10^{-3}X-1.56*10^{-5}X^2+3.17*10^{-8}X^3$	0.0029	0.4793
IdaGold Sealed	**Linear**	$Y=0.70-2.62*10^{-3}X$	<.0001	0.8859
	Quadratic	$Y=0.74-3.96*10^{-3}X+4.49*10^{-6}X^2$	<.0001	0.904
	Cubic	$Y=0.69+6.17*10^{-4}X-3.98*10^{-5}X^2+1.00*10^{-7}X^3$	<.0001	0.9592
Pacific Gold Unsealed	**Linear**	$Y=0.68-2.04*10^{-3}X$	<.0001	0.9079
	Quadratic	$Y=0.69-2.25*10^{-3}X-7.12*10^{-7}X^2$	<.0001	0.9086
	Cubic	$Y=0.69-2.34*10^{-3}X-1.57*10^{-6}X^2-1.92*10^{-9}X^3$	<.0001	0.9086
Pacific Gold Sealed	**Linear**	$Y=0.33-1.50*10^{-3}X$	<.0001	0.412
	Quadratic	$Y=0.52-6.67*10^{-3}X+1.70*10^{-5}X^2$	<.0001	0.7788
	Cubic	$Y=0.61-0.01X+8.21*10^{-5}X^2-1.46*10^{-7}X^3$	<.0001	0.9501

Table 6. Regression analysis of emergence index (EI) of large crabgrass seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealed or unsealed conditions in petri dishes.

Regression Analysis of Emergence Index				
	Model		***P*-value**	**R-Square**
IdaGold Unsealed	**Linear**	$Y=0.80-1.15*10^{-3}X$	<.0001	0.7609
	Quadratic	$Y=0.79-6.98*10^{-4}X-1.49*10^{-6}X^2$	<.0001	0.7697
	Cubic	$Y=0.77+4.43*10^{-4}X-1.23*10^{-5}X^2+2.42*10^{-8}X^3$	<.0001	0.7846
IdaGold Sealed	**Linear**	$Y=0.71-2.78*10^{-3}X$	<.0001	0.8397
	Quadratic	$Y=0.80-5.51*10^{-3}X+9.16*10^{-6}X^2$	<.0001	0.9029
	Cubic	$Y=0.77-2.33*10^{-3}X-2.16*10^{-5}X^2+6.97*10^{-8}X^3$	<.0001	0.9253
Pacific Gold Unsealed	**Linear**	$Y=0.69-2.44*10^{-3}X$	<.0001	0.8394
	Quadratic	$Y=0.78-5.40*10^{-3}X-9.79*10^{-6}X^2$	<.0001	0.9297
	Cubic	$Y=0.82-7.88*10^{-3}X+3.30*10^{-5}X^2-5.18*10^{-8}X^3$	<.0001	0.9459
Pacific Gold Sealed	**Linear**	$Y=0.37-1.67*10^{-3}X$	<.0001	0.3743
	Quadratic	$Y=0.59-7.70*10^{-3}X+1.98*10^{-5}X^2$	<.0001	0.7406
	Cubic	$Y=0.70-0.02X+1.01*10^{-4}X^2-1.82*10^{-7}X^3$	<.0001	0.9349

Table 7. Regression analysis of the height of large crabgrass seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealed or unsealed conditions in petri dishes.

Regression Analysis of Height of Large crabgrass Seedlings				
	Model		***P*-value**	**R-Square**
IdaGold Unsealed	**Linear**	Y=9.79-0.02X	<.0001	0.4861
	Quadratic	$Y=12.18-0.09X+2.18*10^{-4}X^2$	<.0001	0.7543
	Cubic	$Y=13.58-0.19X+1.18*10^{-3}X^2-2.15*10^{-6}X^3$	<.0001	0.9188
IdaGold Sealed	**Linear**	Y=13.47-0.05X	<.0001	0.792
	Quadratic	$Y=15.9-0.13X+2.44*10^{-4}X^2$	<.0001	0.9065
	Cubic	$Y=16.25-0.15X+5.10*10^{-4}X^2-6.03*10^{-7}X^3$	<.0001	0.9109
Pacific Gold Unsealed	**Linear**	Y=13.07-0.03X	<.0001	0.7801
	Quadratic	$Y=13.28-0.03X+1.94*10^{-5}X^2$	<.0001	0.7828
	Cubic	$Y=14.17-0.1X-6.27*10^{-4}X^2-1.36*10^{-6}X^3$	<.0001	0.8664
Pacific Gold Sealed	**Linear**	Y=9.31-0.04X	<.0001	0.5393
	Quadratic	$Y=13.52-0.16X+3.90*10^{-4}X^2$	<.0001	0.892
	Cubic	$Y=15.1-0.28X+1.57*10^{-3}X^2-2.64*10^{-6}X^3$	<.0001	0.9893

2.4.2 Effects of MSMs on Emergence of Palmer Amaranth Seedlings in Petri Dishes

Except for the effects of the interaction between MSM type and sealing conditions (sealed and unsealed) on EP and EI, the effects of MSM type and rate, sealing conditions and their interactions on EP, EI and the height of Palmer amaranth seedlings were significant (Table 8). When there was no MSM and 50 and 100 g/m^2 of 'IdaGold' in petri dishes, sealing conditions did not affect EP at 6 DAS or EI of Palmer amaranth seedlings (Table 9 and Figure 2). The EP at 6 DAS, EI and the height of Palmer amaranth seedlings were zero at 200 g/m^2 and 300 g/m^2 of 'Pacific Gold' in sealed petri dishes (Tables 9 and 10, Figure 2). The EP at 6 DAS of Palmer amaranth seedlings was below 5% at 100 g/m^2 of 'Pacific Gold' under sealed conditions and at 300 g/m^2 of 'Pacific Gold' under unsealed conditions (Figure 2). The EI of Palmer amaranth seedlings was below 10% at 200 and 300 g/m^2 of 'IdaGold', 100 g/m^2 of 'Pacific Gold' under sealed conditions and 200 and 300 g/m^2 of 'Pacific Gold' under unsealed conditions (Table 9). At 100, 200 and 300 g/m^2, EP at 6 DAS was 11.2 to 44.3 percentage points lower in 'Pacific Gold' than 'IdaGold', while EI of Palmer amaranth seedlings was 6.8 to 69.0 percentage points lower in 'Pacific Gold' than 'IdaGold' at 50, 100, 200 and 300 g/m^2 under all sealing conditions (Table 9 and Figure 2). For 'IdaGold', EP at 6 DAS and EI of Palmer amaranth seedlings were up to 52.2 percentage points lower in sealed than unsealed dishes at 200 and 300 g/m^2. For 'Pacific Gold, EP at 6 DAS of Palmer amaranth seedlings was up to 30.0 percentage points lower in sealed dishes than unsealed dishes at 100 and 200 g/m^2, while EI was up to 28.0 percentage points lower in sealed dishes than unsealed dishes at 50, 100, 200 and 300 g/m^2. The EP at 2 and 4 DAS showed similar trends as the EP at 6 DAS (Figure 2).

Table 8. ANOVA of emergence percentage (EP), emergence index (EI) and the height of Palmer amaranth seedlings exposed to different types (‘IdaGold’ and ‘Pacific Gold’) and rates (0 to 300 g/m^2) of mustard seed meal and sealing conditions (sealed and unsealed) in petri dishes.

Source	***P*-value**		
	EP	**EI**	**Height**
Rate	<.0001	<.0001	<.0001
Sealing Condition	<.0001	<.0001	<.0001
Type	<.0001	<.0001	<.0001
Type*Sealing Condition	0.0712	0.0789	0.0062
Type*Rate	<.0001	<.0001	<.0001
Rate*Sealing Condition	<.0001	<.0001	<.0001
Type*Rate*Sealing Condition	<.0001	<.0001	<.0001

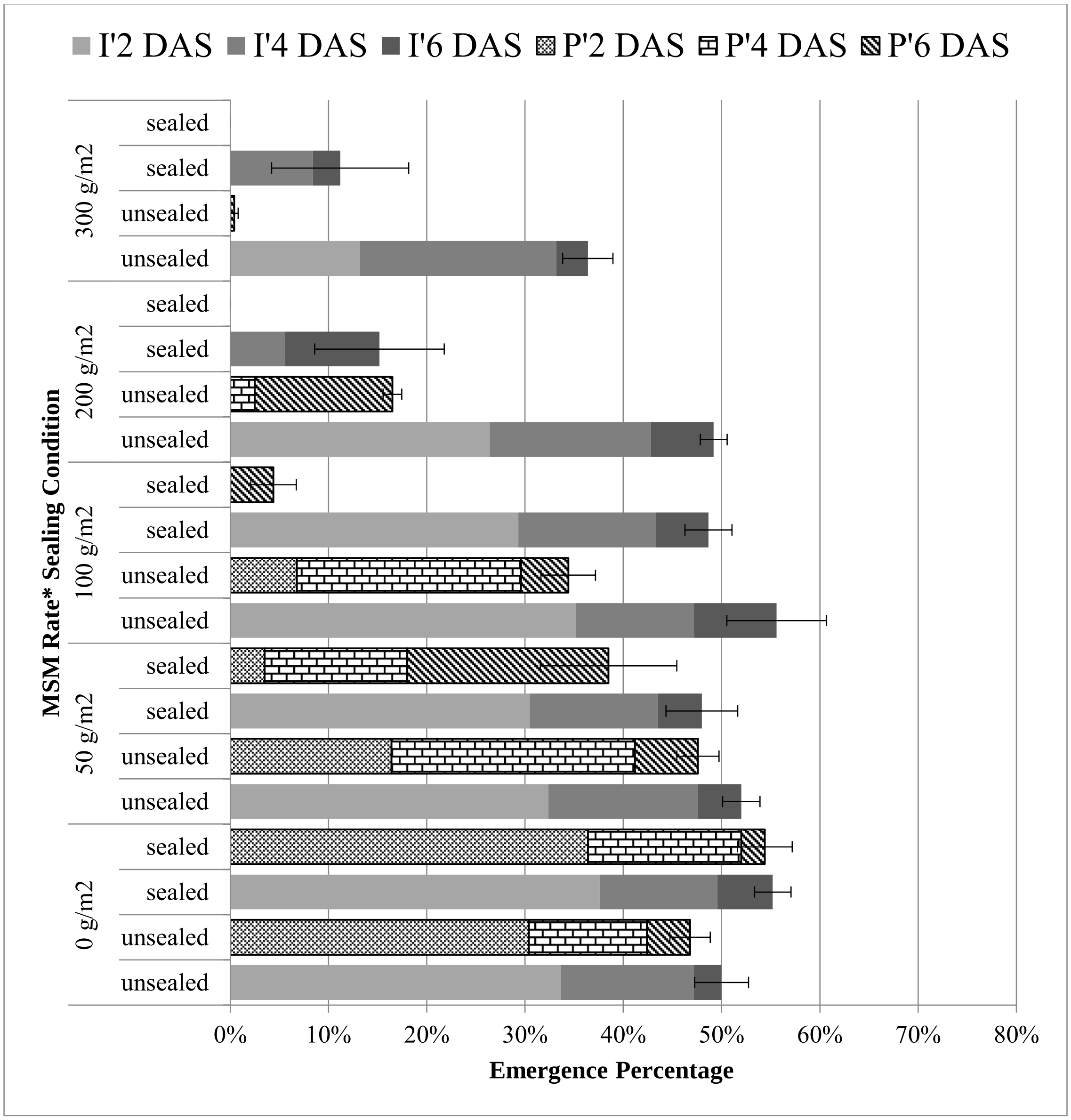
Table 9. Effects of different types ('IdaGold' and 'Pacific Gold') and rates (0 to 300 g/m^2) of mustard seed meal (MSM) and sealing conditions (sealed and unsealed) on emergence index (± standard error) of Palmer amaranth seedlings in petri dishes.

MSM Rate	Emergence Index (%) of Palmer Amaranth Seedlings			
	IdaGold		Pacific Gold	
	Unsealed	Sealed	Unsealed	Sealed
0 g/m^2	74.7 ± 6.4	86.8 ± 4.0	68.0 ± 3.4	80.3 ± 7.6
50 g/m^2	73.4 ± 1.9	71.3 ± 1.6	48.4 ± 2.8	20.4 ± 4.5
100 g/m^2	78.7 ± 7.7	70.1 ± 1.5	28.9 ± 2.6	1.1 ± 0.6
200 g/m^2	59.0 ± 1.5	6.8 ± 3.7	6.0 ± 0.4	0.0
300 g/m^2	38.8 ± 4.6	7.6 ± 4.9	0.1 ± 0.1	0.0

Table 10. Effects of different types ('IdaGold' and 'Pacific Gold') and rates (0 to 300 g/m^2) of mustard seed meal (MSM) and sealing conditions (sealed and unsealed) on the height (± standard error) of Palmer amaranth seedlings in petri dishes.

MSM Rate	Height (mm) of Palmer Amaranth Seedlings			
	IdaGold		Pacific Gold	
	Unsealed	Sealed	Unsealed	Sealed
0 g/m^2	31.2 ± 0.5	32.7 ± 0.6	30.2 ± 0.6	33.4 ± 1.0
50 g/m^2	23.7 ± 0.7	17.8 ± 1.9	25.6 ± 0.3	15.8 ± 1.2
100 g/m^2	21.8 ± 0.8	15.7 ± 3.2	23.9 ± 0.4	2.28 ± 1.3
200 g/m^2	15.0 ± 0.6	10.2 ± 3.4	6.5 ± 0.2	0.0
300 g/m^2	8.8 ± 0.8	3.4 ± 1.9	0.2 ± 0.2	0.0

Figure 2. Effects of different types (I'- 'IdaGold' and P'- 'Pacific Gold') and rates (0 to 300 g/m^2) of mustard seed meal (MSM) and sealing conditions (sealed and unsealed) on emergence percentage (EP) of Palmer amaranth seedlings at 2, 4 and 6 days after sowing (DAS) in petri dishes. Bars represent standard error of EP at 6 DAS.



When there was no MSM in petri dishes, sealing conditions did not affect the height of Palmer amaranth seedlings at 7 DAS (Table 10). At 300 g/m^2 of 'IdaGold', the height of Palmer amaranth seedlings was almost zero in unsealed petri dishes. At 200 and 300 g/m^2, the height of Palmer amaranth seedlings was 3.4 to 8.6 mm higher in 'IdaGold' than 'Pacific Gold' under all sealing conditions, respectively. Also at 50, 100, 200 and 300 g/m^2, the seedlings in sealed petri dishes were up to 21.6 mm (90%) shorter than those in unsealed dishes, for both types of MSM, respectively.

The EP at 6 DAS, the EI and the height of Palmer amaranth seedlings were significantly correlated with MSM rate under each combination of MSM type and sealing condition (Tables 11, 12 and 13). The significant linear, quadratic and cubic correlation indicated that increasing MSM rate under each combination of MSM type and sealing condition decreased the EP at 6 DAS, EI and the height of Palmer amaranth seedlings.

Table 11. Regression analysis of emergence percentage (EP) of Palmer amaranth seedlings at 6 days after sowing (DAS) in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealed or unsealed conditions in petri dishes.

Regression Analysis of Emergence Percentage at 6 DAS				
	Model		***P*-value**	**R-Square**
IdaGold Unsealed	**Linear**	$Y=0.54-4.65*10^{-4}X$	0.0033	0.3188
	Quadratic	$Y=0.50+9.1*10^{-4}X-4.53*10^{-6}X^2$	0.0002	0.5297
	Cubic	$Y=0.50+9.99*10^{-4}X-5.37*10^{-6}X^2+1.89*10^{-9}X^3$	0.0010	0.5299
IdaGold Sealed	**Linear**	$Y=0.56-1.62*10^{-3}X$	<.0001	0.7271
	Quadratic	$Y=0.57-2.12*10^{-3}X+1.66*10^{-6}X^2$	<.0001	0.7321
	Cubic	$Y=0.54+8.63*10^{-4}X-2.59*10^{-5}X^2+6.07*10^{-8}X^3$	<.0001	0.7727
Pacific Gold Unsealed	**Linear**	$Y=0.51-1.67*10^{-3}X$	<.0001	0.9340
	Quadratic	$Y=0.49-1.26*10^{-3}X-1.34*10^{-6}X^2$	<.0001	0.9380
	Cubic	$Y=0.48+7.11*10^{-5}X-1.43*10^{-5}X^2-2.95*10^{-8}X^3$	<.0001	0.9498
Pacific Gold Sealed	**Linear**	$Y=0.42-1.76*10^{-3}X$	<.0001	0.6589
	Quadratic	$Y=0.55-5.43*10^{-3}X+1.21*10^{-5}X^2$	<.0001	0.8822
	Cubic	$Y=0.57-6.62*10^{-3}X+2.33*10^{-5}X^2-2.51*10^{-8}X^3$	<.0001	0.8880

Table 12. Regression analysis of emergence index (EI) of Palmer amaranth seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealed or unsealed conditions in petri dishes.

Regression Analysis of Emergence Index				
	Model		***P*-value**	**R-Square**
IdaGold Unsealed	**Linear**	$Y=0.81-1.24*10^{-3}X$	<.0001	0.5679
	Quadratic	$Y=0.75+5.45*10^{-4}X-5.89*10^{-6}X^2$	<.0001	0.6568
	Cubic	$Y=0.74+1.35*10^{-3}X-1.35*10^{-5}X^2+1.70*10^{-8}X^3$	<.0001	0.6615
IdaGold Sealed	**Linear**	$Y=0.85-2.96*10^{-3}X$	<.0001	0.8531
	Quadratic	$Y=0.92-4.86*10^{-3}X+6.33*10^{-6}X^2$	<.0001	0.8784
	Cubic	$Y=0.85+1.20*10^{-3}X-4.96*10^{-5}X^2+1.23*10^{-7}X^3$	<.0001	0.9374
Pacific Gold Unsealed	**Linear**	$Y=0.60-2.25*10^{-3}X$	<.0001	0.8870
	Quadratic	$Y=0.69-4.75*10^{-3}X-8.19*10^{-6}X^2$	<.0001	0.9666
	Cubic	$Y=0.68-4.44*10^{-3}X+5.12*10^{-6}X^2+6.98*10^{-9}X^3$	<.0001	0.967
Pacific Gold Sealed	**Linear**	$Y=0.49-2.14*10^{-3}X$	<.0001	0.5098
	Quadratic	$Y=0.71-8.35*10^{-3}X+2.05*10^{-5}X^2$	<.0001	0.8440
	Cubic	$Y=0.8-1.51*10^{-3}X+8.41*10^{-5}X^2-1.43*10^{-7}X^3$	<.0001	0.9420

Table 13. Regression analysis of the height of Palmer amaranth seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealed or unsealed conditions in petri dishes.

Regression Analysis of Height of Palmer Amaranth Seedlings				
	Model		***P*-value**	**R-Square**
IdaGold Unsealed	**Linear**	$Y=29.21-0.07X$	<.0001	0.9392
	Quadratic	$Y=30.25-0.1X+9.54*10^{-5}X^2$	<.0001	0.9514
	Cubic	$Y=30.89-0.15X+5.34*10^{-4}X^2-9.85*10^{-7}X^3$	<.0001	0.9595
IdaGold Sealed	**Linear**	$Y=26.99-0.08X$	<.0001	0.7458
	Quadratic	$Y=30.25-0.18X+3.20*10^{-4}X^2$	<.0001	0.8118
	Cubic	$Y=32.14-0.34X+1.86*10^{-3}X^2-3.54*10^{-6}X^3$	<.0001	0.8584
Pacific Gold Unsealed	**Linear**	$Y=31.20-0.11X$	<.0001	0.9598
	Quadratic	$Y=31.21-0.11X-1.30*10^{-6}X^2$	<.0001	0.9598
	Cubic	$Y=29.57+0.01X-1.13*10^{-3}X^2-2.54*10^{-6}X^3$	<.0001	0.9835
Pacific Gold Sealed	**Linear**	$Y=23.20-0.10X$	<.0001	0.6485
	Quadratic	$Y=31.67-0.34X+7.83*10^{-4}X^2$	<.0001	0.9405
	Cubic	$Y=33.83-0.51X+2.40*10^{-3}X^2-3.62*10^{-6}X^3$	<.0001	0.9782

2.4.3 Effects of MSMs on Emergence of Large Crabgrass Seedlings in Greenhouse Containers

Except for the effects of the interaction between MSM type and rate and the interaction among three main factors (MSM type and rate and application method) on EP and EI, the effects of the three main factors and their interactions on EP and EI were significant (Table 14). The EP at 10 DAS of large crabgrass seedlings was below 5% at 4.5 g/pot of 'Pacific Gold' when applied on the substrate surface in pots (Figure 3). The EI of large crabgrass seedlings was below 10% at 3.0 and 4.5 g/pot of 'Pacific Gold' when applied on the substrate surface in pots (Table 15). When 1.5, 3.0 and 4.5 g/pot were incorporated into the substrate in the top layer, there was no difference between EP and EI at 10 DAS of large crabgrass seedlings with 'Pacific Gold' and 'IdaGold' (Table 15 and Figure 3). The EP at 10 DAS and EI of large crabgrass seedlings were 12.3 to 24.7 percentage points lower in 'Pacific Gold' than 'IdaGold' at 3.0 and 4.5 g/pot when applied on the substrate surface in pots, respectively. For both types of MSM at 3.0, and 4.5 g/pot, the EP at 10 DAS of large crabgrass seedlings was up to 33.5 percentage points lower when MSM was applied on the surface than when incorporated into the substrate (Figure 3). For 'IdaGold', there was no difference in EI of large crabgrass seedlings between the two application methods, but for 'Pacific Gold', EI was up to 35.0 percentage points lower when MSMs were applied on the surface than when incorporated into the substrate (Table 15). The EP at 2 and 6 DAS showed similar trends as the EP at 10 DAS (Figure 3).

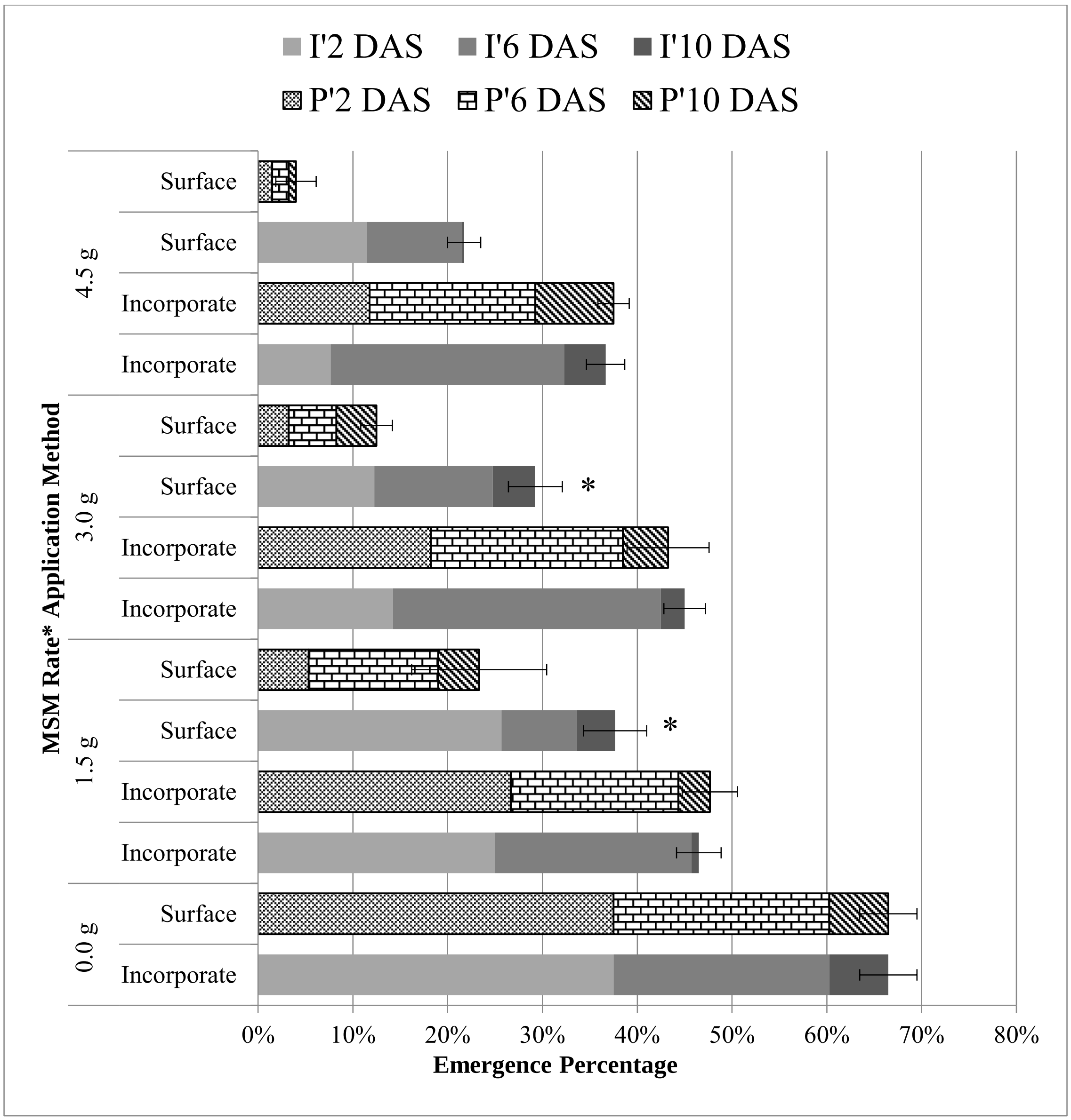
Table 14. ANOVA of emergence percentage (EP) and emergence index (EI) of large crabgrass seedlings exposed to different types ('IdaGold' and 'Pacific Gold') and rates (0 to 4.5 g/pot) of mustard seed meal and application methods (surface applied and incorporated) in greenhouse containers.

Source	***P*-value**	
	EP	**EI**
Rate	<.0001	<.0001
Application method	<.0001	<.0001
Type	0.0001	0.0005
Type*Application method	0.0001	0.0001
Type*Rate	0.1147	0.1812
Rates*Application method	0.0002	0.0047
Types*Rates*Application method	0.1035	0.0916

Table 15. Effects of different types ('IdaGold' and 'Pacific Gold') and rates (0 to 4.5 g/pot) of mustard seed meal (MSM) and application methods (surface applied and incorporated) on emergence index (± standard error) of large crabgrass seedlings in greenhouse containers.

MSM Rate	**Emergence Index (%) of Large Crabgrass Seedlings**			
	IdaGold		**Pacific Gold**	
	Incorporate	**Surface**	**Incorporate**	**Surface**
0.0 g/pot	85.1 ± 1.2	85.1 ± 1.2	85.1 ± 1.2	85.1 ± 1.2
1.5 g/pot	51.2 ± 3.0	51.5 ± 12.1	54.2 ± 7.9	22.6 ± 7.9
3.0 g/pot	44.7 ± 3.0	32.4 ± 4.6	44.7 ± 7.8	9.7 ± 2.9
4.5 g/pot	32.9 ± 3.2	28.2 ± 0.6	34.5 ± 5.9	3.5 ± 1.2

Figure 3. Effects of different types (I'- 'IdaGold' and P'- 'Pacific Gold') and rates (0 to 4.5 g/pot) of mustard seed meal (MSM) and application methods (surface applied and incorporated) on emergence percentage (EP) of large crabgrass seedlings at 2, 6 and 10 days after sowing (DAS) in greenhouse. Bars represent standard error of EP at 10 DAS.



* Due to seedling dieback after 6 DAS, EP of 6 DAS was presented as EP of 10 DAS and vice versa.

The EP at 10 DAS and the EI of large crabgrass seedlings were significantly correlated ($P < 0.01$) with the MSM rate under each combination of MSM type and application method (Tables 16 and 17). The significant linear, quadratic and cubic correlation indicated that increasing MSM rate under each combination of MSM type and application method decreased the EP and EI at 10 DAS of large crabgrass seedlings.

Table 16. Regression analysis of emergence percentage (EP) of large crabgrass seedlings at 10 days after sowing (DAS) in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal in surface applied or incorporated methods in greenhouse containers.

Regression Analysis of Emergence Percentage at 10 DAS				
	Model		***P*-value**	**R-Square**
IdaGold Incorporate	**Linear**	$Y=0.63-0.06X$	0.0004	0.6259
	Quadratic	$Y=0.67-0.15X+0.02X^2$	0.0003	0.7447
	Cubic	$Y=0.69-0.37X+0.16X^2-0.02X^3$	<.0001	0.8791
IdaGold Surface	**Linear**	$Y=0.60-0.10X$	<.0001	0.7231
	Quadratic	$Y=0.68-0.27X+0.04X^2$	<.0001	0.9128
	Cubic	$Y=0.69-0.39X+0.11X^2-0.01X^3$	<.0001	0.9253
Pacific Gold Incorporate	**Linear**	$Y=0.65-0.07X$	0.0001	0.683
	Quadratic	$Y=0.68-0.14X+0.02X^2$	0.0002	0.7538
	Cubic	$Y=0.69-0.24X+0.08X^2-0.01X^3$	0.0007	0.7738
Pacific Gold Surface	**Linear**	$Y=0.60-0.14X$	<.0001	0.8194
	Quadratic	$Y=0.68-0.31X+0.04X^2$	<.0001	0.9281
	Cubic	$Y=0.69-0.50X+0.16X^2-0.02X^3$	<.0001	0.9483

Table 17. Regression analysis of emergence index (EI) of large crabgrass seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal in surface applied or incorporated methods in greenhouse containers.

Regression Analysis of Emergence Index				
	Model		***P*-value**	**R-Square**
IdaGold Incorporate	**Linear**	$Y=0.78-0.11X$	<.0001	0.8339
	Quadratic	$Y=0.83-0.22X+0.03X^2$	<.0001	0.9144
	Cubic	$Y=0.85-0.39X+0.13X^2-0.02X^3$	<.0001	0.9507
IdaGold Surface	**Linear**	$Y=0.78-0.12X$	<.0001	0.7869
	Quadratic	$Y=0.85-0.27X+0.03X^2$	<.0001	0.8743
	Cubic	$Y=0.85-0.27X+0.03X^2+1.33*10^{-4}X^3$	<.0001	0.8743
Pacific Gold Incorporate	**Linear**	$Y=0.80-0.11X$	<.0001	0.7271
	Quadratic	$Y=0.84-0.21X+0.02X^2$	0.0001	0.7764
	Cubic	$Y=0.85-0.33X+0.10X^2-0.01X^3$	0.0005	0.7881
Pacific Gold Surface	**Linear**	$Y=0.71-0.18X$	<.0001	0.7918
	Quadratic	$Y=0.83-0.45X+0.06X^2$	<.0001	0.9518
	Cubic	$Y=0.85-0.68X+0.21X^2-0.02X^3$	<.0001	0.9703

2.4.4 Effects of MSMs on Emergence of Palmer Amaranth Seedlings in Greenhouse Containers

The effects of the interaction among three main factors (MSM type and rate and application methods) and the effects of interaction between two main factors on EP and EI were not significant, but the effect of the three main factors on EP and EI were significant (Table 18). The EP and EI at 10 DAS of Palmer amaranth seedlings were zero at 3.0 and 4.5 g/pot of 'IdaGold' when applied on the surface or when incorporated into the substrate in pots (Table 19 and Figure 4). The EP at 10 DAS of Palmer amaranth seedlings was below 5% at 1.5 g/pot of ‘IdaGold’ when applied on the surface or when incorporated into the substrate in pots and at 4.5 g/pot of ‘Pacific Gold’ when applied on the substrate surface in pots (Figure 4). The EI of Palmer amaranth seedlings was below 10% at 1.5 g/pot of ‘IdaGold’ when applied on the surface or when incorporated into the substrate in pots and at 1.5, 3.0 and 4.5 g/pot of ‘Pacific Gold’ when applied on the substrate surface in pots (Table 19). The EP at 10 DAS of Palmer amaranth seedlings was 10.8 and 13.2 percentage points lower in ‘IdaGold’ than ‘Pacific Gold’ at 1.5 g/pot when applied on the surface and when incorporated into the substrate (Figure 4). The EI of Palmer amaranth seedlings was 22.2 percentage points lower in ‘IdaGold’ than ‘Pacific Gold’ only at 1.5 g/pot when incorporated into the substrate in pots, but there was no difference in EI when MSMs were applied on the substrate surface in pots. For ‘IdaGold’, there was no difference in EP and EI at 10 DAS of Palmer amaranth seedlings between the two application methods (Table 19 and Figure 4). For ‘Pacific Gold’, there was no difference in EP at 10 DAS of Palmer amaranth seedlings between the application methods, but EI was 20.8 percentage points lower at 1.5 g/pot when applied on the surface than when incorporated into the substrate in pots. The EP at 2 and 6 DAS showed similar trends as the EP at 10 DAS (Figure 4).

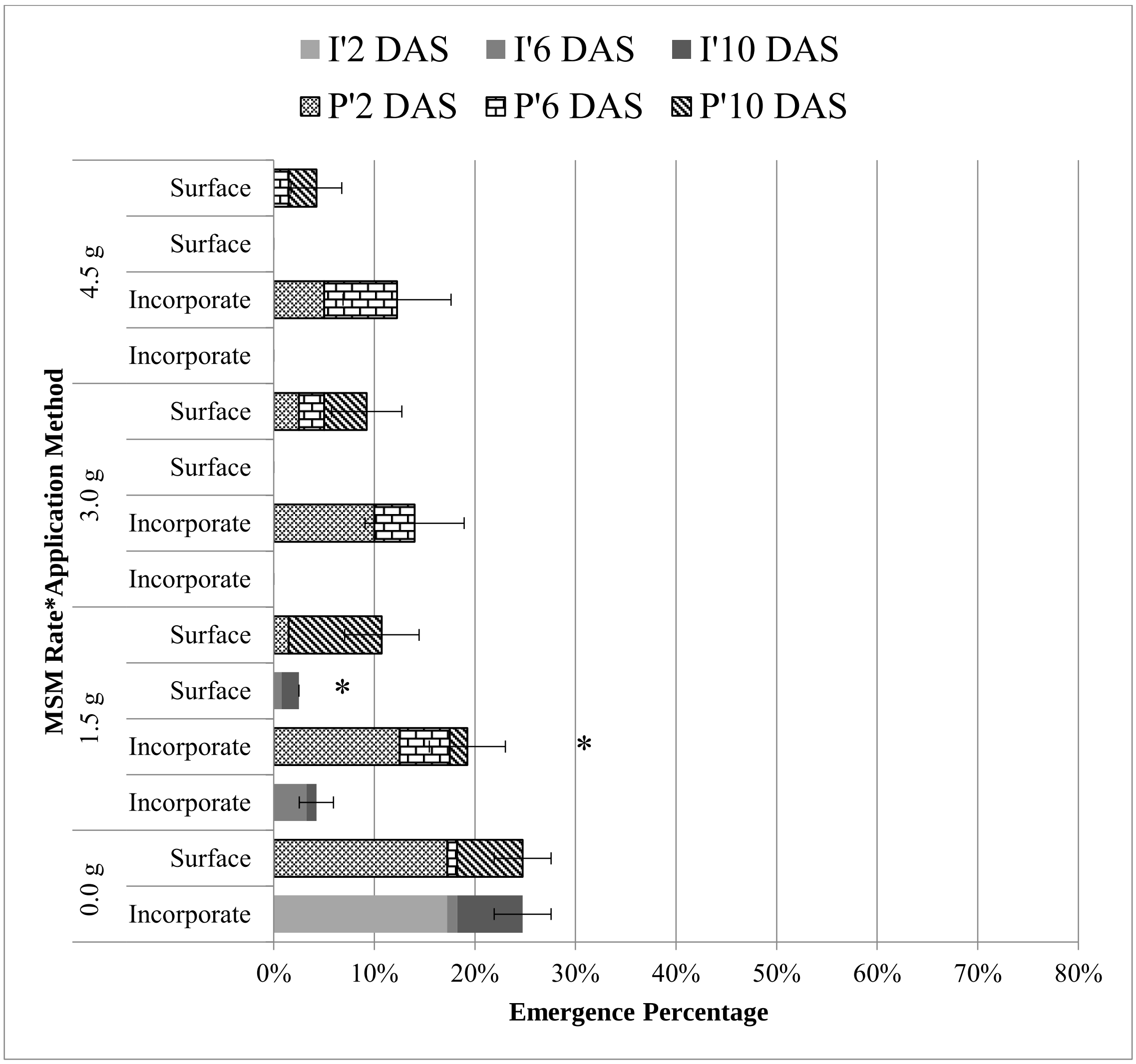
Table 18. ANOVA of emergence percentage (EP) and emergence index (EI) of Palmer amaranth seedlings exposed to different types ('IdaGold' and 'Pacific Gold') and rates (0 to 4.5 g/pot) of mustard seed meal and application methods (surface applied and incorporated) in greenhouse containers.

Source	*P*-value	
	EP	EI
Rate	<.0001	<.0001
Application method	0.0054	0.0095
Type	<.0001	0.0002
Type*Application method	0.0129	0.014
Type*Rate	0.0482	0.1057
Rates*Application method	0.2636	0.3204
Types*Rate*Application method	0.4648	0.4218

Table 19. Effects of different types ('IdaGold' and 'Pacific Gold') and rates (0 to 4.5 g/pot) of mustard seed meal (MSM) and application methods (surface applied and incorporated) on emergence index (± standard error) of Palmer amaranth seedlings in greenhouse containers.

	Emergence Index (%) of Palmer Amaranth Seedlings			
MSM	IdaGold		Pacific Gold	
Rate	Incorporate	Surface	Incorporate	Surface
0.0 g/pot	32.8 ± 6.5	32.8 ± 6.5	32.8 ± 6.5	32.8 ± 6.5
1.5 g/pot	3.4 ± 1.2	2.2 ± 1.6	25.6 ± 7.3	4.8 ± 1.4
3.0 g/pot	0.0	0.0	18.4 ± 6.2	7.9 ± 3.1
4.5 g/pot	0.0	0.0	13.8 ± 5.6	1.8 ± 1.0

Figure 4. Effects of different types (I'- 'IdaGold' and P'- 'Pacific Gold') and rates (0 to 4.5 g/pot) of mustard seed meal (MSM) and application methods (surface applied and incorporated) on emergence percentage (EP) of Palmer amaranth seedlings at 2, 6 and 10 days after sowing (DAS) in greenhouse. Bars represent standard error of EP at 10 DAS.



* Due to seedling dieback after 6 DAS, EP of 6 DAS was presented as EP of 10 DAS and vice versa.

The EP at 10 DAS and the EI of Palmer amaranth seedlings were significantly correlated ($P < 0.01$) with MSM rate under each combination of MSM type and application method (Tables 20 and 21). The significant linear, quadratic and cubic correlation indicated that increasing MSM rate under each combination of MSM type and application method decreased the EP and EI at 10 DAS of Palmer amaranth seedlings.

Table 20. Regression analysis of emergence percentage (EP) of Palmer amaranth seedlings at 10 days after sowing (DAS) in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal in surface applied or incorporated methods in greenhouse containers.

	Regression Analysis of Emergence Percentage at 10 DAS			
	Model		***P*-value**	**R-Square**
IdaGold Incorporate	**Linear**	$Y=0.19-0.05X$	<.0001	0.7046
	Quadratic	$Y=0.24-0.15X+0.02X^2$	<.0001	0.9166
	Cubic	$Y=0.25-0.2X+0.05X^2-0.004X^3$	<.0001	0.9256
IdaGold Surface	**Linear**	$Y=0.17-0.05X$	0.0007	0.5700
	Quadratic	$Y=0.24-0.17X+0.03X^2$	<.0001	0.8867
	Cubic	$Y=0.25-0.30X+0.11X^2-0.01X^3$	<.0001	0.9500
Pacific Gold Incorporate	**Linear**	$Y=0.21-0.03X$	0.05	0.2459
	Quadratic	$Y=0.24-0.09X+0.01X^2$	0.04	0.3860
	Cubic	$Y=0.25-0.18X+0.07X^2-0.008X^3$	0.07	0.434
Pacific Gold Surface	**Linear**	$Y=0.22-0.04X$	0.0008	0.5626
	Quadratic	$Y=0.24-0.09X+0.01X^2$	0.0019	0.6200
	Cubic	$Y=0.25-0.17X+0.06X^2-0.008X^3$	0.0041	0.6563

Table 21. Regression analysis of emergence index (EI) of Palmer amaranth seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal in surface applied or incorporated methods in greenhouse containers.

Regression Analysis of Emergence Index				
	Model		***P*-value**	**R-Square**
IdaGold Incorporate	**Linear**	$Y=0.24-0.07X$	0.0006	0.5826
	Quadratic	$Y=0.32-0.21X+0.03X^2$	<.0001	0.8251
	Cubic	$Y=0.33-0.33X+0.11X^2-0.01X^3$	<.0001	0.8536
IdaGold Surface	**Linear**	$Y=0.24-0.07X$	0.0009	0.5569
	Quadratic	$Y=0.31-0.22X+0.03X^2$	<.0001	0.8150
	Cubic	$Y=0.32-0.36X+0.12X^2-0.01X^3$	<.0001	0.8530
Pacific Gold Incorporate	**Linear**	$Y=0.32-0.04X$	0.03	0.2938
	Quadratic	$Y=0.33-0.06X+0.003X^2$	0.1	0.2962
	Cubic	$Y=0.32-0.04X-0.006X^2+0.001X^3$	0.2225	0.2967
Pacific Gold Surface	**Linear**	$Y=0.25-0.06X$	0.0015	0.5264
	Quadratic	$Y=0.31-0.17X+0.02X^2$	0.0006	0.6815
	Cubic	$Y=0.33-0.38X+0.16X^2-0.02X^3$	0.0002	0.7868

2.4.5 Effects of MSMs on Emergence of Large Crabgrass and Palmer Amaranth Seedlings in Outdoor Containers

For large crabgrass seedlings, the effects of MSM rate and type and the interaction between MSM type and rate on EP, and the effect of MSM type and rate on EI was significant (Table 22), but the effects of the interaction between MSM rate and type on EI was not significant. For Palmer amaranth seedlings, the effects of MSM rate on EP and EI was significant, but the effects of MSM type and the interaction between MSM type and rate on EI were not significant. For large crabgrass seedlings, the EP at 14 DAS and EI were not different between 'IdaGold' and 'Pacific Gold' at 1.5 g/pot, while EP at 14 DAS and EI were 22.0 and 37.3 percentage points lower in 'Pacific Gold' than 'IdaGold' at 3.0 g/pot, respectively (Table 23 and Figure 5). For Palmer amaranth seedlings, there was no difference in EP at 14 DAS and EI between 'IdaGold' and 'Pacific Gold' at 1.5 and 3.0 g/pot. The EP at 4 and 9 DAS showed similar trends as the EP at 14 DAS (Figure 5).

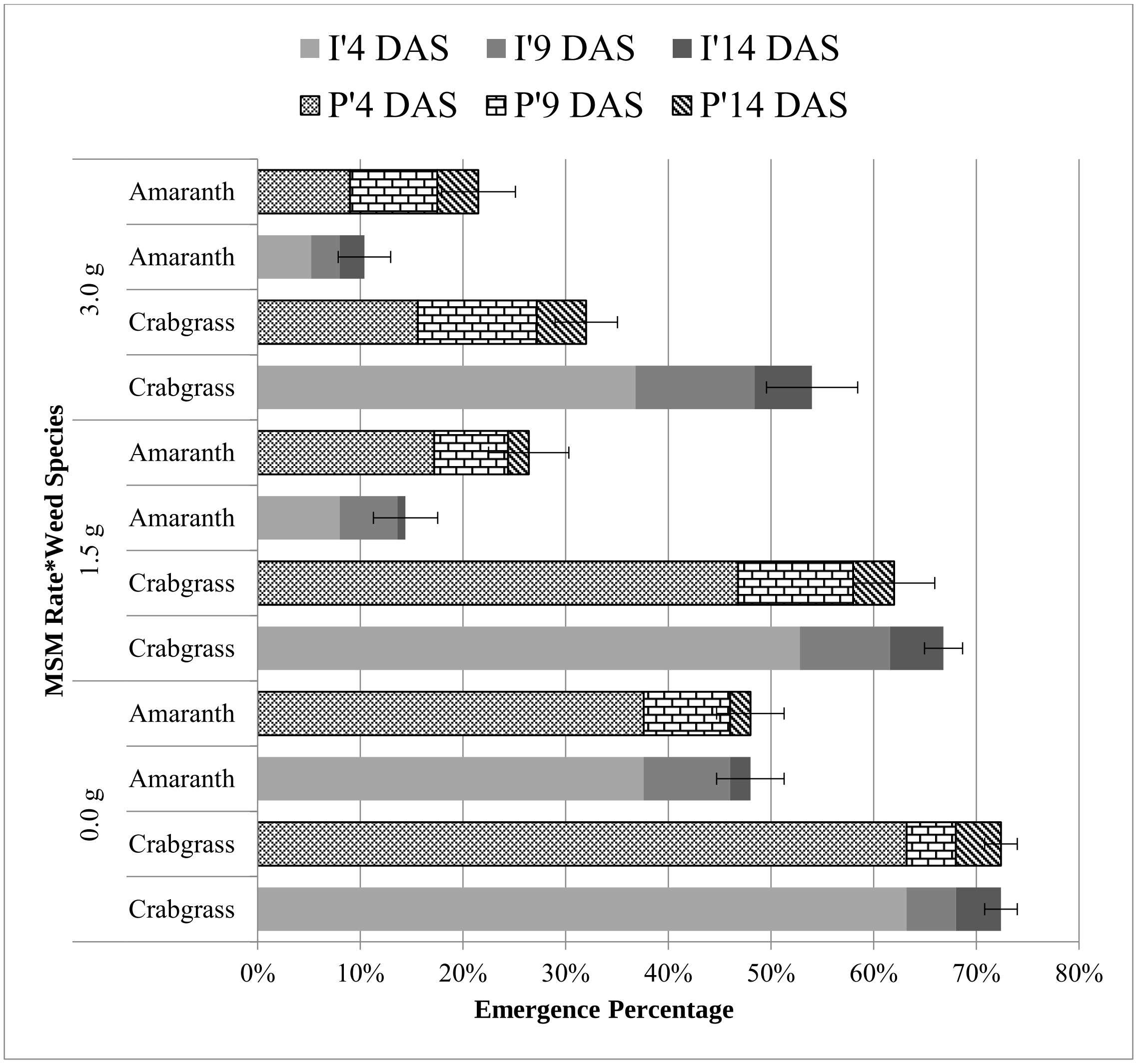
Table 22. ANOVA of emergence percentage (EP) and emergence index (EI) of large crabgrass and Palmer amaranth seedlings exposed to different types ('IdaGold' and 'Pacific Gold') and rates (0 to 3.0 g/pot) of mustard seed meal in outdoor containers.

Source	***P* value**	
	Large Crabgrass	
	EP	**EI**
Rate	<.0001	<.0001
Type	0.0013	0.0020
Type*Rate	0.0061	0.0170
	Palmer Amaranth	
	EP	**EI**
Rate	<.0001	<.0001
Type	0.0313	0.0441
Type*Rate	0.2620	0.2831

Table 23. Effects of different types ('IdaGold' and 'Pacific Gold') and rates (0 to 3.0 g/pot) of mustard seed meal (MSM) on emergence index (± standard error) of large crabgrass and Palmer amaranth seedlings in outdoor containers.

	Emergence Index (%)			
MSM	**Large Crabgrass**		**Palmer Amaranth**	
Rate	**IdaGold**	**Pacific Gold**	**IdaGold**	**Pacific Gold**
0.0 g/pot	121.1 ± 6.5	121.1 ± 6.5	71.0 ± 5.9	71.0 ± 5.9
1.5 g/pot	109.2 ± 3.4	95.1 ± 8.8	17.7 ± 4.1	33.7 ± 5.3
3.0 g/pot	73.2 ± 4.8	35.9 ± 4.8	10.3 ± 2.3	20.8 ± 6.2

Figure 5. Effects of different types (I'- 'IdaGold' and P'- 'Pacific Gold') and rates (0 to 3.0 g/pot) of mustard seed meal (MSM) on emergence percentage (EP) of large crabgrass and palmer amaranth seedlings at 4, 9 and 14 days after sowing (DAS) in greenhouse. Bars represent standard error of EP at 14 DAS.



The EP and the EI at 14 DAS of large crabgrass and Palmer amaranth seedlings were significantly correlated ($P < 0.01$) with the MSM rate under same MSM type (Tables 24 and 25). The significant linear, quadratic correlation indicated that increasing MSM rate under same MSM type decreased the EP at 14 DAS and EI of large crabgrass and Palmer amaranth seedlings.

Table 24. Regression analysis of emergence percentage (EP) of large crabgrass and Palmer amaranth seedlings at 14 days after sowing (DAS) in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal in outdoor containers.

Regression Analysis of Emergence Percentage				
	Model		***P*-value**	**R-Square**
Crabgrass IdaGold	**Linear**	$Y=0.74-0.06X$	0.0007	0.6039
	Quadratic	$Y=0.72-0.01X-0.02X^2$	0.0024	0.6347
Crabgrass Pacific Gold	**Linear**	$Y=0.76-0.13X$	<.0001	0.8247
	Quadratic	$Y=0.72-0.004X-0.04X^2$	<.0001	0.8894
Amaranth IdaGold	**Linear**	$Y=0.43-0.13X$	<.0001	0.7353
	Quadratic	$Y=0.48-0.32X+0.07X^2$	<.0001	0.8872
Amaranth Pacific Gold	**Linear**	$Y=0.45-0.09X$	0.0005	0.6464
	Quadratic	$Y=0.48-0.2X+0.04X^2$	0.0007	0.7339

Table 25. Regression analysis of emergence index (EI) of large crabgrass and Palmer amaranth seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal in outdoor containers.

Regression Analysis of Emergence Index				
	Model		***P*-value**	**R-Square**
Crabgrass IdaGold	**Linear**	Y=1.24-0.16X	<.0001	0.7389
	Quadratic	$Y=1.21+0.0007X-0.05X^2$	<.0001	0.801
Crabgrass Pacific Gold	**Linear**	Y=1.27-0.28X	<.0001	0.8284
	Quadratic	$Y=1.21-0.06X-0.07X^2$	<.0001	0.8702
Amaranth IdaGold	**Linear**	Y=0.63-0.2X	<.0001	0.7606
	Quadratic	$Y=0.71-0.51X+0.1X^2$	<.0001	0.9057
Amaranth Pacific Gold	**Linear**	Y=0.67-0.17X	0.0001	0.7269
	Quadratic	$Y=0.71-0.33X+0.05X^2$	0.0002	0.7862

2.5 Discussion

In the petri dish experiments, for both types of MSM at 50, 100, 200 and 300 g/m^2, the EP at 6 DAS and EI of large crabgrass seedlings were up to 60.6 percentage points lower in sealed petri dishes than unsealed dishes (Table 3 and Figure 1). For 'IdaGold', the EP at 6 DAS and EI of Palmer amaranth seedlings were up to 52.2 percentage points lower in sealed than unsealed condition at 200 and 300 g/m^2. For 'Pacific Gold, the EP at 6 DAS and EI of Palmer amaranth seedlings were up to 30.0 percentage points lower in sealed than unsealed condition at 100, 200 and 300 g/m^2 (Table 9 and Figure 2). Earlywine and Smeda (2010) also found similar results in a greenhouse experiment where annual blue grass (*Poa annua* L.), large crabgrasss (*Digitaria sanguinalis*), buckhorn plantain (*Plantago lanceolata* L.), white clover (*Trifolium repens* L.) and common chickweed (*Stellaria media* L.) showed up to a 50% reduction of emergence and a 57% reduction of biomass in tarped containers than untarped containers after application of 'Pacific Gold' seed meal. Sealing or tarping maintained volatile isothiocyanates (ITCs) in petri dishes or containers and reduced weed emergence. Glucosinolates (GSLs) found in the *Brassicaceae* family were hydrolyzed or degraded quickly and volatile ITCs would be released after incorporation of MSM in the soil (Morra and Kirkegaard, 2002). Since ITCs are relatively insoluble in water, their activity would be in the vapor phase as volatiles, including allyl isothiocyanate (allyl-ITC), 3-butenyl isothiocyanate, benzyl isothiocyanate (benzyl-ITC) and methyl-ITC (methyl-ITC). Among these, allyl-ITC and methyl-ITC were the most inhibiting compounds to seed germination of several crops and weed species when applied as volatiles (Brown and Morra, 1997). Five aliphatic (ethyl, propyl, butyl, allyl, and 3-methylthiopropyl) ITCs indicated great suppressive effects on large crabgrass and Palmer amaranth (Norsworthy and Meehan IV, 2005a; Norsworthy and Meehan IV, 2005b). For large crabgrass planted in greenhouse trays, ethyl, propyl, and butyl ITCs reduced density by 72 to 79%, whereas allyl and 3-methylthiopropyl ITC reduced density by 98 and 100%, at 10,000 nmol/g of substrate, respectively (Norsworthy and Meehan IV, 2005a). For Palmer amaranth planted in greenhouse trays, all ITCs (ethyl, propyl, butyl, allyl, and 3-methylthiopropyl) inhibited emergence of Palmer amaranth >95% at 10,000 nmol/g of substrate (Norsworthy and Meehan IV, 2005b). Allyl (2-propenyl)-ITC (allyl-ITC) was the dominant GSL hydrolysis product from 'Pacific Gold' seed meal, which has herbicidal effects (Bending and Lincoln, 1999). The ionic thiocyanate (SCN^-), as the primary toxic product from hydrolysis of unstable 4-hydroxybenzyl ITC in 'IdaGold' was relatively water soluble, so the benzyl-ITC and 3-butenyl ITC found in 'IdaGold' may be responsible for additional inhibition of weed seedling emergence in sealed petri dishes (Borek and Morra, 2005; Tollsten and Bergström, 1988).

Under all sealing conditions in the petri dish experiments, the EP and EI of large crabgrass seedlings were up to 49.6 percentage points lower in 'Pacific Gold' than 'IdaGold' at 50, 100, 200 and 300 g/m^2, respectively, and the EP and EI of Palmer amaranth were up to 69.0 percentage points lower in 'Pacific Gold' than 'IdaGold' at 100, 200 and 300 g/m^2, respectively (Tables 3 and 9, Figures 1 and 2). Similar to the petri dish experiments, the EP and EI of large crabgrass seedlings were up to 24.7 percentage points lower in 'Pacific Gold' than 'IdaGold' at 3.0 g and 4.5 g/pot when applied on the substrate surface in greenhouse containers, and the EP and EI of large crabgrass seedlings were up to 37.3 percentage points lower in 'Pacific Gold' than 'IdaGold' at 3.0 g/pot in outdoor containers (Table 15 and Figure 3). In contrast to the results of Palmer amaranth in petri dishes, the EP and EI of Palmer amaranth seedlings was up to 22.2 percentage points lower in 'IdaGold' than 'Pacific Gold' when applied at 3.0 g and 4.5 g/pot on the surface or incorporated into the substrate in greenhouse containers (Table 19 and Figure 4). These results suggested differences in herbicidal efficacy of the two MSMs on large crabgrass (grass weed) and Palmer amaranth (broadleaf weed) in greenhouse containers.

In a field study by Rice et al (2007), MSMs were incorporated into a 3 cm depth of soil (silt loam) at 1 and 3% w/w (420 and 1258 g/m^2) on an organic farm. Results showed that biomass of redroot pigweed (*Amaranthus retroflexus*) was lower in 3% (w/w) of 'IdaGold' than in 3% of 'Pacific Gold', which was different from our results from the petri dish (both unsealed and sealed conditions) experiments where the height of Palmer amaranth was lower in 'Pacific Gold' than 'IdaGold' at 200 and 300 g/m^2, respectively, when incorporated into germination mix (Table 9). Similar to our greenhouse container experiments, Handiseni et al (2011) found in a field experiment that seedling emergence of redroot pigweed (*Amaranthus retroflexus*) was lower at both 1,000 and 2,000 kg/ha (100 g/m^2 and 200 g/m^2) of 'IdaGold' than 'Pacific Gold', while seedling emergence of a grass weed, wild oat (*Avena fatua* L.) was lower in 'Pacific Gold' than 'IdaGold' at both 1,000 and 2,000 kg/ha. Handiseni et al (2011) also found in the field that the biomass of redroot pigweed was higher at 2,000 kg/ha of 'IdaGold', but lower at 1,000 kg/ha of 'IdaGold' than 'Pacific Gold', but the biomass of wild oat was higher at 2,000 kg/ha of 'Pacific Gold' than 'IdaGold'. Based on our results in the greenhouse and these studies, 'IdaGold' exhibits better weed suppression efficacy on broadleaf weeds (redroot pigweed and Palmer amaranth), whereas 'Pacific Gold' is more effective on grass weed (wild oat and large crabgrass). The difference of weed suppression efficacy may result from difference in the primary products of glucosinolate hydrolysis (allyl-ITC produced from 'Pacific Gold' and SCN^- produced from 'IdaGold'). However, 'IdaGold' did not show better herbicidal efficacy on emergence of Palmer amaranth than 'Pacific Gold' in our petri dish and outdoor containers experiments. The results from the petri dish experiments might be caused by microbial activity, which was mainly responsible for SCN^- from 'IdaGold' disappearance in the substrate incubated at or below 30 ^oC (Brown and Morra, 1993). The environment in petri dishes might be suitable for microbial activity, as more fungal growth appeared in petri dishes with 'IdaGold' than 'Pacific Gold'. Since SCN^- was more water soluble and less volatile than allyl-ITC, it is possible that high precipitation during the outdoor experiment (Table 1) caused SCN^- leaching through the substrate (Hansson et al., 2008) and decreased the suppressive effects of 'IdaGold' on Palmer amaranth seedlings.

In the greenhouse experiments, surface applied MSMs had better suppressive effects on emergence of large crabgrass at higher rates (3.0 and 4.5 g/pot or 226 g/m^2 and 339 g/m^2) than MSM incorporated into the top layer (2.5 cm) of the container substrate (Table 15 and Figure 3). After surface application, MSM formed a layer of seed meal material and its hydrolysis products, which might have provided higher concentrations of herbicidal products around the seeding area than MSM incorporated with the substrate. However, the difference between surface applied and incorporated MSM at the lower rate (1.5 g/pot) was not significant, which suggested that MSM coverage on the substrate may be important to acquire herbicidal efficacy.

Degradation of ITCs depends on temperature, soil moisture, soil texture and microbial activity (Hansson et al., 2008; Price et al., 2005), which may explain some of the differences among the petri dish, greenhouse and outdoor experiments. Higher temperatures generally increased disappearance rates of ITC and SCN^- in soil (Borek et al, 1995; Brown and Morra, 1993). Increasing water content in soil increased the half-life of allyl-ITC (Borek et al. 1995). Bending and Lincoln (1999) found that higher levels of ITCs were released by Indian mustard ('Pacific Gold') tissues incorporated into sandy loam soil than clay loam soil. Allyl-ITC concentration in autoclaved soils was three times over that in non-autoclaved soils (Price et al., 2005).

2.6 Conclusion

Data from the petri dish experiments suggested that emergence percentage (EP), emergence index (EI) and the height of large crabgrass and Palmer amaranth seedlings decreased with increasing rate of MSM under both types of MSM and sealing conditions, while sealing further decreased emergence of seedlings due to reduced release of volatile ITCs from MSM degradation. 'Pacific Gold' was more effective on weeds (large crabgrass and Palmer amaranth) suppression than 'IdaGold' in petri dishes.

Consistent with the petri dish experiment, the greenhouse and outdoor experiment results also indicated the reduction in EP and EI of the weeds as the rate of MSM increased. At the same time, different herbicidal efficacy of 'Idagold' and 'Pacific Gold' was shown on the grass weed (large crabgrass) and the broadleaf weed (Palmer amaranth). 'IdaGold' exhibited better herbicidal efficacy on broadleaf weeds, whereas 'Pacific Gold' was more effective on grass weeds. Comparing the two application methods in the greenhouse experiment, surface application may be more effective than substrate incorporation, and could be used for weed suppression in container nursery production.

As preemergent bio-herbicides, one time application of MSM may not be adequate to control weeds throughout the growing season and may result in higher late-season weed biomass due to nitrogen supplementation by MSM. Due to the large amount of MSM required for weed suppression, growers need to consider the cost of MSM and transportation before using MSM for weed control.

CHAPTER III

RESPONSE OF VEGETABLE AND WEED SEEDLING EMERGENCE TO MUSTARD (*Sinapis alba* 'IdaGold' and *Brassica juncea* 'Pacific Gold') SEED MEAL

3.1 Synopsis

Mustard Seed Meals (MSMs) as by-products of biodiesel are residues remaining after oil extraction. Petri dish experiments were conducted to determine the effects of MSMs on vegetable and weed emergence. Six types of vegetable seeds (onion *Allium cepa* 'Texas Grano 1015Y', lettuces *Lactuca sativa* 'Black Seeded Simpson' and 'Buttercrunch', mustard *Brassica juncea* 'Green Wave', kale *Brassica oleracea* 'Vates Blue Curled', green *Brassica rapa* 'Mizuna') and two types of weeds, large crabgrass (*Digitaria sanguinalis*) and Palmer amaranth (*Amaranthus palmeri*) were sowed in a germination mix incorporated with MSMs (*Sinapis alba* 'IdaGold' and *Brassica juncea* 'Pacific Gold') at 0, 88, 176 or 265 g/m^2. Petri dishes were unsealed for 1, 3, 5 or 7 days after sowing. For crabgrass and amaranth, 'Pacific Gold' had more suppressive effects on crabgrass emergence. Increasing sealing duration did not cause additional reduction in weed emergence, and both MSMs suppressed amaranth emergence almost completely under 176 and 265 g/m^2 regardless of sealing durations. For onion, phytotoxicity (reflected by fresh weight) increased with sealing duration, and 'Pacific Gold' had greater suppressive effects on onion seedlings than 'Idagold'. For kale and mustard, 'IdaGold' and 'Pacific Gold' had

similar suppressive effects on seedling emergence, however 'IdaGold' had greater phytotoxicity on mustard and 'Pacific Gold' delayed emergence of kale at 88 g/m^2 when sealed for 3, 5 and 7 days. For green, 'IdaGold' had more suppressive effects than 'Pacific Gold' on seedling emergence, while sealing delayed but did not decrease emergence at the lower rate (88 g/m^2) compared to 0.0 g/m^2. 'IdaGold' had greater phytotoxicity on green than 'Pacific Gold'. For lettuce 'Buttercrunch', there were no different suppressive effects between two MSMs. For lettuce 'Black Seeded Simpson', '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 higher rates (176 and 265 g/m^2) for shorter durations (1 and 3 days). Results suggest that there might be suppressive effects and phytotoxicity of MSMs at higher rates (176 and 265 g/m^2) on vegetable and weed emergence, and volatile hydrolysis products of glucosinolates might strengthen the suppressive effect when sealed longer than 7 days after sowing.

3.2 Introduction

Organic farming is rapidly growing in U.S. agriculture. Weeds were listed as the number one problem for organic producers (Walz, 1999). Only a few organically approved herbicides can be used in organic farming systems (Webber III, 2012). Mustard seed meals (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 MSMs not only assists the biodiesel industry to be economically and environmentally viable but also offers a solution to organic agricultural production systems.

The herbicidal activity of MSMs is due to glucosinolates induced allelopathy

(Hoagland et al., 2008). Early development of vegetables may be the most vulnerable part of the life cycle when exposed to allelopathic chemicals (Russo et al., 1997). Certain plants in the *Brassicaceae* family are known to possess allelopathic properties, and they can be used as cover crops in many different cropping systems (Haramoto and Gallandt, 2005). There are approximately twenty glucosinolates (GSLs) in *Brassica* species, with concentrations varying among species and also within different plant tissues (Kirkegaard and Sarwar, 1998). *Sinapis alba* 'IdaGold' seed meal was dominated by 4-hydroxybenzyl GSL (glucosinalbin), whereas *Brassica juncea* seed meal was dominated by 2-propenyl GSL (sinigrin) (Hansson et al., 2008). GSLs were enzymatically degraded by myrosinase, which was activated when tissues of GSL-containing plants are damaged (Gimsing and Kirkegaard, 2009). The endogenous enzyme myrosinase hydrolize the GSLs to several biologically active compounds, including isothiocyanates (ITCs), nitriles, thiocyanates (SCN-) and oxazolidinethione (OZT). Among them, ITCs are believed to be the most toxic to a wide range of organisms and the toxicity is due to a non-specific and irreversible reaction with sulphur containing groups in proteins. The chemical side chain structure of ITCs determines important chemical and physical properties like hydrophobicity and volatility (Brown and Morra, 1997). It is expected that GSLs hydrolyze or degrade quickly and volatiles would be released after incorporation of MSM in soil (Morra and Kirkegaard, 2002). Since ITCs are relatively insoluble in water, their activity would be in the vapor phase as volatiles, including allyl isothiocyanate (allyl-ITC), 3-butenyl isothiocyanate (3-butenyl-ITC), benzyl isothiocyanate (benzyl-ITC), methyl-ITC (methyl-ITC) and 0-phenylethyl-ITC. Among these, allyl-ITC and methyl-ITC were the most inhibiting compounds to seed germination of several crops and weeds species when applied as volatiles (Brown and Morra, 1997). Compared to GSLs, ITCs are hydrophobic with long side chains, while the ITCs are adsorbed mainly by the organic matter in the soil and leaching losses are likely to be lower than GSLs (Gimsing and Kirkegaard, 2009). In *Sinapis alba* 'IdaGold' seed meal, 4-hydroxybenzyl-ITC produced by 4-hydroxybenzyl GSL is rapidly hydrolyzed to SCN^- expected in most soils (Borek and Morra, 2005).

MSMs have been reported to have potential herbicidal, insecticidal, nematicidal, and fungicidal effects (Hansson et al., 2008). In a greenhouse experiment, onion (*Allium cepa*) was severely injured when applied MSM (*S. alba*) from planting to one-leaf stage at 110, 220, and 440 g/m^2, while redroot pigweed (*Amaranthus retroflexus*) was almost killed by 70 and 280 g/m^2 MSM when surface applied at cotyledon stage or one-leaf stage (Boydston et al., 2011). Canola (*B. napus*) and mustard (*S. alba*) seed meal were not only used as organic sources of fertilizer to increase essential nutrients in the strawberry production, but also greatly reduced summer annual weeds like large crabgrass (*Digitaria sanguinalis*), barnyardgrass (*Echinocloa crus-galli*), common purslane (*Portulaca oleracea*), redroot pigweed (*Amaranthus retroflexus*) from all rates of seed meals (Ban˜uelos and Hanson, 2010). In a field experiment, *B. juncea* 'Pacific Gold' and *S. alba* 'IdaGold' seed meal at a rate of 2,000 kg/ha greatly reduced weed seedling emergence and biomass of Italian ryegrass (*Lolium perenne* spp. *multiflorum*), prickly lettuce (*Lactuca serriola*), redroot pigweed (*Amaranthus retroflexus*) and wild oat (*Avena fatua*) which are major weeds in vegetable production systems (Handiseni and Brown, 2011). Rice et al. (2007) also proved that 'Pacific Gold' and 'IdaGold' greatly reduced the emergence and biomass of redroot pigweed (*Amaranthus retroflexus*), common chickweed (*Stellaria media*), lettuce and beet. However, tomato and pepper seedling emergence in *P. ultimum* infested soils was improved by *B. napus* and *B. juncea* seed meals (Handiseni et al, 2012). 'Pacific Gold' and 'IdaGold' seed meals applied at 1 and 2 t/ha did not influence carrot (*Daucus carota subsp. sativus*) emergence when applied 36 days before planting, whereas carrot emergence decreased up to 40% in *S. alba* treatments when applied 15 days before planting (Snyder et al., 2009).

In addition to weed control benefits of GSLs hydrolysis, the MSM contains between 5 and 6% N that when mineralized represents an important nutrient source to crop plants (Snyder et al., 2009). In order to apply MSM for weed control in organic production systems, rates and timing of application of MSM must be determined to minimize the potential phytotoxicity to vegetable crop emergence. Large crabgrass (*Digitaria sanguinalis*) and Palmer amaranth (*Amaranthus palmeri*) were chosen to evaluate the herbicidal activities of MSM. Weeds commonly infesting fruiting vegetable fields throughout the southeastern United States include Palmer amaranth, pitted morningglory (*Ipomoea lacunose*), and yellow nutsedge (*Cyperus esculentus*). Large crabgrass is also among the top 10 most common and troublesome weeds for many states in the southeastern United States (Webster, 2002). Our objectives were to determine the effects of MSM types (*B. juncea* 'Pacific Gold' and *S. alba* 'IdaGold'), rates and sealing durations on vegetable and weed seedling emergence and biomass in petri dishes.

3.3 Materials and Methods

3.3.1 Effects of MSMs on Emergence of Weed and Vegetable Seedlings

Two MSMs ('IdaGold' and 'Pacific Gold') were incorporated uniformly into 10 g of germination mix formulated with Canadian Sphagnum peat moss, 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/petri dish (0, 5, 10 or 15% w/w) and were evenly applied at the bottom of 10-cm petri dishes (0, 88, 176 or 265 g/m^2 or 0, 785, 1570 or 2364 lb/acre) and 25 ml water was added. Ten seeds of six vegetables (onion *Allium cepa* 'Texas Grano 1015Y', lettuces *Lactuca sativa* 'Black Seeded Simpson' and 'Buttercrunch', mustard *Brassica juncea* 'Green Wave', kale *Brassica oleracea* 'Vates Blue Curled', green *Brassica rapa* 'Mizuna') purchased from Morgan County Seeds (Barnett, MO) and thirty seeds of two weeds (large crabgrass *Digitaria sanguinalis* or Palmer amaranth *Amaranthus palmeri*) were sowed 2 mm below the substrate surface in petri dishes. Thirty large crabgrass and thirty Palmer amaranth seeds were sowed in two separated parts of one petri dish; ten onion, ten kale and ten 'Buttercrunch' lettuce seeds were sowed in three separated parts of one petri dish, ten mustard, ten green and ten 'Black Seeded Simpson' lettuce seeds were sowed in three separated parts of one petri dish. All petri dishes were covered and sealed with parafilm right after sowing. Each MSM rate and plant seed combination was sealed for 1, 3, 5 or 7 days before uncovering. All petri dishes were placed on a shelf in a laboratory. Supplemental lighting was provided by two 40W fluorescent light tubes (50 $\mu mol/m^2 \cdot s$, 25 cm above shelf) employing a 12-h photoperiod at a room temperature of 18 to 22^o 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 and weed seedlings with at least 3 mm above substrate surface) were counted daily for 14 consecutive days after sowing. Seedlings of vegetables and weeds were clipped at the substrate surface and weighted at 18 days after sowing.

3.3.2 Data Analysis and Statistics

In all experiments, emergence percentage (EP) was calculated as: EP= (No. of emerged seedlings/total No. of seeds) x 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 ($i \geq 2$), and T_i is the number of days after sowing. Different from EP, EI was related with EP of everyday during emergence. EI provides an evidence if emergence was delayed by MSM treatments.

Within each weed or vegetable specie, the petri dish experiment was arranged in a three-factor (MSM type, rate and sealing duration) factorial design with four replications. In each experiment, the independent variables were analyzed with analysis of variance (ANOVA; Statistical Analysis System Version 9.3; SAS Institute, Cary, N.C.). Dependent variables (EP, EI and fresh weight of seedlings) in response to MSM rates were subjected to regression analyses in all experiments. Each vegetable or weed species was separately analyzed.

3.4 Results and Discussion

3.4.1 Effects of MSMs on Emergence of Two Weeds Seedlings in Petri Dishes

The effects of the three main factors (MSM type and rate and sealing duration) and the interaction between MSM type and rate were significant on EP and EI of large crabgrass seedlings. The effects of MSM rate on fresh weight (FW) of large crabgrass seedlings was significant (Table 26). Also, the effects of the interaction between MSM type and sealing duration on EP was significant. All the other effects of interactions between two main factors or among the three main factors and the main factors on EP, EI and FW of large crabgrass seedlings were not significant. When there was no MSM incorporated into the germination mix, sealing durations did not affect EP at 14 days after sowing (DAS), EI or FW of large crabgrass seedlings (Tables 27 and 28, Figure 6). At 88 g/m^2 of MSM, the EP at 14 DAS and EI of large crabgrass seedlings were 17.2 to 44.2 percentage points lower in ‘Pacific Gold’ than ‘IdaGold’ under all sealing durations (1, 3, 5 and 7 days), while there was no difference in EP at 14 DAS and EI among all sealing durations under the same MSM type (Table 27 and Figure 6). The EP at 14 DAS and EI of large crabgrass seedlings were zero at 176 g/m^2 of ‘Pacific Gold’ when sealed for 3, 5 and 7 days and 265 g/m^2 of ‘Pacific Gold’ under all sealing durations (1, 3, 5 and 7 days). The EP at 14 DAS and EI of large crabgrass seedlings were almost zero at 176 g/m^2 of ‘Pacific Gold’ when sealed for 1 day. At 176 and 265 g/m^2 of ‘IdaGold’, there was no difference in EP at 14 DAS of large crabgrass seedlings among all sealing durations, while EI was up to 16.5 percentage points lower at 176 g/m^2 when sealed for 5 and 7 days than 1 and 3 days. Although emergence was exhibited at 88, 176 and 265 g/m^2 of ‘IdaGold’, the FW of large crabgrass seedlings was zero or almost zero (Table 28). The same was shown for ‘Pacific Gold’ where the FW of large crabgrass seedlings were zero or almost zero at 88, 176 and 265 g/m^2. However, the EP at 14 DAS and EI were not zero at 88 and 176 g/m^2. The EP at 14 DAS, EI and the FW of large crabgrass seedlings were significantly correlated ($P < 0.01$) with the MSM rate under each combination of MSM type and sealing duration (Tables 29, 30 and 31). The significant linear, quadratic and cubic correlation indicated that increasing MSM rate under each combination of MSM type and sealing duration decreased the EP at 14 DAS, EI and the FW of large crabgrass seedlings. The EP at 4 and 9 DAS showed a similar trends as the EP at 14 DAS (Figure 6). These results suggested that 'Pacific Gold' had more suppressive effects on large crabgrass seedling emergence, but increasing sealing duration from 1 to 7 days did not cause additional reductions in weed seedling emergence. Consistent with our previous petri dish experiment, the EP at 6 DAS and EI of large crabgrass were up to 49.6 percentage points lower in 'Pacific Gold' than 'IdaGold' at 50, 100, 200 and 300 g/m^2. Earlywine et al. (2010) found that emergence of large crabgrass was reduced by 50 to 62% at all 'Pacific Gold' rates (1,350, 2,350, and 3,360 kg/ha or 135 g/m^2, 235 g/m^2, 336 g/m^2), and biomass of large crabgrass seedlings was reduced 37% at the high rate examined (3,360 kg/ha or 336 g/m^2), but there was no difference in weed emergence between tarped and untarped treatments in greenhouse containers. However, in our previous petri dish experiment (Chapter I), the EP at 6 DAS and EI of large crabgrass was lower in sealed petri dishes than unsealed (covered with lids) dishes.

Table 26. ANOVA of emergence percentage (EP), emergence index (EI) and seedlings fresh weight (FW) of large crabgrass seedlings exposed to different types ('IdaGold' and 'Pacific Gold') and rates (0 to 265 g/m^2) of mustard seed meal and sealing durations (1 day, 3 days, 5 days, 7 days).

Source	EP	EI	FW
	Pr > F	Pr > F	Pr > F
Rate	<.0001	<.0001	<.0001
Sealing Duration	0.0003	0.003	0.2401
Type	<.0001	<.0001	0.9508
Type*Rate	<.0001	0.0002	0.8946
Rate*Sealing Duration	0.5875	0.4716	0.3975
Type*Sealing Duration	0.0305	0.0882	0.1361
Type*Rate*Sealing Duration	0.5694	0.7445	0.0589

Table 27. 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 day, 3 days, 5 days, 7 days) on emergence index (± standard error) of large crabgrass seedlings at 14 days after sowing.

		Emergence Index (%) of Large Crabgrass Seedlings			
		Sealing Duration			
MSM	**Rate**	**1 Day**	**3 Days**	**5 Days**	**7 Days**
IdaGold	**0.0 g/m^2**	62.4± 8.6	50.4 ± 2.5	58.2 ± 8.9	55.4 ± 7.1
	88 g/m^2	37.5 ± 2.1	31.3 ± 8.8	19.6 ± 4.3	17.8 ± 6.9
	176 g/m^2	20.9 ± 2.2	18.3 ± 3.3	4.4 ± 2.5	4.4 ± 2.1
	265 g/m^2	9.2 ± 5.2	7.6 ± 4.1	1.8 ± 1.5	0.5 ± 0.5
Pacific Gold	**0.0 g/m^2**	54.5 ± 7.5	50.9 ± 8.5	59.0 ± 9.6	43.6 ± 8.0
	88 g/m^2	8.7 ± 6.2	0.6 ± 0.2	0.9 ± 0.4	0.6 ± 0.3
	176 g/m^2	0.1 ± 0.1	0.0	0.0	0.0
	265 g/m^2	0.0	0.0	0.0	0.0

Table 28. 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 day, 3 days, 5 days, 7 days) on fresh weight (± standard error) of large crabgrass seedlings at 18 days after sowing.

		Fresh Weight (g) of Large Crabgrass Seedlings			
		Sealing Duration			
MSM	**Rate**	**1 Day**	**3 Days**	**5 Days**	**7 Days**
IdaGold	**0.0 g/m^2**	0.15 ± 0.02	0.14 ± 0.02	0.15 ± 0.02	0.16 ± 0.04
	88 g/m^2	0.02 ± 0.01	0.01 ± 0.01	0.01 ± 0.00	0.01 ± 0.00
	176 g/m^2	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
	265 g/m^2	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Pacific Gold	**0.0 g/m^2**	0.20 ± 0.05	0.17 ± 0.05	0.17 ± 0.04	0.07 ± 0.03
	88 g/m^2	0.01 ± 0.01	0.00 ± 0.00	0.01 ± 0.01	0.00 ± 0.00
	176 g/m^2	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
	265 g/m^2	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00

Table 29. Regression analysis of emergence percentage at 14 DAS of large crabgrass seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealing durations (1 day, 3 days, 5 days or 7 days).

Regression Analysis of Emergence Percentage at 14 DAS				
	Model		**P-value**	**R-Square**
IdaGold Sealed 1 Day	**Linear**	$Y=0.66-0.35X$	<.0001	0.8475
	Quadratic	$Y=0.65-0.30X-0.03X^2$	<.0001	0.8489
	Cubic	$Y=0.65-0.34X+0.04X^2-0.03X^3$	<.0001	0.8491
IdaGold Sealed 3 Days	**Linear**	$Y=0.60-0.28X$	0.0001	0.6856
	Quadratic	$Y=0.57-0.13X-0.10X^2$	0.0007	0.7025
	Cubic	$Y=0.58-0.25X+0.15X^2-0.11X^3$	0.003	0.7048
IdaGold Sealed 5 Days	**Linear**	$Y=0.55-0.35X$	<.0001	0.7309
	Quadratic	$Y=0.56-0.40X+0.04X^2$	0.0002	0.7324
	Cubic	$Y=0.55-0.01X-0.72X^2+0.33X^3$	0.0007	0.7473
IdaGold Sealed 7 Days	**Linear**	$Y=0.56-0.40X$	<.0001	0.8115
	Quadratic	$Y=0.60-0.66X+0.18X^2$	<.0001	0.8422
	Cubic	$Y=0.57+0.26X-1.54X^2+0.75X^3$	<.0001	0.9002
Pacific Gold Sealed 1 Day	**Linear**	$Y=0.49-0.39X$	<.0001	0.774
	Quadratic	$Y=0.58-0.99X+0.40X^2$	<.0001	0.9326
	Cubic	$Y=0.58-1.16X+0.72X^2-0.14X^3$	<.0001	0.9346
Pacific Gold Sealed 3 Days	**Linear**	$Y=0.43-0.36X$	0.0005	0.5952
	Quadratic	$Y=0.57-1.20X+0.56X^2$	<.0001	0.8801
	Cubic	$Y=0.59-1.98X+2.05X^2-0.66X^3$	<.0001	0.9246
Pacific Gold Sealed 5 Days	**Linear**	$Y=0.45-0.38X$	0.0003	0.6231
	Quadratic	$Y=0.60-1.26X+0.59X^2$	<.0001	0.9138
	Cubic	$Y=0.63-2.05X+2.10X^2-0.67X^3$	<.0001	0.9571
Pacific Gold Sealed 7 Days	**Linear**	$Y=0.37-0.31X$	0.0003	0.6275
	Quadratic	$Y=0.49-1.03X+0.48X^2$	<.0001	0.9204
	Cubic	$Y=0.51-1.68X+1.72X^2-0.55X^3$	<.0001	0.9642

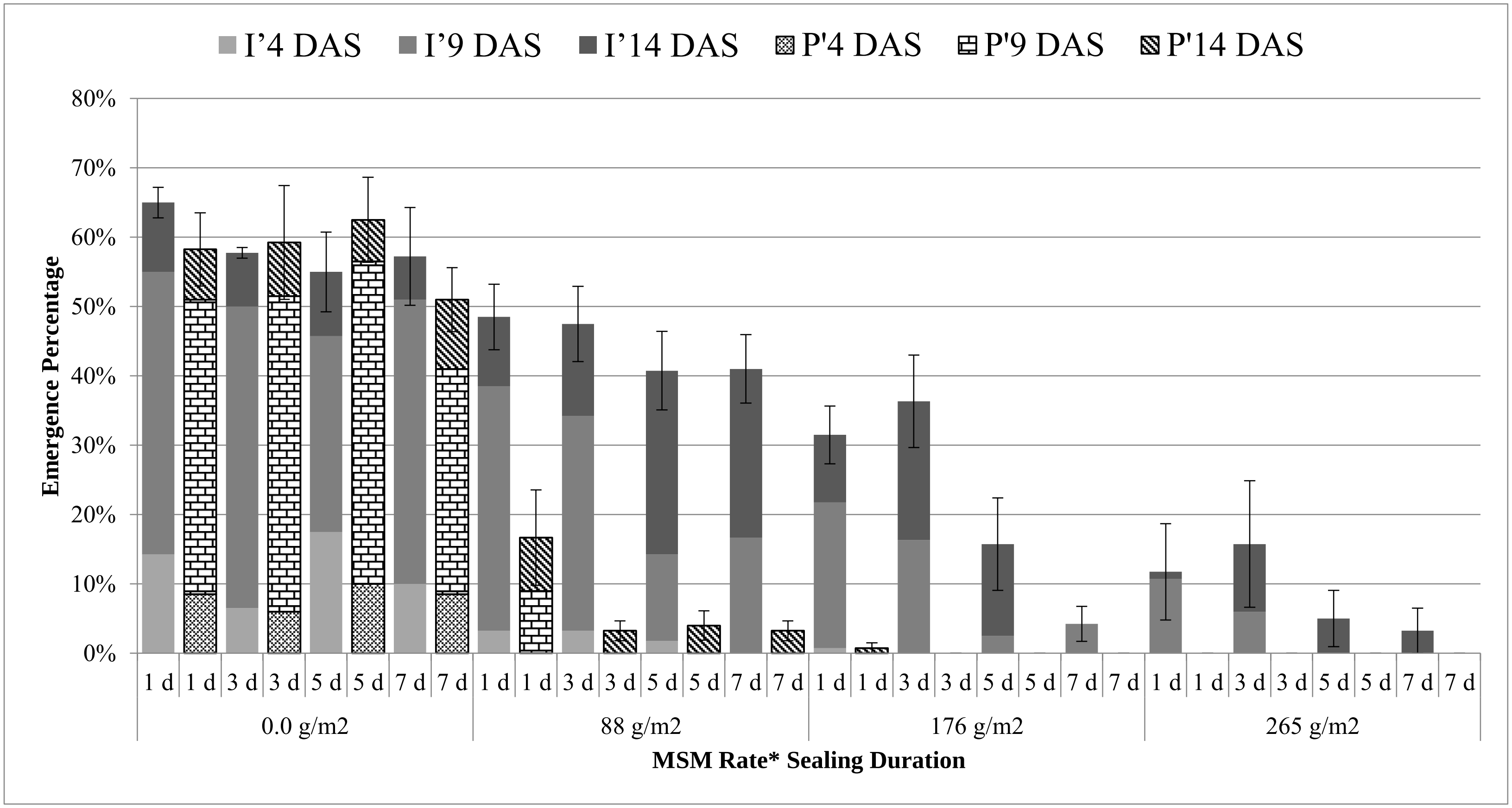
Table 30. Regression analysis of emergence index of large crabgrass seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealing durations (1 day, 3 days, 5 days or 7 days).

Regression Analysis of Emergence Index				
	Model		**P-value**	**R-Square**
IdaGold Sealed 1 Day	**Linear**	$Y=0.59-0.35X$	<.0001	0.8061
	Quadratic	$Y=0.62-0.55X+0.13X^2$	<.0001	0.8288
	Cubic	$Y=0.62-0.60X+0.23X^2-0.04X^3$	<.0001	0.8291
IdaGold Sealed 3 Days	**Linear**	$Y=0.48-0.28X$	<.0001	0.7458
	Quadratic	$Y=0.50-0.41X+0.09X^2$	0.0002	0.7591
	Cubic	$Y=0.50-0.47X+0.20X^2-0.05X^3$	0.001	0.7596
IdaGold Sealed 5 Days	**Linear**	$Y=0.49-0.37X$	<.0001	0.7238
	Quadratic	$Y=0.58-0.91X+0.36X^2$	<.0001	0.8615
	Cubic	$Y=0.58-1.08X+0.68X^2-0.14X^3$	<.0001	0.8639
IdaGold Sealed 7 Days	**Linear**	$Y=0.47-0.36X$	<.0001	0.7646
	Quadratic	$Y=0.55-0.85X-0.33X^2$	<.0001	0.8847
	Cubic	$Y=0.55-1.09X+0.77X^2-0.19X^3$	<.0001	0.8891
Pacific Gold Sealed 1 Day	**Linear**	$Y=0.43-0.35X$	0.0002	0.6796
	Quadratic	$Y=0.53-1.01X+0.44X^2$	<.0001	0.8839
	Cubic	$Y=0.54-1.47X+1.31X^2-0.38X^3$	<.0001	0.8995
Pacific Gold Sealed 3 Days	**Linear**	$Y=0.36-0.31X$	0.001	0.5486
	Quadratic	$Y=0.48-1.06X+0.50X^2$	<.0001	0.8432
	Cubic	$Y=0.51-1.83X+1.97X^2-0.65X^3$	<.0001	0.8992
Pacific Gold Sealed 5 Days	**Linear**	$Y=0.42-0.36X$	0.001	0.5533
	Quadratic	$Y=0.56-1.22X+0.58X^2$	<.0001	0.848
	Cubic	$Y=0.59-2.11X+2.27X^2-0.75X^3$	<.0001	0.9033
Pacific Gold Sealed 7 Days	**Linear**	$Y=0.31-0.26X$	0.0012	0.5378
	Quadratic	$Y=0.42-0.91X+0.43X^2$	<.0001	0.8262
	Cubic	$Y=0.44-1.56X+1.68X^2-0.56X^3$	<.0001	0.8808

Table 31. Regression analysis of fresh weight of large crabgrass seedlings in response to application rate of ‘IdaGold’ or ‘Pacific Gold’ mustard seed meal under sealing durations (1 day, 3 days, 5 days or 7 days).

Regression Analysis of Fresh Weight				
	Model		**P-value**	**R-Square**
IdaGold Sealed 1 Day	**Linear**	Y=0.11-0.09X	0.0002	0.6338
	Quadratic	$Y=0.14-0.29X+0.13X^2$	<.0001	0.8869
	Cubic	$Y=0.15-0.44X+0.42X^2-0.13X^3$	<.0001	0.9139
IdaGold Sealed 3 Days	**Linear**	Y=0.10-0.08X	0.0005	0.5901
	Quadratic	$Y=0.13-0.27X+0.13X^2$	<.0001	0.8577
	Cubic	$Y=0.14-0.44X+0.44X^2-0.14X^3$	<.0001	0.8955
IdaGold Sealed 5 Days	**Linear**	Y=0.11-0.09X	0.0006	0.5788
	Quadratic	$Y=0.14-0.30X+0.14X^2$	<.0001	0.8589
	Cubic	$Y=0.15-0.50X+0.52X^2-0.17X^3$	<.0001	0.9035
IdaGold Sealed 7 Days	**Linear**	Y=0.12-0.10X	0.0014	0.529
	Quadratic	$Y=0.15-0.33X+0.15X^2$	<.0001	0.7879
	Cubic	$Y=0.16-0.54X+0.57X^2-0.18X^3$	<.0001	0.83
Pacific Gold Sealed 1 Day	**Linear**	Y=0.13-0.11X	0.0034	0.4959
	Quadratic	$Y=0.19-0.41X+0.20X^2$	<.0001	0.8109
	Cubic	$Y=0.20-0.72X+0.76X^2-0.25X^3$	<.0001	0.8733
Pacific Gold Sealed 3 Days	**Linear**	Y=0.12-0.11X	0.0046	0.4477
	Quadratic	$Y=0.16-0.35X+0.17X^2$	0.0005	0.6868
	Cubic	$Y=0.17-0.60X+0.66X^2-0.22X^3$	0.001	0.7318
Pacific Gold Sealed 5 Days	**Linear**	Y=0.12-0.10X	0.0021	0.5015
	Quadratic	$Y=0.16-0.35X+0.17X^2$	<.0001	0.7589
	Cubic	$Y=0.17-0.60X+0.63X^2-0.21X^3$	<.0001	0.8043
Pacific Gold Sealed 7 Days	**Linear**	Y=0.04-0.04X	0.0189	0.356
	Quadratic	$Y=0.06-0.13X+0.06X^2$	0.006	0.5737
	Cubic	$Y=0.07-0.23X+0.24X^2-0.08X^3$	0.0123	0.6143

Figure 6. Effects of different types (I'- 'IdaGold' and P'- 'Pacific Gold') and rates (0 to 265 g/m^2) of mustard seed meal (MSM) and sealing durations (1 day, 3 days, 5 days, 7 days) on emergence percentage of large crabgrass seedlings at 4, 9 and 14 days after sowing (DAS). Bars represent standard error of EP at 14 DAS.



The effects of the interaction among three main factors (MSM type and rate and sealing duration) and the interaction between MSM type and sealing duration were not significant on EP, EI and FW of Palmer amaranth seedlings (Table 32). Also, the effects of MSM type and the interaction between MSM type and rate were not significant on the FW of Palmer amaranth seedlings. All the other effects of interactions between main factors and the main factors on EP, EI and FW of Palmer amaranth seedlings were significant. When there was no MSM incorporated into the germination mix, sealing durations did not affect EP at 14 days after sowing (DAS), EI or FW of Palmer amaranth seedlings (Tables 33 and 34, Figure 7). At 88 g/m^2, the EP at 14 DAS and EI of Palmer amaranth seedlings were up to 21.9 percentage points lower in 'Pacific Gold' than 'IdaGold' when sealed for 3 days. At 88 g/m^2 of 'IdaGold', there was no difference in EP at 14 DAS and EI of Palmer amaranth seedlings among all sealing durations (1, 3, 5 and 7 days) (Table 33 and Figure 7). However, at 88 g/m^2 of 'Pacific Gold', the EP at 14 DAS of Palmer amaranth seedlings was up to 25.0 percentage points lower when sealed for 1, 3, 5 days than 7 days (Figure 7), and there was no difference of EI among all sealing durations (Table 33). The EP at 14 DAS and EI of Palmer amaranth seedlings were zero when sealed with 176 g/m^2 of 'Pacific Gold' for 3 and 7 days and 265 g/m^2 of both MSM types for 1, 3, 5 and 7 days (Table 33 and Figure 7). The EP at 14 DAS and EI of Palmer amaranth seedlings were below 4% when sealed with 176 g/m^2 of 'IdaGold' for 1, 3, 5 and 7 days and 176 g/m^2 of 'Pacific Gold' for 1 and 5 days. Palmer amaranth seedlings showed weak and slow growth in MSM incorporated substrate. The FW of Palmer amaranth seedlings were very low and there was no difference in FW between two MSM types or among all sealing durations (Table 34). The EP at 14 DAS, EI and the FW of Palmer amaranth seedlings were significantly correlated ($P < 0.01$) with the MSM rate under each combination of MSM type and sealing duration (Tables 35, 36 and 37). The significant linear, quadratic and cubic correlation indicated that increasing MSM rate under each combination of MSM type and sealing duration decreased the EP at 14 DAS, EI and the FW of Palmer amaranth seedlings. The EP at 4 and 9 DAS showed similar trends as the EP at 14 DAS (Figure 7). These results were not consistent with our previous experiments in petri dishes, which indicated EP and EI of Palmer amaranth were greatly reduced in sealed conditions than unsealed (covered with lids), while EP and EI were lower in 'Pacific Gold' than 'IdaGold'. Since lids were removed after different sealing durations in this experiment, soil moisture and temperature in petri dishes between four sealing durations may be variable. Higher soil moisture and temperature is of benefit for seed germination in sealed petri dishes than uncovered ones. Besides, higher temperature generally increased disappearance rates of ITC and SCN^- in soil (Borek et al, 1995; Brown and Morra, 1993) and increasing water content in soil increased the half-life of allyl-ITC (Borek et al. 1995). Lower reduction of weed emergence may be caused by higher soil moisture and temperature in longer sealing duration (5 and 7 days).

Table 32. ANOVA of emergence percentage (EP), emergence index (EI) and seedlings fresh weight (FW) of Palmer amaranth seedlings exposed to different types ('IdaGold' and 'Pacific Gold') and rates (0 to 265 g/m^2) of mustard seed meal and sealing durations (1 day, 3 days, 5 days, 7 days).

Source	**EP**	**EI**	**FW**
	Pr > F	**Pr > F**	**Pr > F**
Rate	<.0001	<.0001	<.0001
Sealing Duration	<.0001	<.0001	0.0223
Type	<.0001	<.0001	0.6013
Type*Rate	0.0007	0.0003	0.9529
Rate*Sealing Duration	<.0001	<.0001	0.0022
Type*Sealing Duration	0.1304	0.1343	0.9632
Type*Rate*Sealing Duration	0.7052	0.6927	0.9993

Table 33. 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 day, 3 days, 5 days, 7 days) on emergence index (± standard error) of Palmer amaranth seedlings at 14 days after sowing.

		Emergence Index (%) of Palmer Amaranth Seedlings			
		Sealing Duration			
MSM	**Rate**	**1 Day**	**3 Days**	**5 Days**	**7 Days**
IdaGold	**0.0 g/m^2**	33.6± 4.8	67.2 ± 5.3	79.5 ± 7.9	79.5 ± 4.4
	88 g/m^2	9.0 ± 1.9	24.5 ± 8.9	21.3 ± 10.5	36.0 ± 12.4
	176 g/m^2	0.9 ± 0.6	1.2 ± 0.7	0.6 ± 0.6	1.3 ± 0.8
	265 g/m^2	0.0	0.0	0.0	0.0
Pacific Gold	**0.0 g/m^2**	30.0 ± 3.8	49.0 ± 3.6	61.1 ± 9.0	68.1 ± 7.4
	88 g/m^2	9.3 ± 4.5	2.6 ± 1.7	4.5 ± 2.6	15.7 ± 6.0
	176 g/m^2	0.7 ± 0.6	0.0	1.2 ± 1.2	0.0
	265 g/m^2	0.0	0.0	0.0	0.0

Table 34. 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 day, 3 days, 5 days, 7 days) on fresh weight (± standard error) of Palmer amaranth seedlings at 18 days after sowing.

		Fresh Weight (g) of Palmer Amaranth Seedlings			
		Sealing Duration			
MSM	**Rate**	**1 Day**	**3 Days**	**5 Days**	**7 Days**
IdaGold	**0.0 g/m^2**	0.03 ± 0.01	0.06 ± 0.01	0.08 ± 0.01	0.07 ± 0.02
	88 g/m^2	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00
	176 g/m^2	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
	265 g/m^2	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Pacific Gold	**0.0 g/m^2**	0.04 ± 0.01	0.06 ± 0.02	0.07 ± 0.02	0.07 ± 0.01
	88 g/m^2	0.01 ± 0.00	0.00 ± 0.00	0.01 ± 0.01	0.02 ± 0.01
	176 g/m^2	0.01 ± 0.01	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
	265 g/m^2	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00

Table 35. Regression analysis of emergence percentage at 14 DAS of Palmer amaranth seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealing durations (1 day, 3 days, 5 days or 7 days).

Regression Analysis of Emergence Percentage at 14 DAS				
	Model		**P-value**	**R-Square**
IdaGold Sealed 1 Day	**Linear**	Y=0.26-0.21X	<.0001	0.7238
	Quadratic	$Y=0.31-0.51X+0.2X^2$	<.0001	0.8616
	Cubic	$Y=0.32-0.61X+0.39X^2-0.08X^3$	<.0001	0.8643
IdaGold Sealed 3 Days	**Linear**	Y=0.41-0.32X	<.0001	0.8589
	Quadratic	$Y=0.47-0.69X+0.25X^2$	<.0001	0.958
	Cubic	$Y=0.46-0.45X-0.2X^2+0.2X^3$	<.0001	0.9645
IdaGold Sealed 5 Days	**Linear**	Y=0.45-0.36X	<.0001	0.8076
	Quadratic	$Y=0.54-0.87X+0.34X^2$	<.0001	0.9534
	Cubic	$Y=0.54-0.86X+0.32X^2+0.01X^3$	<.0001	0.9534
IdaGold Sealed 7 Days	**Linear**	Y=0.48-0.37X	<.0001	0.7906
	Quadratic	$Y=0.54-0.75X+0.25X^2$	<.0001	0.8606
	Cubic	$Y=0.53-0.29X-0.61X^2+0.38X^3$	<.0001	0.8769
Pacific Gold Sealed 1 Day	**Linear**	Y=0.24-0.17X	<.0001	0.8448
	Quadratic	$Y=0.26-0.33X+0.1X^2$	<.0001	0.9
	Cubic	$Y=0.26-0.3X+0.06X^2+0.02X^3$	<.0001	0.9003
Pacific Gold Sealed 3 Days	**Linear**	Y=0.27-0.22X	0.0003	0.6259
	Quadratic	$Y=0.35-0.69X+0.31X^2$	<.0001	0.8607
	Cubic	$Y=0.36-1.01X+0.93X^2-0.28X^3$	<.0001	0.8821
Pacific Gold Sealed 5 Days	**Linear**	Y=0.33-0.26X	0.0001	0.6609
	Quadratic	$Y=0.4-0.69X+0.29X^2$	<.0001	0.8185
	Cubic	$Y=0.41-0.98X+0.84X^2-0.25X^3$	<.0001	0.8318
Pacific Gold Sealed 7 Days	**Linear**	Y=0.46-0.35X	<.0001	0.8691
	Quadratic	$Y=0.5-0.65X+0.2X^2$	<.0001	0.9243
	Cubic	$Y=0.49+0.02X-1.06X^2+0.55X^3$	<.0001	0.9674

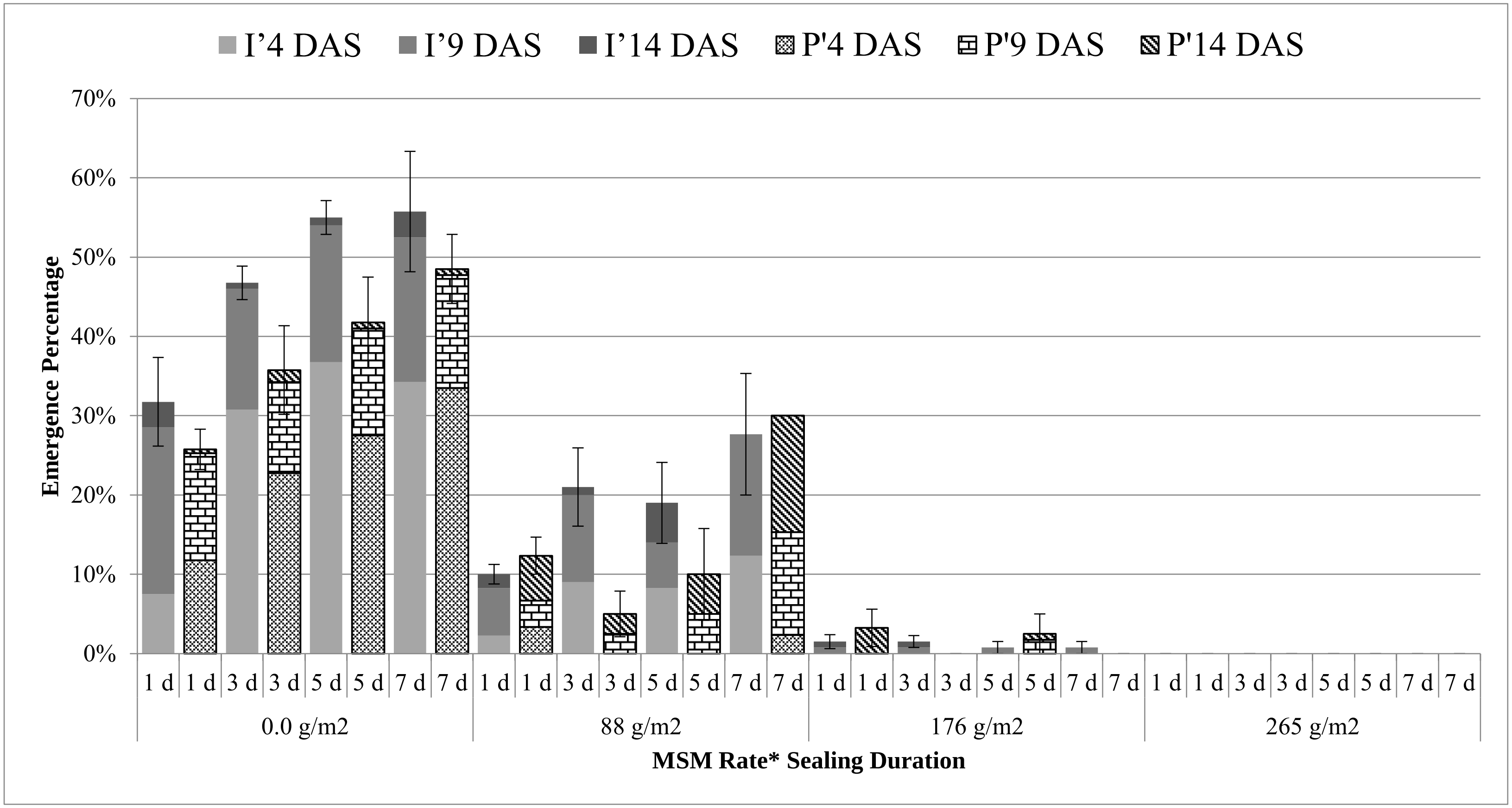
Table 36. Regression analysis of emergence index of Palmer amaranth seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealing durations (1 day, 3 days, 5 days or 7 days).

Regression Analysis of Emergence Index				
	Model		**P-value**	**R-Square**
IdaGold Sealed 1 Day	**Linear**	$Y=0.27-0.22X$	<.0001	0.723
	Quadratic	$Y=0.33-0.57X+0.24X^2$	<.0001	0.8951
	Cubic	$Y=0.34-0.72X+0.52X^2-0.12X^3$	<.0001	0.9005
IdaGold Sealed 3 Days	**Linear**	$Y=0.58-0.45X$	<.0001	0.808
	Quadratic	$Y=0.67-1.07X+0.42X^2$	<.0001	0.9352
	Cubic	$Y=0.67-1.03X+0.33X^2+0.04X^3$	<.0001	0.9353
IdaGold Sealed 5 Days	**Linear**	$Y=0.64-0.52X$	<.0001	0.7106
	Quadratic	$Y=0.79-1.38X+0.58X^2$	<.0001	0.8865
	Cubic	$Y=0.8-1.66X+1.1X^2-0.23X^3$	<.0001	0.8897
IdaGold Sealed 7 Days	**Linear**	$Y=0.71-0.55X$	<.0001	0.8318
	Quadratic	$Y=0.81-1.19X+0.43X^2$	<.0001	0.9293
	Cubic	$Y=0.8-0.8X-0.31X^2+0.33X^3$	<.0001	0.9351
Pacific Gold Sealed 1 Day	**Linear**	$Y=0.25-0.2X$	<.0001	0.7488
	Quadratic	$Y=0.3-0.49X+0.2X^2$	<.0001	0.8868
	Cubic	$Y=0.3-0.56X+0.33X^2-0.06X^3$	<.0001	0.8879
Pacific Gold Sealed 3 Days	**Linear**	$Y=0.35-0.3X$	0.0003	0.6253
	Quadratic	$Y=0.47-1X+0.46X^2$	<.0001	0.9261
	Cubic	$Y=0.49-1.64X+1.7X^2-0.55X^3$	<.0001	0.9736
Pacific Gold Sealed 5 Days	**Linear**	$Y=0.45-0.37X$	0.0004	0.5995
	Quadratic	$Y=0.59-1.2X+0.55X^2$	<.0001	0.8632
	Cubic	$Y=0.61-2X+2.09X^2-0.68X^3$	<.0001	0.9083
Pacific Gold Sealed 7 Days	**Linear**	$Y=0.56-0.45X$	<.0001	0.7438
	Quadratic	$Y=0.67-1.21X+0.51X^2$	<.0001	0.9285
	Cubic	$Y=0.68-1.55X+1.15X^2-0.28X^3$	<.0001	0.9342

Table 37. Regression analysis of fresh weight of Palmer amaranth seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealing durations (1 day, 3 days, 5 days or 7 days).

Regression Analysis of Fresh Weight				
	Model		**P-value**	**R-Square**
IdaGold Sealed 1 Day	**Linear**	Y=0.02-0.02X	0.0007	0.5685
	Quadratic	$Y=0.03-0.06X+0.03X^2$	<.0001	0.7654
	Cubic	$Y=0.03-0.08X+0.07X^2-0.02X^3$	0.0003	0.7795
IdaGold Sealed 3 Days	**Linear**	Y=0.04-0.04X	0.0006	0.5813
	Quadratic	$Y=0.06-0.12X+0.06X^2$	<.0001	0.8382
	Cubic	$Y=0.06-0.19X+0.19X^2-0.06X^3$	<.0001	0.8726
IdaGold Sealed 5 Days	**Linear**	Y=0.05-0.05X	0.0008	0.5628
	Quadratic	$Y=0.07-0.15X+0.07X^2$	<.0001	0.8234
	Cubic	$Y=0.08-0.25X+0.25X^2-0.08X^3$	<.0001	0.8617
IdaGold Sealed 7 Days	**Linear**	Y=0.05-0.05X	0.0036	0.4644
	Quadratic	$Y=0.07-0.14X+0.07X^2$	0.0009	0.6583
	Cubic	$Y=0.07-0.22X+0.22X^2-0.07X^3$	0.0026	0.6812
Pacific Gold Sealed 1 Day	**Linear**	Y=0.03-0.02X	0.0016	0.5201
	Quadratic	$Y=0.03-0.06X+0.02X^2$	0.0015	0.634
	Cubic	$Y=0.04-0.1X+0.11X^2-0.04X^3$	0.0033	0.6681
Pacific Gold Sealed 3 Days	**Linear**	Y=0.04-0.04X	0.0056	0.4327
	Quadratic	$Y=0.06-0.12X+0.06X^2$	0.0014	0.6347
	Cubic	$Y=0.06-0.21X+0.24X^2-0.08X^3$	0.0025	0.6828
Pacific Gold Sealed 5 Days	**Linear**	Y=0.05-0.04X	0.0024	0.4939
	Quadratic	$Y=0.07-0.13X+0.06X^2$	0.0006	0.6776
	Cubic	$Y=0.07-0.2X+0.18X^2-0.05X^3$	0.0021	0.6939
Pacific Gold Sealed 7 Days	**Linear**	Y=0.06-0.05X	<.0001	0.6947
	Quadratic	$Y=0.07-0.13X+0.06X^2$	<.0001	0.8849
	Cubic	$Y=0.07-0.16X+0.12X^2-0.03X^3$	<.0001	0.8899

Figure 7. Effects of different types (I'- 'IdaGold' and P'- 'Pacific Gold') and rates (0 to 265 g/m^2) of mustard seed meal (MSM) and sealing durations (1 day, 3 days, 5 days, 7 days) on emergence percentage of Palmer amaranth seedlings at 4, 9 and 14 days after sowing (DAS). Bars represent standard error of EP at 14 DAS.



3.4.2 Effects of MSMs on Emergence of Onion *Allium cepa* 'Texas Grano 1015Y' Seedlings in Petri Dishes

The effects of the interaction among three main factors (MSM type and rate and sealing duration) and the interaction between MSM type and sealing duration were not significant on EP, EI and FW of onion seedlings (Table 38). The effects of the interaction of MSM rate and sealing duration was not significant on EP and EI, and the effects of MSM type and the interaction between MSM type and rate were not significant on FW of onion seedlings. All the other effects of interactions between main factors and the main factors on EP, EI and FW of onion seedlings were significant. When there was no MSM incorporated into the germination mix, sealing durations did not affect EP at 14 DAS, EI or FW of onion seedlings (Tables 39 and 40, Figure 8). The EP at 14 DAS, EI and FW of onion seedlings was zero when sealed with 176 g/m^2 of 'Pacific Gold' for 7 days and 265 g/m^2 of 'Pacific Gold' for 5 days. At 88 g/m^2 of MSM, the EP at 14 DAS and EI of onion seedlings were 17.2 to 35 percentage points lower in 'Pacific Gold' than 'IdaGold' when sealed for 5 and 7 days, while there was no difference in EP at 14 DAS and EI between two types of MSM when sealed for 1 and 3 days (Table 39 and Figure 8). The EP at 14 DAS of onion seedlings was up to 57.5 percentage points lower when sealed with 88 g/m^2 of MSM for 7 days compared to 1, 3 and 5 days, while EI was up to 42.9 percentage points lower when sealed with 88 g/m^2 of 'Pacific Gold' for 7 days compared to for 1, 3 and 5 days. At 176 g/m^2 of MSM, the EP at 14 DAS and EI of onion seedlings were 9.9 to 37.5 percentage points lower in 'Pacific Gold' than 'IdaGold' when sealed for 3 and 5 days. The EP at 14 DAS and EI of onion seedlings were up to 60.0 percentage points lower when sealed with 176 g/m^2 of ‘IdaGold’ for 7 days compared to for 1, 3, and 5 days. There was no difference in EP 14 DAS and EI among all sealing durations when sealed with 176 g/m^2 of ‘Pacific Gold’. At 265 g/m^2 of MSM, the EP at 14 DAS of onion seedlings was up to 35.0 percentage points lower in ‘Pacific Gold’ than ‘IdaGold’ when sealed for 1, 3 and 5 days, respectively, while EI was 14.5 and 7.1 percentage points lower in ‘Pacific Gold’ than ‘IdaGold’ when sealed for 1 and 5 days, respectively. The EP at 14 DAS of onion seedlings was up to 38.3 percentage points lower when sealed with 265 g/m^2 of ‘IdaGold’ for 5 and 7 days than for 1 and 3 days, but there was no difference in EI among all sealing durations. There was no difference in EP 14 DAS and EI of onion seedlings among all sealing durations when sealed with 265 g/m^2 of ‘Pacific Gold’, and there was no difference in FW between two MSM types at 88, 176 and 265 g/m^2 under all sealing durations. Also, there was no difference in FW of onion seedlings among all sealing durations under the same MSM type and rate (Table 40). The EP at 6 DAS, EI and the FW of onion seedlings were significantly correlated ($P < 0.01$) with MSM rate under each combination of MSM type and sealing duration (Tables 41, 42 and 43). The significant linear, quadratic and cubic correlation indicated that increasing the MSM rate under each combination of MSM type and sealing duration decreased the EP at 14 DAS, EI and the FW of onion seedlings. The EP at 4 and 9 DAS showed a similar trends as the EP at 14 DAS (Figure 8). These results indicated that phytotoxicity increased as sealing duration became longer, and ‘Pacific Gold’ had greater suppressive effects on onion seedlings than ‘Idagold’. Boydston et al. (2011) also found that ‘IdaGold’ applied prior to onion planting at 110, 220 and 440 g/m^2 resulted in a reduction of onion stand and caused injury. Besides, when 'IdaGold' was applied as a biofumigant, onion yield was reduced in the low and high-lime soil (Geary et al., 2008).

Table 38. ANOVA of emergence percentage (EP), emergence index (EI) and seedlings fresh weight (FW) of 'Texas Grano 1015Y' onion seedlings exposed to different types ('IdaGold' and 'Pacific Gold') and rates (0 to 265 g/m2g/dish) of mustard seed meal (MSM) and sealing durations (1 day, 3 days, 5 days, 7 days).

Source	EP	EI	FW
	Pr > F	**Pr > F**	**Pr > F**
Rate	<.0001	<.0001	<.0001
Sealing Duration	<.0001	<.0001	<.0001
Type	<.0001	<.0001	0.3546
Type*Rate	0.024	0.0223	0.7847
Rate*Sealing Duration	0.0616	0.1203	0.0015
Type*Sealing Duration	0.1037	0.117	0.2691
Type*Rate*Sealing Duration	0.9871	0.9983	0.9081

Table 39. 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 day, 3 days, 5 days, 7 days) on emergence index (± standard error) of 'Texas Grano 1015Y' onion seedlings at 14 days after sowing.

		Emergence Index (%) of Onion Seedlings			
		Sealing Duration			
MSM	**Rates**	**1 Day**	**3 Days**	**5 Days**	**7 Days**
IdaGold	**0.0 g/m^2**	81.6 ±10.4	72.2 ± 7.4	55.0 ± 5.3	50.3 ± 8.5
	88 g/m^2	69.7 ± 13.7	52.0 ± 11.5	36.6 ± 9.5	19.3 ± 7.2
	176 g/m^2	41.6 ± 4.9	22.3 ± 4.8	10.1 ± 1.4	2.3 ± 0.8
	265 g/m^2	16.0 ± 3.7	21.8 ± 14.9	7.1 ± 2.4	0.8 ± 1.2
Pacific Gold	**0.0 g/m^2**	78.5 ±7.2	66.6 ± 16.1	61.7 ± 13.2	53.6 ± 2.1
	88 g/m^2	45.0 ± 19.2	22.0 ± 9.5	14.2 ± 1.0	2.1 ± 0.7
	176 g/m^2	18.5 ±10.2	3.0 ± 3.0	0.2 ± 0.2	0.0
	265 g/m^2	1.5 ±1.1	0.2 ± 0.2	0.0	0.2 ± 0.2

Table 40. 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 day, 3 days, 5 days, 7 days) on fresh weight (± standard error) of 'Texas Grano 1015Y' onion seedlings at 18 days after sowing.

		Fresh Weight (g) of Onion Seedlings			
		Sealing Duration			
MSM	**Rates**	**1 Day**	**3 Days**	**5 Days**	**7 Days**
IdaGold	**0.0 g/m^2**	0.30 ± 0.03	0.34 ± 0.03	0.26 ± 0.02	0.26 ± 0.02
	88 g/m^2	0.22 ± 0.04	0.22 ± 0.03	0.18 ± 0.02	0.09 ± 0.01
	176 g/m^2	0.08 ± 0.01	0.06 ± 0.01	0.05 ± 0.02	0.02 ± 0.01
	265 g/m^2	0.02 ± 0.01	0.02 ± 0.01	0.02 ± 0.01	0.01 ± 0.00
Pacific Gold	**0.0 g/m^2**	0.31 ± 0.04	0.33 ± 0.01	0.30 ± 0.03	0.25 ± 0.02
	88 g/m^2	0.24 ± 0.05	0.17 ± 0.04	0.17 ± 0.04	0.06 ± 0.01
	176 g/m^2	0.13 ± 0.05	0.02 ± 0.02	0.02 ± 0.01	0.00
	265 g/m^2	0.01 ± 0.01	0.01 ± 0.01	0.00	0.00

Table 41. Regression analysis of emergence percentage at 14 DAS of 'Texas Grano 1015Y' onion seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealing durations (1 day, 3 days, 5 days or 7 days).

Regression Analysis of Emergence Percentage at 14 DAS				
	Model		**P-value**	**R-Square**
IdaGold Sealed 1 Day	**Linear**	Y=0.88-0.27X	0.0003	0.6221
	Quadratic	$Y=0.85-0.08X-0.13X^2$	0.0011	0.6498
	Cubic	$Y=0.85-0.12X-0.05X^2-0.03X^3$	0.0045	0.6501
IdaGold Sealed 3 Days	**Linear**	Y=0.93-0.39X	<.0001	0.6996
	Quadratic	$Y=0.93-0.35X-0.03X^2$	0.0004	0.7002
	Cubic	$Y=0.9+0.48X-1.6X^2+0.7X^3$	0.0006	0.7522
IdaGold Sealed 5 Days	**Linear**	Y=0.96-0.58X	<.0001	0.838
	Quadratic	$Y=0.92-0.3X+-0.19X^2$	<.0001	0.8571
	Cubic	$Y=0.9+0.27X-1.28X^2+0.49X^3$	<.0001	0.8723
IdaGold Sealed 7 Days	**Linear**	Y=0.73-0.5X	<.0001	0.7911
	Quadratic	$Y=0.83-1.1X+0.4X^2$	<.0001	0.8924
	Cubic	$Y=0.8-0.32X-1.1X^2+0.67X^3$	<.0001	0.9241
Pacific Gold Sealed 1 Day	**Linear**	Y=0.75-0.52X	0.0001	0.6688
	Quadratic	$Y=0.79-0.76X+0.16X^2$	0.0006	0.6824
	Cubic	$Y=0.79-0.72X+0.09X^2+0.03X^3$	0.0026	0.6825
Pacific Gold Sealed 3 Days	**Linear**	Y=0.76-0.53X	0.0001	0.6913
	Quadratic	$Y=0.82-0.89X+0.23X^2$	0.0005	0.7166
	Cubic	$Y=0.8-0.37X-0.8X^2+0.47X^3$	0.002	0.727
Pacific Gold Sealed 5 Days	**Linear**	Y=0.82-0.62X	<.0001	0.8828
	Quadratic	$Y=0.88-1.05X+0.29X^2$	<.0001	0.9204
	Cubic	$Y=0.85+0.21X-2.07X^2+1.03X^3$	<.0001	0.9697
Pacific Gold Sealed 7 Days	**Linear**	Y=0.63-0.49X	0.0004	0.6659
	Quadratic	$Y=0.78-1.58X+0.73X^2$	<.0001	0.9198
	Cubic	$Y=0.8-2.32X+2.15X^2-0.63X^3$	<.0001	0.9394

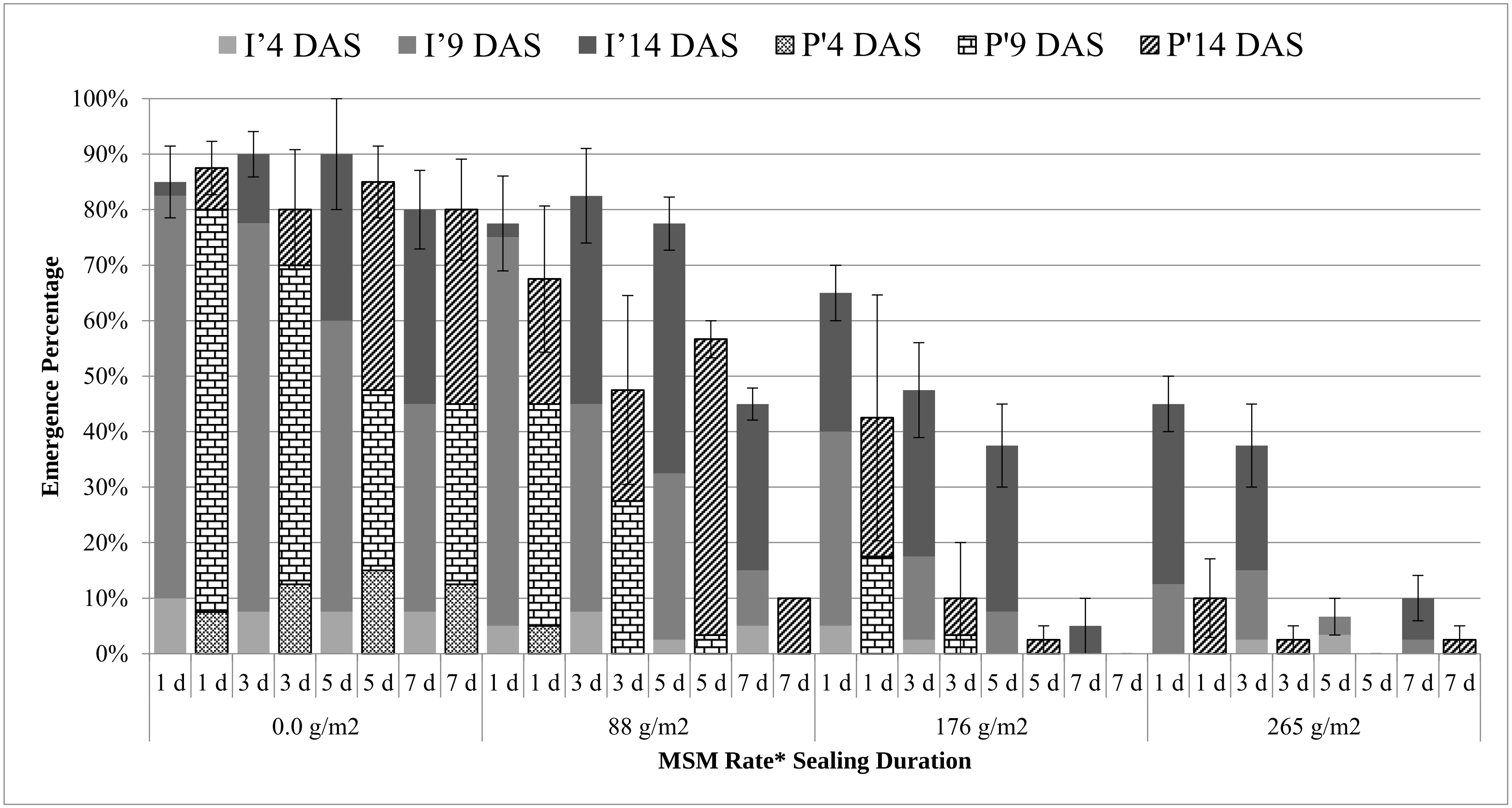
Table 42. Regression analysis of emergence index of 'Texas Grano 1015Y' onion seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealing durations (1 day, 3 days, 5 days or 7 days).

Regression Analysis of Emergence Index				
	Model		**P-value**	**R-Square**
IdaGold Sealed 1 Day	**Linear**	$Y=0.86-0.45X$	<.0001	0.704
	Quadratic	$Y=0.83-0.24X-0.14X^2$	0.0003	0.7176
	Cubic	$Y=0.82+0.04X-0.68X^2+0.24X^3$	0.0012	0.7221
IdaGold Sealed 3 Days	**Linear**	$Y=0.69-0.36X$	0.0016	0.5215
	Quadratic	$Y=0.74-0.67X+0.21X^2$	0.0051	0.5563
	Cubic	$Y=0.72-0.03X-1.01X^2+0.54X^3$	0.0123	0.5831
IdaGold Sealed 5 Days	**Linear**	$Y=0.53-0.35X$	<.0001	0.7411
	Quadratic	$Y=0.57-0.57X+0.15X^2$	0.0002	0.7693
	Cubic	$Y=0.55-0.08X-0.79X^2+0.42X^3$	0.0004	0.7962
IdaGold Sealed 7 Days	**Linear**	$Y=0.43-0.33X$	<.0001	0.6728
	Quadratic	$Y=0.51-0.81X+0.32X^2$	<.0001	0.8071
	Cubic	$Y=0.5-0.69X+0.1X^2+0.1X^3$	0.0001	0.8086
Pacific Gold Sealed 1 Day	**Linear**	$Y=0.91-0.52X$	0.0005	0.5962
	Quadratic	$Y=0.87-0.33X-0.13X^2$	0.0025	0.6032
	Cubic	$Y=0.88-0.37X-0.05X^2-0.03X^3$	0.0093	0.6033
Pacific Gold Sealed 3 Days	**Linear**	$Y=0.56-0.43X$	0.0006	0.6078
	Quadratic	$Y=0.66-1.07X+0.42X^2$	0.0005	0.7173
	Cubic	$Y=0.67-1.21X+0.7X^2-0.13X^3$	0.0023	0.7183
Pacific Gold Sealed 5 Days	**Linear**	$Y=0.5-0.41X$	0.0002	0.6616
	Quadratic	$Y=0.61-1.1X+0.46X^2$	<.0001	0.8249
	Cubic	$Y=0.62-1.41X+1.0X^2-0.26X^3$	0.0002	0.8303
Pacific Gold Sealed 7 Days	**Linear**	$Y=0.41-0.33X$	0.0144	0.4051
	Quadratic	$Y=0.52-1.11X+0.52X^2$	0.0087	0.578
	Cubic	$Y=0.54-1.84X+1.93X^2-0.63X^3$	0.0216	0.6039

Table 43. Regression analysis of fresh weight of 'Texas Grano 1015Y' onion seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealing durations (1 day, 3 days, 5 days or 7 days).

Regression Analysis of Fresh Weight				
	Model		**P-value**	**R-Square**
IdaGold Sealed 1 Day	**Linear**	$Y=0.3-0.2X$	<.0001	0.8511
	Quadratic	$Y=0.3-0.22X+0.01X^2$	<.0001	0.8518
	Cubic	$Y=0.3-0X-0.4X^2+0.18X^3$	<.0001	0.8683
IdaGold Sealed 3 Days	**Linear**	$Y=0.32-0.22X$	<.0001	0.8583
	Quadratic	$Y=0.34-0.34X+0.08X^2$	<.0001	0.8795
	Cubic	$Y=0.34-0.09X-0.4X^2+0.21X^3$	<.0001	0.897
IdaGold Sealed 5 Days	**Linear**	$Y=0.25-0.17X$	<.0001	0.8778
	Quadratic	$Y=0.26-0.24X+0.05X^2$	<.0001	0.8914
	Cubic	$Y=0.26-0.03X-0.35X^2+0.18X^3$	<.0001	0.9126
IdaGold Sealed 7 Days	**Linear**	$Y=0.21-0.16X$	<.0001	0.7643
	Quadratic	$Y=0.27-0.44X+0.18X^2$	<.0001	0.9555
	Cubic	$Y=0.27-0.5X+0.31X^2-0.06X^3$	<.0001	0.9578
Pacific Gold Sealed 1 Day	**Linear**	$Y=0.32-0.2X$	<.0001	0.7544
	Quadratic	$Y=0.31-0.13X+-0.04X^2$	0.0002	0.761
	Cubic	$Y=0.31-0.09X-0.13X^2+0.04X^3$	0.0009	0.7617
Pacific Gold Sealed 3 Days	**Linear**	$Y=0.29-0.21X$	<.0001	0.8191
	Quadratic	$Y=0.34-0.44X+0.15X^2$	<.0001	0.895
	Cubic	$Y=0.33-0.29X-0.16X^2+0.14X^3$	<.0001	0.9024
Pacific Gold Sealed 5 Days	**Linear**	$Y=0.28-0.21X$	<.0001	0.8419
	Quadratic	$Y=0.3-0.38X+0.11X^2$	<.0001	0.8898
	Cubic	$Y=0.3-0.09X-0.43X^2+0.24X^3$	<.0001	0.9119
Pacific Gold Sealed 7 Days	**Linear**	$Y=0.2-0.16X$	<.0001	0.7295
	Quadratic	$Y=0.24-0.45X+0.2X^2$	<.0001	0.9431
	Cubic	$Y=0.25-0.58X+0.44X^2-0.11X^3$	<.0001	0.9501

Figure 8. Effects of different types (I'- 'IdaGold' and P'- 'Pacific Gold') and rates (0 to 265 g/m^2) of mustard seed meal (MSM) and sealing durations (1 day, 3 days, 5 days, 7 days) on emergence percentage of 'Texas Grano 1015Y' onion seedlings at 4, 9 and 14 days after sowing (DAS). Bars represent standard error of EP at 14 DAS.



3.4.3 Effects of MSMs on Emergence of Three *Brassica* Seedlings in Petri Dishes

The effects of the interaction among three main factors (MSM type and rate and sealing duration) was not significant on EP, EI and FW of kale seedlings (Table 44). The effects of MSM type and the interaction between MSM type and sealing duration were not significant on EP and EI of kale seedlings. Also, the effect of the interaction between MSM rate and sealing durations was not significant on FW of kale seedlings. All the other effects of interactions between the main factors and the main factors on EP, EI and FW of kale seedlings were significant. When there was no MSM incorporated into the germination mix, sealing durations did not affect EP at 14 DAS, EI or FW of kale seedlings (Tables 45 and 46, Figure 9). Under the same MSM type, there was no difference in EP at 14 DAS and FW of kale seedlings among all sealing durations at 88, 176 and 265 g/m^2, respectively. However EI of kale seedlings was up to 81.4 percentage points lower when sealed 3, 5 and 7 days than 1 day at 88 g/m^2 of ‘Pacific Gold’ (Table 45). There was also no difference in EP at 14 DAS and EI of kale seedlings between ‘IdaGold’ and ‘Pacific Gold’ under the same rate and sealing duration, but the FW was up to 0.44 g (89.8%) lower in ‘IdaGold’ than ‘Pacific Gold’ at 176 g/m^2 when sealed for 1 day and at 265 g/m^2 when sealed for 1 and 3 days, respectively (Tables 45 and 46, Figure 9).

Table 44. ANOVA of emergence percentage (EP), emergence index (EI) and seedlings fresh weight (FW) of 'Vates Blue Curled' kale seedlings exposed to different types ('IdaGold' and 'Pacific Gold') and rates 0 to 265 g/m^2) of mustard seed meal (MSM) and sealing durations (1 day, 3 days, 5 days, 7 days).

Source	**EP**	**EI**	**FW**
	Pr > F	**Pr > F**	**Pr > F**
Rate	<.0001	<.0001	<.0001
Sealing Duration	<.0001	<.0001	<.0001
Type	0.4969	0.1861	<.0001
Type*Rate	0.0003	0.0058	0.0148
Rate*Sealing Duration	0.0002	0.0048	0.1812
Type*Sealing Duration	0.7975	0.7627	0.007
Type*Rate*Sealing Duration	0.9526	0.9378	0.973

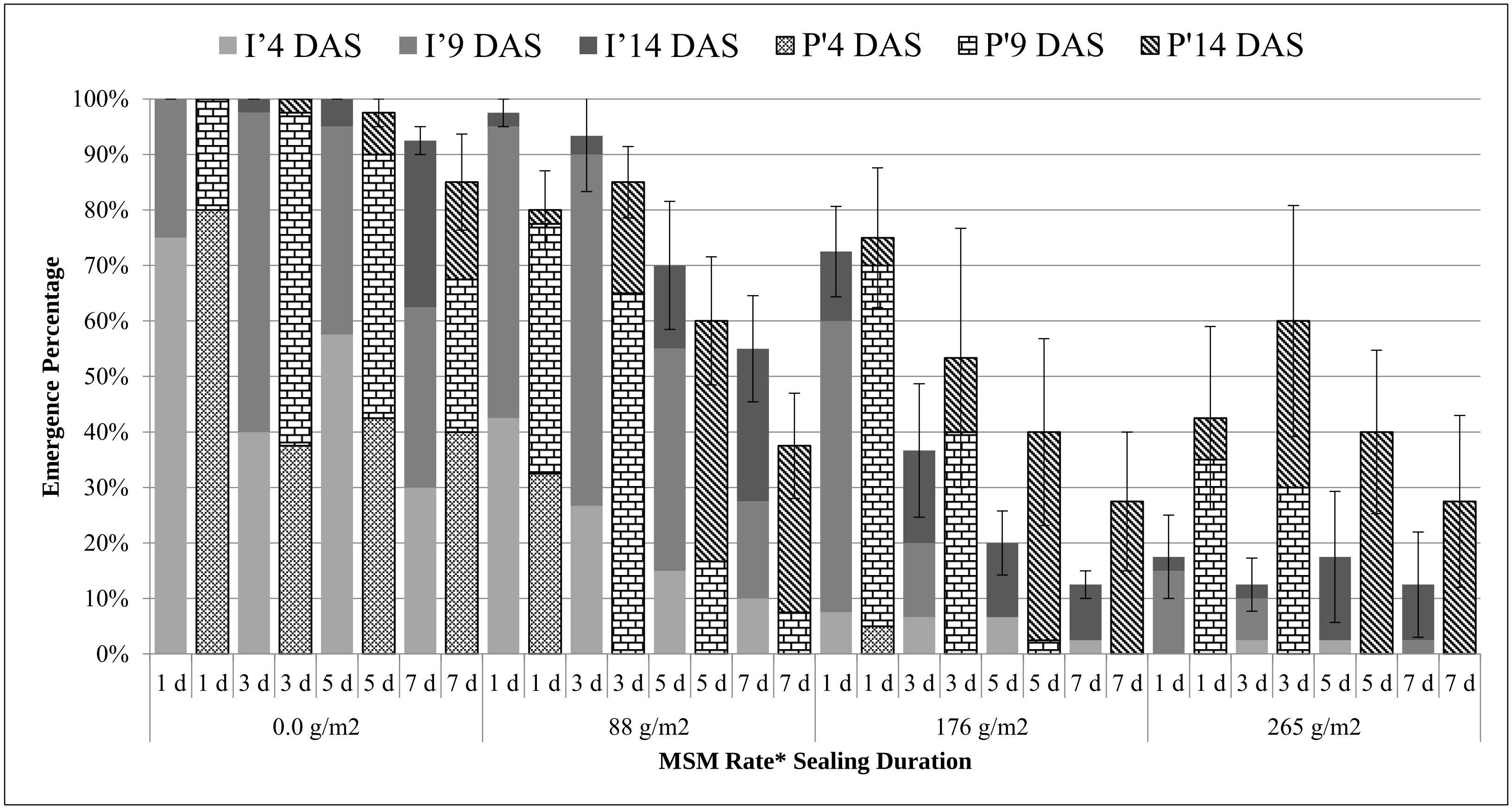
Table 45. Effects of different types ('IdaGold' and 'Pacific Gold') and rates (0 to 265 g/m^2) of mustard seed meal (MSM) and sealing durations (1 day, 3 days, 5 days, 7 days) on emergence index (± standard error) of 'Vates Blue Curled' kale seedlings at 14 days after sowing.

		Emergence Index (%) of Kale Seedlings			
		Sealing Duration			
MSM	**Rate**	**1 Day**	**3 Days**	**5 Days**	**7 Days**
IdaGold	**0.0 g/m^2**	150.6±13.2	127.3 ± 15.4	130.5 ± 17.1	84.4 ± 18.3
	88 g/m^2	119.8 ± 11.5	95.6 ± 26.0	54.9 ± 11.0	38.0 ± 13.5
	176 g/m^2	60.1 ± 8.3	25.9 ± 10.2	12.9 ± 2.5	4.5 ± 2.1
	265 g/m^2	12.1 ± 5.5	11.1 ± 7.0	6.2 ± 3.2	4.4 ± 3.9
Pacific Gold	**0.0 g/m^2**	153.4± 11.2	120.5 ± 20.1	112.5 ± 9.9	99.7 ± 27.5
	88 g/m^2	96.0 ± 10.9	51.0 ± 5.1	24.2 ± 1.5	14.6 ± 5.1
	176 g/m^2	64.3 ± 6.8	29.6 ± 13.3	10.5 ± 6.2	3.1 ± 1.4
	265 g/m^2	29.4 ± 13.4	27.5 ± 9.3	9.7 ± 4.4	3.7 ± 2.5

Table 46. 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 day, 3 days, 5 days, 7 days) on fresh weight (± standard error) of 'Vates Blue Curled' kale seedlings at 18 days after sowing.

		Fresh Weight (g) of Kale Seedlings			
		Sealing Duration			
MSM	**Rate**	**1 Day**	**3 Days**	**5 Days**	**7 Days**
IdaGold	**0.0 g/m^2**	0.52 ± 0.04	0.50 ± 0.03	0.54 ± 0.02	0.48 ± 0.03
	88 g/m^2	0.30 ± 0.12	0.30 ± 0.12	0.15 ± 0.07	0.11 ± 0.03
	176 g/m^2	0.05 ± 0.01	0.05 ± 0.03	0.05 ± 0.04	0.04 ± 0.03
	265 g/m^2	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.01
Pacific Gold	**0.0 g/m^2**	0.62 ± 0.03	0.55 ± 0.06	0.49 ± 0.01	0.46 ± 0.07
	88 g/m^2	0.72 ± 0.13	0.58 ± 0.13	0.26 ± 0.08	0.22 ± 0.09
	176 g/m^2	0.49 ± 0.12	0.32 ± 0.20	0.20 ± 0.10	0.16 ± 0.09
	265 g/m^2	0.26 ± 0.12	0.37 ± 0.11	0.14 ± 0.07	0.10 ± 0.05

Figure 9. Effects of different types (I'- 'IdaGold' and P'- 'Pacific Gold') and rates (0 to 265 g/m^2) of mustard seed meal (MSM) and sealing durations (1 day, 3 days, 5 days, 7 days) on emergence percentage of 'Vates Blue Curled' kale seedlings at 4, 9 and 14 days after sowing (DAS). Bars represent standard error of EP at 14 DAS.



The effects of the interaction among three main factors (MSM type and rate and sealing duration) was not significant on EP, EI and FW of green seedlings (Table 47). The effects of the interaction between MSM type and sealing duration were not significant on EP and EI of green seedlings. Also, the effect of the interaction between MSM rate and sealing duration was not significant on FW of green seedlings, the effect of types of MSM was not significant on EI, and the effect of the interaction between type and rate was not significant on EP. All the other effects of interactions between the main factors and the main factor on EP, EI and FW of green seedlings were significant. When there was no MSM incorporated into the germination mix, sealing durations did not affect EP at 14 DAS, EI or FW of green seedlings (Tables 48 and 49, Figure 10). At 88 g/m^2 of MSM, the EP at 14 DAS of green seedlings was 37.5 percentage points lower in 'IdaGold' than 'Pacific Gold' when sealed for 7 days, while there was no difference in EP at 14 DAS between two MSM types when sealed for 1, 3 and 5 days, and there was no difference in EP at 14 DAS among all sealing durations (Figure 10). At 88 g/m^2, there was no difference in EI of green seedlings between two MSM types under all sealing durations, but EI was up to 93.7 percentage points lower when sealed for 3, 5 and 7 days than 1 day under both MSM types (Table 48). At 176 g/m^2 of MSM, there was no difference in EP at 14 DAS and EI of green seedlings between 'IdaGold' and 'Pacific Gold' under the same sealing durations, and there was no difference in EP at 14 DAS among sealing durations under the same type of MSM (Table 48 and Figure 10). The EP at 14 DAS and EI of green seedlings were zero when sealed with 265 g/m^2 of MSM for 3, 5 and 7 days and there was no difference in EP at 14 DAS between two MSM types when sealed for 1 day. The FW of green seedlings was 0.57 and 0.23 g (91.9 and 95.8%) lower when sealed with 88 and 176 g/m^2 of ‘IdaGold’ than ‘Pacific Gold’ for 1 day, respectively, and there was no difference in FW between ‘IdaGold’ and ‘Pacific Gold’ at 88 and 176 g/m^2 when sealed for 3, 5 and 7 days and 265 g/m^2 under all sealing durations (Table 49). There was no difference in the FW of green seedlings among all sealing durations under the same MSM type and rate.

Table 47. ANOVA of emergence percentage (EP), emergence index (EI) and seedlings fresh weight (FW) of ‘Mizuna’ green seedlings exposed to different types (‘IdaGold’ and ‘Pacific Gold’) and rates (0 to 265 g/m^2) of mustard seed meal (MSM) and sealing durations (1 day, 3 days, 5 days, 7 days).

Source	**EP**	**EI**	**FW**
	Pr > F	**Pr > F**	**Pr > F**
Rate	<.0001	<.0001	<.0001
Sealing Duration	<.0001	<.0001	<.0001
Type	0.0024	0.3853	<.0001
Type*Rate	0.5758	0.0225	<.0001
Rate*Sealing Duration	<.0001	0.0019	0.499
Type*Sealing Duration	0.4833	0.5217	0.0005
Type*Rate*Sealing Duration	0.3322	0.2491	0.1442

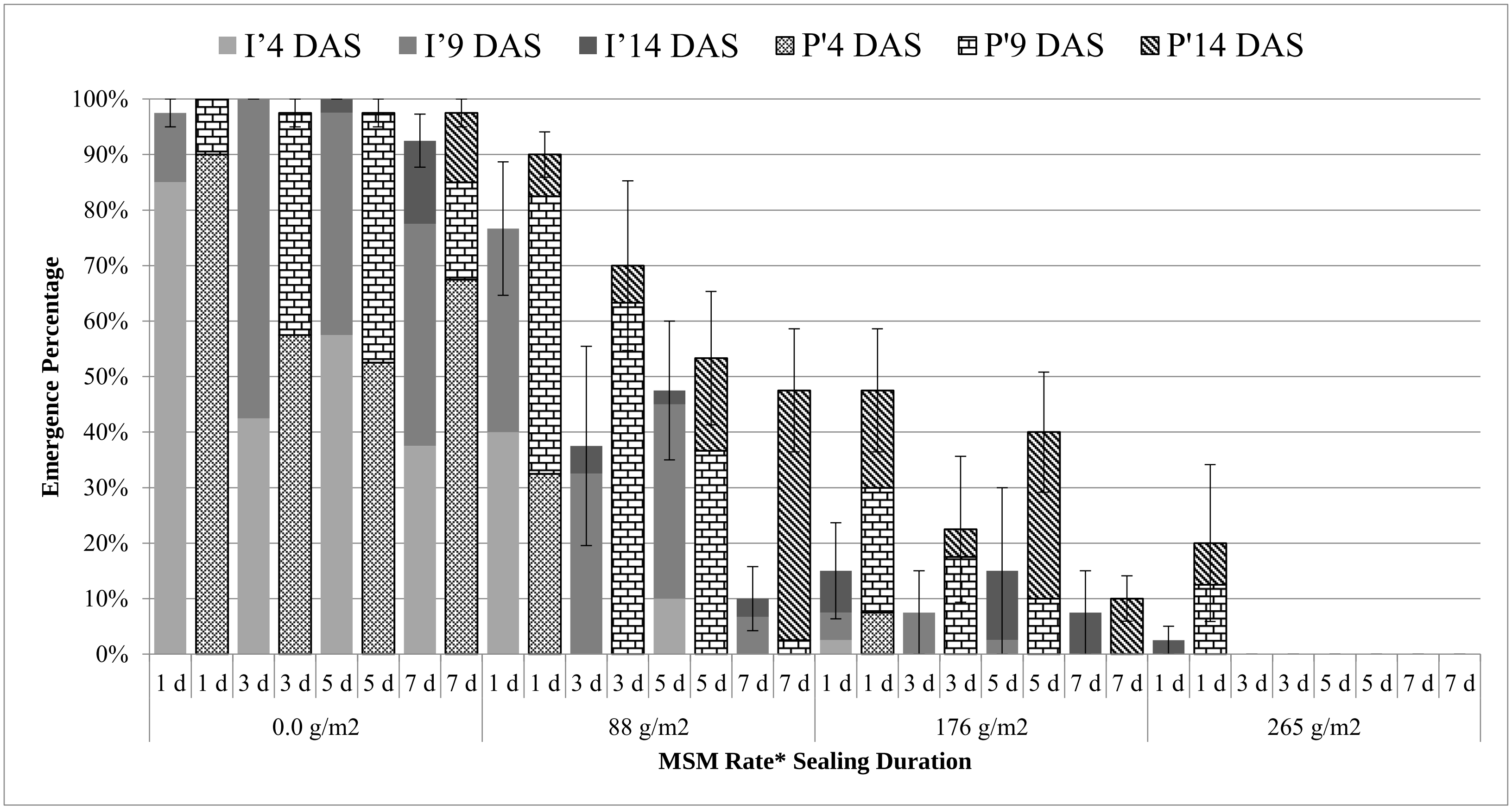
Table 48. Effects of different types ('IdaGold' and 'Pacific Gold') and rates (0 to 265 g/m^2) of mustard seed meal (MSM) and sealing durations (1 day, 3 days, 5 days, 7 days) on emergence index (± standard error) of 'Mizuna' green seedlings at 14 days after sowing.

		Emergence Index (%) of 'Mizuna' Seedlings			
		Sealing Duration			
MSM	**Rate**	**1 Day**	**3 Days**	**5 Days**	**7 Days**
IdaGold	**0.0 g/m^2**	153.3± 6.9	130.5 ± 4.7	134.5 ± 6.2	105.2 ± 18.3
	88 g/m^2	95.6 ± 16.2	27.2 ± 12.5	37.9 ± 11.3	7.3 ± 5.5
	176 g/m^2	12.5 ± 6.9	6.2 ± 4.8	3.2 ± 2.0	1.4 ± 0.9
	265 g/m^2	0.8 ± 0.8	0.0	0.0	0.0
Pacific Gold	**0.0 g/m^2**	153.0± 2.3	146.3 ± 17.2	134.7 ± 17.1	136.7 ± 14.5
	88 g/m^2	105.4 ± 13.8	50.9 ± 8.5	26.8 ± 5.6	11.7 ± 5.5
	176 g/m^2	35.2 ± 16.9	12.9 ± 7.5	14.8 ± 4.8	0.9 ± 0.3
	265 g/m^2	9.7 ± 7.7	0.0	0.0	0.0

Table 49. 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 day, 3 days, 5 days, 7 days) on fresh weight (± standard error) of 'Mizuna' green seedlings at 18 days after sowing.

		Fresh Weight (g) of 'Mizuna' Seedlings			
		Sealing Duration			
MSM	**Rate**	**1 Day**	**3 Days**	**5 Days**	**7 Days**
IdaGold	**0.0 g/m^2**	0.55 ± 0.09	0.61 ± 0.07	0.59 ± 0.08	0.50 ± 0.03
	88 g/m^2	0.05 ± 0.03	0.07 ± 0.06	0.06 ± 0.03	0.02 ± 0.02
	176 g/m^2	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.01
	265 g/m^2	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Pacific Gold	**0.0 g/m^2**	0.67 ± 0.06	0.56 ± 0.04	0.60 ± 0.03	0.62 ± 0.05
	88 g/m^2	0.62 ± 0.06	0.35 ± 0.16	0.24 ± 0.09	0.24 ± 0.10
	176 g/m^2	0.24 ± 0.07	0.08 ± 0.04	0.14 ± 0.03	0.03 ± 0.00
	265 g/m^2	0.04 ± 0.02	0.03 ± 0.03	0.00 ± 0.00	0.00 ± 0.00

Figure 10. Effects of different types (I'- 'IdaGold' and P'- 'Pacific Gold') and rates (0 to 265 g/m^2) of mustard seed meal (MSM) and sealing durations (1 day, 3 days, 5 days, 7 days) on emergence percentage of 'Mizuna' green seedlings at 4, 9 and 14 days after sowing (DAS). Bars represent standard error of EP at 14 DAS.



The effects of the interaction among three main factors (the types, rates of MSM and sealing durations) was not significant on EP, EI and FW of mustard seedlings (Table 50). The effects of MSM type was not significant on EP and EI of mustard seedlings. Also, the effect of the interaction between MSM rate and sealing duration was not significant on FW of mustard seedlings. All the other effects of interactions between the main factors and the main factors on EP, EI and FW of mustard seedlings were significant. When there was no MSM incorporated into the germination mix, sealing durations did not affect EP at 14 DAS, EI or FW of mustard seedlings (Tables 51 and 52, Figure 11). At 88 g/m^2, there was no difference in EP at 14 DAS and EI of mustard seedlings among all sealing durations in petri dishes containing 'IdaGold', but EP at 14 DAS and EI were up to 102.1 percentage points lower when sealed with 'Pacific Gold' for 3, 5 and 7 days than for 1 day (Table 51 and Figure 11). Also, there was no difference in EP at 14 DAS and EI of mustard seedlings between 88 g/m^2 of 'IdaGold' and 'Pacific Gold' under all sealing durations. At 176 g/m^2, there was no difference in EP at 14 DAS of mustard seedlings among all sealing durations and there was no difference in EP at 14 DAS between 'IdaGold' and 'Pacific Gold' under all sealing durations (Figure 11). However, the EI of mustard seedlings was lower up to 82.3 percentage points when sealed with 176 g/m^2 of 'IdaGold' and 'Pacific Gold' for 3, 5 and 7 days than for 1 day, while there was no difference in EI between 'IdaGold' and 'Pacific Gold' at 176 g/m^2 when sealed for 1, 5 and 7 days, the exception being 3 days (Table 51). At 265 g/m^2, there was no difference in EP at 14 DAS and EI of mustard seedlings among all sealing durations and there was no difference in EP at 14 DAS and EI between 'IdaGold' and 'Pacific Gold' under all sealing durations (Table 51 and Figure 11).

Under the same MSM type, there was no difference in FW of mustard seedlings among all sealing durations at 88, 176 and 265 g/m^2 (Table 52). The FW of mustard seedlings was up to 0.48 g (84.2%) lower in 'IdaGold' than 'Pacific Gold' at 88 g/m^2 when sealed for 1 day, at 176 g/m^2 when sealed for 1 and 3 days and at 265 g/m^2 when sealed for 1, 3, 5 and 7 days, respectively.

Table 50. ANOVA of emergence percentage (EP), emergence index (EI) and seedlings fresh weight (FW) of 'Green Wave' mustard seedlings exposed to different types ('IdaGold' and 'Pacific Gold') and rates (0 to 265 g/m^2) of mustard seed meal (MSM) and sealing durations (1 day, 3 days, 5 days, 7 days).

Source	**EP**	**EI**	**FW**
	Pr > F	**Pr > F**	**Pr > F**
Rate	<.0001	<.0001	<.0001
Sealing Duration	<.0001	<.0001	<.0001
Type	0.6798	0.3853	<.0001
Type*Rate	0.0154	0.0225	<.0001
Rate*Sealing Duration	0.0025	0.0019	0.499
Type*Sealing Duration	0.216	0.5217	0.0005
Type*Rate*Sealing Duration	0.4073	0.2491	0.1442

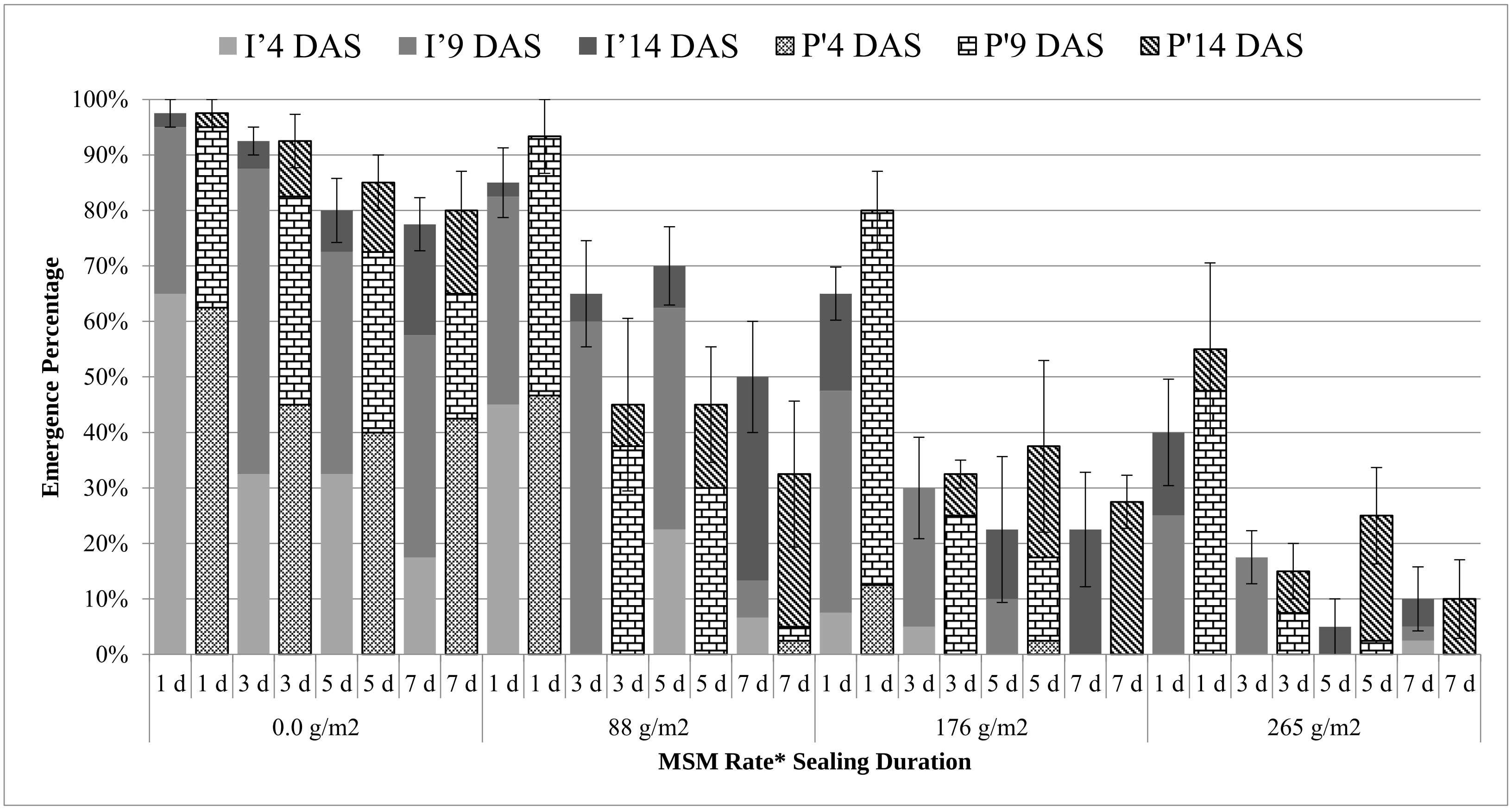
Table 51. Effects of different types ('IdaGold' and 'Pacific Gold') and rates (0 to 265 g/m^2) of mustard seed meal (MSM) and sealing durations (1 day, 3 days, 5 days, 7 days) on emergence index (± standard error) of 'Green Wave' mustard seedlings at 14 days after sowing.

		Emergence Index (%) of 'Green Wave' Seedlings			
		Sealing Duration			
MSM	**Rate**	**1 Day**	**3 Days**	**5 Days**	**7 Days**
IdaGold	**0.0 g/m^2**	138.9 ± 12.2	109.9 ± 6.9	94.1 ± 5.9	69.8 ± 4.2
	88 g/m^2	112.1 ± 12.2	52.1 ± 7.1	66.7 ± 25.2	29.7 ± 13.3
	176 g/m^2	67.9 ± 8.0	26.8 ± 6.1	10.4 ± 4.8	4.8 ± 2.2
	265 g/m^2	32.2 ± 10.9	12.7 ± 1.1	1.9 ± 1.9	9.1 ± 6.3
Pacific Gold	**0.0 g/m^2**	125.5 ± 5.5	111.3 ± 17.8	93.2 ± 8.0	95.3 ± 20.3
	88 g/m^2	115.2 ± 6.7	31.2 ± 10.1	22.1 ± 0.04	13.1 ± 5.5
	176 g/m^2	87.7 ± 13.0	20.1 ± 1.5	19.5 ± 7.1	5.4 ± 2.1
	265 g/m^2	41.1 ± 15.2	6.7 ± 2.5	9.4 ± 4.3	1.7 ± 1.5

Table 52. 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 day, 3 days, 5 days, 7 days) on fresh weight (± standard error) of 'Green Wave' mustard seedlings at 18 days after sowing.

		Fresh Weight (g) of 'Green Wave' Seedlings			
		Sealing Duration			
MSM	**Rate**	**1 Day**	**3 Days**	**5 Days**	**7 Days**
IdaGold	**0.0 g/m^2**	0.45 ± 0.07	0.40 ± 0.02	0.38 ± 0.04	0.33 ± 0.03
	88 g/m^2	0.09 ± 0.05	0.06 ± 0.04	0.10 ± 0.07	0.03 ± 0.01
	176 g/m^2	0.00 ± 0.00	0.00 ± 0.00	0.02 ± 0.02	0.02 ± 0.01
	265 g/m^2	0.01 ± 0.00	0.01 ± 0.01	0.00 ± 0.00	0.01 ± 0.00
Pacific Gold	**0.0 g/m^2**	0.44 ± 0.04	0.40 ± 0.05	0.38 ± 0.03	0.40 ± 0.03
	88 g/m^2	0.57 ± 0.13	0.28 ± 0.08	0.28 ± 0.11	0.19 ± 0.08
	176 g/m^2	0.47 ± 0.12	0.14 ± 0.03	0.13 ± 0.07	0.10 ± 0.04
	265 g/m^2	0.17 ± 0.07	0.04 ± 0.00	0.04 ± 0.01	0.03 ± 0.02

Figure 11. Effects of different types (I'- 'IdaGold' and P'- 'Pacific Gold') and rates (0 to 265 g/m^2) of mustard seed meal (MSM) and sealing durations (1 day, 3 days, 5 days, 7 days) on emergence percentage of 'Green Wave' mustard seedlings at 4, 9 and 14 days after sowing (DAS). Bars represent standard error of EP at 14 DAS.



The EP at 14 DAS, EI and FW of kale seedlings were significantly ($P < 0.01$) correlated with MSM rate under combination of 'IdaGold' and sealing duration (Tables 53, 54 and 55). For 'Pacific Gold', EP at 14 DAS of kale seedlings when sealed for 3 day and FW of kale seedlings when sealed for 1 and 3 days were not significantly correlated with MSM rate. However, EP at 14 DAS and the FW of kale seedlings under the other combinations of 'Pacific Gold' and sealing duration, and EI under combination of 'Pacific Gold' and sealing duration combinations were significantly ($P < 0.01$) correlated with MSM rate. The significant linear, quadratic and cubic correlation indicated that increasing MSM rate under each combination of MSM type and sealing duration decreased EP at 14 DAS, EI and the FW of kale seedlings. EP at 14 DAS, EI and the FW of green and mustard seedlings were significantly correlated ($P < 0.01$) with MSM rate under each combination of MSM type and sealing duration (Tables 56, 57 and 58; Tables 59, 60 and 61). The significant linear, quadratic and cubic correlation indicated that increasing MSM rate under each combination of MSM type and sealing duration decreased EP at 14 DAS, EI and the FW of green and mustard seedlings. The EP at 4 and 9 DAS showed similar trends as the EP at 14 DAS (Figures 9, 10 and 11).

Table 53. Regression analysis of emergence percentage at 14 DAS of 'Vates Blue Curled' kale seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealing durations (1 day, 3 days, 5 days or 7 days).

Regression Analysis of Emergence Percentage at 14 DAS				
	Model		**P-value**	**R-Square**
IdaGold Sealed 1 Day	**Linear**	$Y=1.12-0.57X$	<.0001	0.8299
	Quadratic	$Y=1.02+0.03X-0.4X^2$	<.0001	0.9116
	Cubic	$Y=1+0.5X-1.3X^2+0.4X^3$	<.0001	0.9208
IdaGold Sealed 3 Days	**Linear**	$Y=1.06-0.62X$	<.0001	0.8733
	Quadratic	$Y=1.03-0.41X+-0.14X^2$	<.0001	0.8813
	Cubic	$Y=1+0.72X-2.32X^2+0.97X^3$	<.0001	0.919
IdaGold Sealed 5 Days	**Linear**	$Y=0.97-0.59X$	<.0001	0.778
	Quadratic	$Y=1.03-0.96X+0.25X^2$	<.0001	0.8039
	Cubic	$Y=1+0.05X-1.75X^2+0.9X^3$	0.0001	0.8403
IdaGold Sealed 7 Days	**Linear**	$Y=0.86-0.57X$	<.0001	0.7924
	Quadratic	$Y=0.95-1.13X+0.38X^2$	<.0001	0.8622
	Cubic	$Y=0.93-0.38X-1.05X^2+0.63X^3$	<.0001	0.8846
Pacific Gold Sealed 1 Day	**Linear**	$Y=1.01-0.36X$	0.0022	0.5003
	Quadratic	$Y=0.98-0.17X-0.13X^2$	0.0093	0.5128
	Cubic	$Y=1-0.83X+1.15X^2-0.57X^3$	0.0212	0.5414
Pacific Gold Sealed 3 Days	**Linear**	$Y=0.98-0.31X$	0.0225	0.3634
	Quadratic	$Y=1.02-0.58X+0.19X^2$	0.066	0.3899
	Cubic	$Y=1+0.23X-1.43X^2+0.73X^3$	0.1123	0.4359
Pacific Gold Sealed 5 Days	**Linear**	$Y=0.89-0.39X$	0.0043	0.4778
	Quadratic	$Y=0.98-0.95X+0.38X^2$	0.0071	0.5618
	Cubic	$Y=0.98-0.91X+0.3X^2+0.03X^3$	0.0239	0.5619
Pacific Gold Sealed 7 Days	**Linear**	$Y=0.72-0.37X$	0.0065	0.4218
	Quadratic	$Y=0.84-1.08X+0.48X^2$	0.0045	0.5646
	Cubic	$Y=0.85-1.51X+1.3X^2-0.37X^3$	0.0139	0.5742

Table 54. Regression analysis of emergence index of 'Vates Blue Curled' kale seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealing durations (1 day, 3 days, 5 days or 7 days).

Regression Analysis of Emergence Index				
	Model		**P-value**	**R-Square**
IdaGold Sealed 1 Day	**Linear**	$Y=1.57-0.95X$	<.0001	0.8918
	Quadratic	$Y=1.53-0.69X-0.17X^2$	<.0001	0.8976
	Cubic	$Y=1.51-0.06X-1.39X^2+0.54X^3$	<.0001	0.9042
IdaGold Sealed 3 Days	**Linear**	$Y=1.27-0.82X$	<.0001	0.7731
	Quadratic	$Y=1.31-1.08X+0.17X^2$	0.0002	0.7789
	Cubic	$Y=1.27+0.36X-2.62X^2+1.24X^3$	0.0006	0.81
IdaGold Sealed 5 Days	**Linear**	$Y=1.14-0.82X$	<.0001	0.7767
	Quadratic	$Y=1.31-1.86X+0.69X^2$	<.0001	0.8804
	Cubic	$Y=1.31-1.84X+0.64X^2+0.02X^3$	<.0001	0.8804
IdaGold Sealed 7 Days	**Linear**	$Y=0.74-0.55X$	0.0002	0.6333
	Quadratic	$Y=0.85-1.24X+0.46X^2$	0.0002	0.7237
	Cubic	$Y=0.84-0.92X-0.16X^2+0.28X^3$	0.0011	0.7274
Pacific Gold Sealed 1 Day	**Linear**	$Y=1.46-0.81X$	<.0001	0.8381
	Quadratic	$Y=1.52-1.15X+0.23X^2$	<.0001	0.8511
	Cubic	$Y=1.53-1.6X+1.09X^2-0.39X^3$	<.0001	0.8554
Pacific Gold Sealed 3 Days	**Linear**	$Y=1.03-0.62X$	0.0011	0.6001
	Quadratic	$Y=1.19-1.64X+0.69X^2$	0.0005	0.7503
	Cubic	$Y=1.2-2.07X+1.54X^2-0.39X^3$	0.0021	0.7555
Pacific Gold Sealed 5 Days	**Linear**	$Y=0.91-0.66X$	0.0001	0.6994
	Quadratic	$Y=1.1-1.92X+0.85X^2$	<.0001	0.9175
	Cubic	$Y=1.13-2.92X+2.72X^2-0.82X^3$	<.0001	0.9388
Pacific Gold Sealed 7 Days	**Linear**	$Y=0.75-0.6X$	0.002	0.5047
	Quadratic	$Y=0.97-1.88X+0.86X^2$	0.0003	0.711
	Cubic	$Y=1-2.85X+2.7X^2-0.82X^3$	0.0009	0.7323

Table 55. Regression analysis of fresh weight of 'Vates Blue Curled' kale seedlings under in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealing durations (1 day, 3 days, 5 days or 7 days).

Regression Analysis of Fresh Weight				
	Model		**P-value**	**R-Square**
IdaGold Sealed 1 Day	**Linear**	$Y=0.48-0.35X$	<.0001	0.7387
	Quadratic	$Y=0.53-0.61X+0.17X^2$	<.0001	0.773
	Cubic	$Y=0.52-0.22X-0.57X^2+0.33X^3$	0.0002	0.7872
IdaGold Sealed 3 Days	**Linear**	$Y=0.47-0.34X$	<.0001	0.7007
	Quadratic	$Y=0.51-0.59X+0.17X^2$	0.0002	0.7344
	Cubic	$Y=0.5-0.17X-0.65X^2+0.36X^3$	0.0006	0.7523
IdaGold Sealed 5 Days	**Linear**	$Y=0.44-0.34X$	<.0001	0.7259
	Quadratic	$Y=0.53-0.86X+0.35X^2$	<.0001	0.8835
	Cubic	$Y=0.54-1.23X+1.06X^2-0.31X^3$	<.0001	0.8977
IdaGold Sealed 7 Days	**Linear**	$Y=0.38-0.3X$	<.0001	0.7298
	Quadratic	$Y=0.47-0.81X+0.34X^2$	<.0001	0.9246
	Cubic	$Y=0.48-1.21X+1.1X^2-0.34X^3$	<.0001	0.9457
Pacific Gold Sealed 1 Day	**Linear**	$Y=0.71-0.26X$	0.0201	0.3295
	Quadratic	$Y=0.63+0.23X-0.33X^2$	0.0247	0.434
	Cubic	$Y=0.62+0.73X-1.29X^2+0.43X^3$	0.0564	0.4543
Pacific Gold Sealed 3 Days	**Linear**	$Y=0.58-0.16X$	0.1864	0.1212
	Quadratic	$Y=0.58-0.2X+0.03X^2$	0.43	0.1218
	Cubic	$Y=0.55+0.75X-1.81X^2+0.81X^3$	0.4556	0.1888
Pacific Gold Sealed 5 Days	**Linear**	$Y=0.44-0.22X$	0.005	0.4419
	Quadratic	$Y=0.48-0.46X+0.16X^2$	0.0124	0.4907
	Cubic	$Y=0.49-0.73X+0.68X^2-0.23X^3$	0.0339	0.5018
Pacific Gold Sealed 7 Days	**Linear**	$Y=0.41-0.23X$	0.0042	0.454
	Quadratic	$Y=0.45-0.5X+0.18X^2$	0.0097	0.5096
	Cubic	$Y=0.46-0.77X+0.71X^2-0.23X^3$	0.0274	0.5201

Table 56. Regression analysis of emergence percentage at 14 DAS of 'Mizuna' green seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealing durations (1 day, 3 days, 5 days or 7 days).

Regression Analysis of Emergence Percentage at 14 DAS				
	Model		**P-value**	**R-Square**
IdaGold Sealed 1 Day	**Linear**	Y=0.99-0.69X	<.0001	0.8705
	Quadratic	$Y=1.01-0.87X+0.12X^2$	<.0001	0.8757
	Cubic	$Y=0.98+0.59X-2.62X^2+1.2X^3$	<.0001	0.9284
IdaGold Sealed 3 Days	**Linear**	Y=0.86-0.66X	<.0001	0.7414
	Quadratic	$Y=1-1.49X+0.55X^2$	<.0001	0.8444
	Cubic	$Y=1-1.64X+0.85X^2-0.13X^3$	<.0001	0.8451
IdaGold Sealed 5 Days	**Linear**	Y=0.91-0.67X	<.0001	0.7871
	Quadratic	$Y=1-1.23X+0.38X^2$	<.0001	0.8371
	Cubic	$Y=1-1.27X+0.45X^2-0.03X^3$	<.0001	0.8372
IdaGold Sealed 7 Days	**Linear**	Y=0.73-0.58X	0.0001	0.6968
	Quadratic	$Y=0.89-1.64X+0.71X^2$	<.0001	0.8979
	Cubic	$Y=0.93-3.02X+3.3X^2-1.13X^3$	<.0001	0.9512
Pacific Gold Sealed 1 Day	**Linear**	Y=1.07-0.57X	<.0001	0.7676
	Quadratic	$Y=1.02-0.3X-0.18X^2$	<.0001	0.7823
	Cubic	$Y=1+0.44X-1.6X^2+0.63X^3$	0.0002	0.804
Pacific Gold Sealed 3 Days	**Linear**	Y=0.98-0.68X	<.0001	0.8382
	Quadratic	$Y=0.99-0.77X+0.06X^2$	<.0001	0.8396
	Cubic	$Y=0.98-0.05X-1.3X^2+0.6X^3$	0.0002	0.8539
Pacific Gold Sealed 5 Days	**Linear**	Y=0.95-0.62X	<.0001	0.8654
	Quadratic	$Y=0.95-0.64X+0.02X^2$	<.0001	0.8656
	Cubic	$Y=0.98-1.58X+1.77X^2-0.77X^3$	<.0001	0.8921
Pacific Gold Sealed 7 Days	**Linear**	Y=0.88-0.66X	<.0001	0.8651
	Quadratic	$Y=0.98-1.26X+0.4X^2$	<.0001	0.9287
	Cubic	$Y=0.98-1.03X-0.05X^2+0.2X^3$	<.0001	0.9305

Table 57. Regression analysis of emergence index of 'Mizuna' green seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealing durations (1 day, 3 days, 5 days or 7 days).

Regression Analysis of Emergence Index				
	Model		**P-value**	**R-Square**
IdaGold Sealed 1 Day	**Linear**	Y=1.46-1.08X	<.0001	0.8954
	Quadratic	$Y=1.58-1.83X+0.5X^2$	<.0001	0.932
	Cubic	$Y=1.53-0.25X-2.45X^2+1.29X^3$	<.0001	0.9574
IdaGold Sealed 3 Days	**Linear**	Y=1.03-0.83X	<.0001	0.7269
	Quadratic	$Y=1.27-2.28X+0.97X^2$	<.0001	0.9285
	Cubic	$Y=1.31-3.34X+3X^2-0.9X^3$	<.0001	0.9481
IdaGold Sealed 5 Days	**Linear**	Y=1.1-0.88X	<.0001	0.7782
	Quadratic	$Y=1.33-2.28X+0.93X^2$	<.0001	0.955
	Cubic	$Y=1.35-2.75X+1.85X^2-0.4X^3$	<.0001	0.9588
IdaGold Sealed 7 Days	**Linear**	Y=0.81-0.66X	0.0005	0.6157
	Quadratic	$Y=1.01-2.04X+0.93X^2$	<.0001	0.8433
	Cubic	$Y=1.05-3.46X+3.59X^2-1.16X^3$	<.0001	0.881
Pacific Gold Sealed 1 Day	**Linear**	Y=1.51-1X	<.0001	0.8637
	Quadratic	$Y=1.56-1.33X+0.22X^2$	<.0001	0.8722
	Cubic	$Y=1.53-0.28X-1.8X^2+0.9X^3$	<.0001	0.8878
Pacific Gold Sealed 3 Days	**Linear**	Y=1.28-1X	<.0001	0.8048
	Quadratic	$Y=1.45-2.18X+0.82X^2$	<.0001	0.9104
	Cubic	$Y=1.46-2.7X+1.8X^2-0.43X^3$	<.0001	0.9137
Pacific Gold Sealed 5 Days	**Linear**	Y=1.11-0.85X	<.0001	0.7333
	Quadratic	$Y=1.3-2.17X+0.89X^2$	<.0001	0.8839
	Cubic	$Y=1.35-3.78X+3.89X^2-1.32X^3$	<.0001	0.9185
Pacific Gold Sealed 7 Days	**Linear**	Y=1-0.84X	0.0002	0.6339
	Quadratic	$Y=1.32-2.7X+1.24X^2$	<.0001	0.9093
	Cubic	$Y=1.37-4.34X+4.37X^2-1.39X^3$	<.0001	0.9481

Table 58. Regression analysis of fresh weight of 'Mizuna' green seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealing durations (1 day, 3 days, 5 days or 7 days).

Regression Analysis of Fresh Weight				
	Model		**P-value**	**R-Square**
IdaGold Sealed 1 Day	**Linear**	$Y=0.4-0.34X$	0.0005	0.5965
	Quadratic	$Y=0.53-1.08X+0.5X^2$	<.0001	0.8573
	Cubic	$Y=0.55-1.75X+1.78X^2-0.57X^3$	<.0001	0.8958
IdaGold Sealed 3 Days	**Linear**	$Y=0.45-0.38X$	0.0002	0.6316
	Quadratic	$Y=0.58-1.17X+0.53X^2$	<.0001	0.8808
	Cubic	$Y=0.61-1.82X+1.78X^2-0.56X^3$	<.0001	0.9121
IdaGold Sealed 5 Days	**Linear**	$Y=0.43-0.36X$	0.0003	0.6178
	Quadratic	$Y=0.57-1.15X+0.53X^2$	<.0001	0.8795
	Cubic	$Y=0.59-1.84X+1.84X^2-0.58X^3$	<.0001	0.9155
IdaGold Sealed 7 Days	**Linear**	$Y=0.36-0.3X$	0.0003	0.6156
	Quadratic	$Y=0.48-1.02X+0.48X^2$	<.0001	0.9184
	Cubic	$Y=0.5-1.74X+1.85X^2-0.61X^3$	<.0001	0.974
Pacific Gold Sealed 1 Day	**Linear**	$Y=0.73-0.45X$	<.0001	0.8255
	Quadratic	$Y=0.7-0.25X-0.14X^2$	<.0001	0.8401
	Cubic	$Y=0.67+0.55X-1.67X^2+0.68X^3$	<.0001	0.8818
Pacific Gold Sealed 3 Days	**Linear**	$Y=0.53-0.37X$	0.0002	0.64
	Quadratic	$Y=0.57-0.61X+0.16X^2$	0.0009	0.6627
	Cubic	$Y=0.56-0.21X-0.6X^2+0.34X^3$	0.003	0.6744
Pacific Gold Sealed 5 Days	**Linear**	$Y=0.53-0.38X$	<.0001	0.7869
	Quadratic	$Y=0.58-0.7X+0.22X^2$	<.0001	0.8394
	Cubic	$Y=0.6-1.18X+1.13X^2-0.4X^3$	<.0001	0.8597
Pacific Gold Sealed 7 Days	**Linear**	$Y=0.53-0.41X$	<.0001	0.7492
	Quadratic	$Y=0.62-0.95X+0.36X^2$	<.0001	0.8625
	Cubic	$Y=0.62-0.94X+0.33X^2+0.01X^3$	<.0001	0.8626

Table 59. Regression analysis of emergence percentage at 14 DAS of 'Green Wave' mustard seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealing durations (1 day, 3 days, 5 days or 7 days).

Regression Analysis of Emergence Percentage at 14 DAS				
	Model		**P-value**	**R-Square**
IdaGold Sealed 1 Day	**Linear**	$Y=1.01-0.51X$	<.0001	0.8533
	Quadratic	$Y=0.99-0.39X-0.08X^2$	<.0001	0.857
	Cubic	$Y=0.98+0.12X-1.05X^2+0.43X^3$	<.0001	0.8712
IdaGold Sealed 3 Days	**Linear**	$Y=0.9-0.52X$	<.0001	0.8256
	Quadratic	$Y=0.94-0.75X+0.15X^2$	<.0001	0.8394
	Cubic	$Y=0.93-0.28X-0.75X^2+0.4X^3$	<.0001	0.8504
IdaGold Sealed 5 Days	**Linear**	$Y=0.85-0.55X$	<.0001	0.7738
	Quadratic	$Y=0.83-0.43X-0.08X^2$	<.0001	0.7767
	Cubic	$Y=0.8+0.63X-2.1X^2+0.9X^3$	<.0001	0.8242
IdaGold Sealed 7 Days	**Linear**	$Y=0.75-0.46X$	<.0001	0.788
	Quadratic	$Y=0.78-0.69X+0.16X^2$	<.0001	0.8052
	Cubic	$Y=0.78-0.45X-0.3X^2+0.2X^3$	0.0003	0.8082
Pacific Gold Sealed 1 Day	**Linear**	$Y=1.02-0.28X$	0.0045	0.4747
	Quadratic	$Y=0.97+0.03X-0.21X^2$	0.0115	0.5252
	Cubic	$Y=0.98-0.01X-0.13X^2-0.03X^3$	0.0362	0.5253
Pacific Gold Sealed 3 Days	**Linear**	$Y=0.83-0.49X$	<.0001	0.7156
	Quadratic	$Y=0.91-0.94X+0.3X^2$	<.0001	0.7693
	Cubic	$Y=0.93-1.57X+1.5X^2-0.53X^3$	0.0002	0.7884
Pacific Gold Sealed 5 Days	**Linear**	$Y=0.76-0.38X$	0.0015	0.523
	Quadratic	$Y=0.83-0.79X+0.28X^2$	0.0036	0.5793
	Cubic	$Y=0.85-1.38X+1.4X^2-0.5X^3$	0.0097	0.6002
Pacific Gold Sealed 7 Days	**Linear**	$Y=0.7-0.43X$	0.0002	0.6465
	Quadratic	$Y=0.77-0.88X+0.3X^2$	0.0003	0.7094
	Cubic	$Y=0.8-1.74X+1.95X^2-0.73X^3$	0.0006	0.7517

Table 60. Regression analysis of emergence index of 'Green Wave' mustard seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealing durations (1 day, 3 days, 5 days or 7 days).

Regression Analysis of Emergence Index				
	Model		**P-value**	**R-Square**
IdaGold Sealed 1 Day	**Linear**	$Y=1.42-0.73X$	<.0001	0.8161
	Quadratic	$Y=1.4-0.6X-0.09X^2$	<.0001	0.8185
	Cubic	$Y=1.39-0.19X-0.87X^2+0.35X^3$	<.0001	0.8226
IdaGold Sealed 3 Days	**Linear**	$Y=0.98-0.63X$	<.0001	0.844
	Quadratic	$Y=1.09-1.29X+0.44X^2$	<.0001	0.9241
	Cubic	$Y=1.1-1.62X+1.07X^2-0.28X^3$	<.0001	0.9278
IdaGold Sealed 5 Days	**Linear**	$Y=0.93-0.67X$	<.0001	0.6913
	Quadratic	$Y=0.98-0.95X+0.19X^2$	0.0004	0.7024
	Cubic	$Y=0.94+0.25X-2.11X^2+1.02X^3$	0.0008	0.7392
IdaGold Sealed 7 Days	**Linear**	$Y=0.6-0.42X$	0.0001	0.6984
	Quadratic	$Y=0.7-1.09X+0.45X^2$	<.0001	0.851
	Cubic	$Y=0.7-0.86X+0.03X^2+0.19X^3$	<.0001	0.8537
Pacific Gold Sealed 1 Day	**Linear**	$Y=1.34-0.56X$	0.0001	0.696
	Quadratic	$Y=1.25-0.02X+-0.36X^2$	0.0002	0.752
	Cubic	$Y=1.26-0.05X-0.3X^2-0.03X^3$	0.0012	0.752
Pacific Gold Sealed 3 Days	**Linear**	$Y=0.91-0.65X$	0.0001	0.6663
	Quadratic	$Y=1.08-1.65X+0.67X^2$	<.0001	0.8063
	Cubic	$Y=1.11-2.76X+2.8X^2-0.95X^3$	<.0001	0.8382
Pacific Gold Sealed 5 Days	**Linear**	$Y=0.74-0.51X$	0.0002	0.6358
	Quadratic	$Y=0.89-1.42X+0.61X^2$	<.0001	0.8192
	Cubic	$Y=0.93-2.61X+2.89X^2-1.01X^3$	<.0001	0.8761
Pacific Gold Sealed 7 Days	**Linear**	$Y=0.72-0.58X$	0.0007	0.5699
	Quadratic	$Y=0.92-1.75X+0.78X^2$	<.0001	0.7807
	Cubic	$Y=0.95-2.86X+2.9X^2-0.94X^3$	0.0001	0.8148

Table 61. Regression analysis of fresh weight of 'Green Wave' mustard seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealing durations (1 day, 3 days, 5 days or 7 days).

Regression Analysis of Fresh Weight				
	Model		**P-value**	**R-Square**
IdaGold Sealed 1 Day	**Linear**	$Y=0.35-0.29X$	0.0002	0.6425
	Quadratic	$Y=0.44-0.83X+0.36X^2$	<.0001	0.8475
	Cubic	$Y=0.45-1.1X+0.89X^2-0.23X^3$	<.0001	0.8572
IdaGold Sealed 3 Days	**Linear**	$Y=0.3-0.25X$	0.0001	0.6666
	Quadratic	$Y=0.39-0.76X+0.34X^2$	<.0001	0.9239
	Cubic	$Y=0.4-1.12X+1.03X^2-0.3X^3$	<.0001	0.9466
IdaGold Sealed 5 Days	**Linear**	$Y=0.31-0.24X$	0.0002	0.6417
	Quadratic	$Y=0.37-0.64X+0.27X^2$	<.0001	0.7966
	Cubic	$Y=0.38-0.84X+0.64X^2-0.16X^3$	0.0002	0.8031
IdaGold Sealed 7 Days	**Linear**	$Y=0.24-0.2X$	0.0003	0.6185
	Quadratic	$Y=0.32-0.64X+0.3X^2$	<.0001	0.9016
	Cubic	$Y=0.33-1.11X+1.2X^2-0.4X^3$	<.0001	0.9601
Pacific Gold Sealed 1 Day	**Linear**	$Y=0.55-0.19X$	0.0701	0.2155
	Quadratic	$Y=0.44+0.46X-0.43X^2$	0.0209	0.4484
	Cubic	$Y=0.44+0.5X-0.51X^2+0.03X^3$	0.0598	0.4486
Pacific Gold Sealed 3 Days	**Linear**	$Y=0.4-0.24X$	<.0001	0.7254
	Quadratic	$Y=0.4-0.28X+0.02X^2$	0.0002	0.7266
	Cubic	$Y=0.4-0.17X-0.18X^2+0.09X^3$	0.001	0.7289
Pacific Gold Sealed 5 Days	**Linear**	$Y=0.38-0.23X$	0.0009	0.56
	Quadratic	$Y=0.38-0.25X+0.01X^2$	0.0048	0.5604
	Cubic	$Y=0.38-0.08X-0.31X^2+0.14X^3$	0.0157	0.5652
Pacific Gold Sealed 7 Days	**Linear**	$Y=0.36-0.24X$	0.0001	0.6627
	Quadratic	$Y=0.39-0.45X+0.14X^2$	0.0003	0.7094
	Cubic	$Y=0.4-0.62X+0.47X^2-0.15X^3$	0.0014	0.7151

Mustard *Brassica juncea* 'Green Wave', kale *Brassica oleracea* 'Vates Blue Curled', green *Brassica rapa* 'Mizuna' all belong to the *Brassicaceae* family. Certain plants in the *Brassicaceae* family are known to possess allelopathic properties, and they can be used as cover crops in many different cropping systems (Haramoto and Gallandt, 2005). There are approximately twenty glucosinolates (GSLs) in *Brassica* species, with concentrations varying among species and also within different plant tissues (Kirkegaard and Sarwar, 1998). *B. oleracea* and *B. rapa* were reported containing 62.4 and 51.3 mmol/g glucosinolates in seeds (Matthaus and Luftmann, 2000), and *B. juncea* 'Pacific Gold' contained 109.9±3.0 mmol/g sinigrin (glucosinolate) (Zasada and Ferris, 2004). However, they had different responses to two types of MSM. For kale seedlings, 'IdaGold' and 'Pacific Gold' had almost the same suppressive effects on kale seedling emergence, however 'IdaGold' had greater phytotoxicity to kale seedlings and 'Pacific Gold' delayed emergence of seedlings (Tables 45 and 46, Figure 9). For green seedlings, 'IdaGold' had more suppressive effects than 'Pacific Gold' on seedling emergence, while sealing delayed but did not decrease emergence at the low rate (88 g/m^2) of MSM, and 'IdaGold' had greater phytotoxicity on green seedlings (Tables 48 and 49, Figure 10). For mustard seedlings, 'IdaGold' and 'Pacific Gold' had almost the same suppressive effects on mustard seedlings emergence, while sealing delayed emergence at low and medium rates (88 and 176 g/m^2) of MSM and decreased emergence at the high rate (265 g/m^2) of MSM, 'IdaGold' had greater phytotoxicity on mustard seedlings (Tables 51 and 52, Figure 11).

3.4.4 Effects of MSMs on Emergence of Two Lettuces (*Lactuca sativa* ‘Buttercrunch’ and ‘Black Seeded Simpson’) Seedlings in Petri Dishes

The effects of the interaction among three main factors (MSM type and rate and sealing duration), the effect the interaction between MSM type and sealing duration and the effect of the interaction between MSM type and rate were not significant on EP, EI and FW of ‘Buttercrunch’ seedlings. The effects of MSM type and sealing duration and the interaction between MSM rate and sealing duration were not significant on FW. All the other effects of interactions between the main factors and the main factor on EP, EI and FW of ‘Buttercrunch’ seedlings were significant (Table 62). When there was no MSM incorporated into the germination mix, sealing durations did not affect EP at 14 DAS, EI or FW of ‘Buttercrunch’ seedlings (Tables 63 and 64, Figure 12). The EP at 14 DAS, EI and FW of ‘Buttercrunch’ seedlings were zero when sealed with 176 g/m^2 of ‘IdaGold’ and ‘Pacific Gold’ for 7 days, 265 g/m^2 of ‘IdaGold’ for 5 days and 265 g/m^2 of ‘Pacific Gold’ for 1, 3, 5 and 7 days. Under the same MSM type, there was no difference in EP at 14 DAS and EI of ‘Buttercrunch’ seedlings among all sealing durations at 88, 176 and 265 g/m^2, respectively (Table 63 and Figure 12). There was also no difference in EP at 14 DAS and EI of ‘Buttercrunch’ seedlings between ‘IdaGold’ and ‘Pacific Gold’ under the same rate and sealing duration. Although EP at 14 DAS and EI of ‘Buttercrunch’ seedlings were not zero when sealed with 176 g/m^2 of ‘IdaGold’ for 1, 3 and 5 days and 265 g/m^2 of ‘Pacific Gold’ for 1, 3, and 7 days, the plants were too small to weigh (Tables 63 and 64, Figure 12). There was no difference in FW of ‘Buttercrunch’ seedlings among all sealing durations at 88 g/m^2 of ‘IdaGold’ and ‘Pacific Gold’, and at 176 g/m^2 of ‘Pacific Gold’ when sealed for 1, 3 and 5 days (Table 64). Besides, there was also no difference in FW of 'Buttercrunch' seedlings between 'IdaGold' and 'Pacific Gold' at 88 g/m^2 under all sealing durations.

Table 62. ANOVA of emergence percentage (EP), emergence index (EI) and seedlings fresh weight (FW) of 'Buttercrunch' lettuce seedlings exposed to different types ('IdaGold' and 'Pacific Gold') and rates (0 to 265 g/m^2) of mustard seed meal (MSM) and sealing durations (1 day, 3 days, 5 days, 7 days).

Source	**EP**	**EI**	**FW**
	Pr > F	**Pr > F**	**Pr > F**
Rate	<.0001	<.0001	<.0001
Sealing Duration	<.0001	<.0001	0.7592
Type	0.0287	0.0223	0.2111
Type*Rate	0.1157	0.2869	0.6288
Rate*Sealing Duration	0.0059	0.0183	0.1326
Type*Sealing Duration	0.8811	0.9761	0.2972
Type*Rate*Sealing Duration	0.8432	0.8514	0.9486

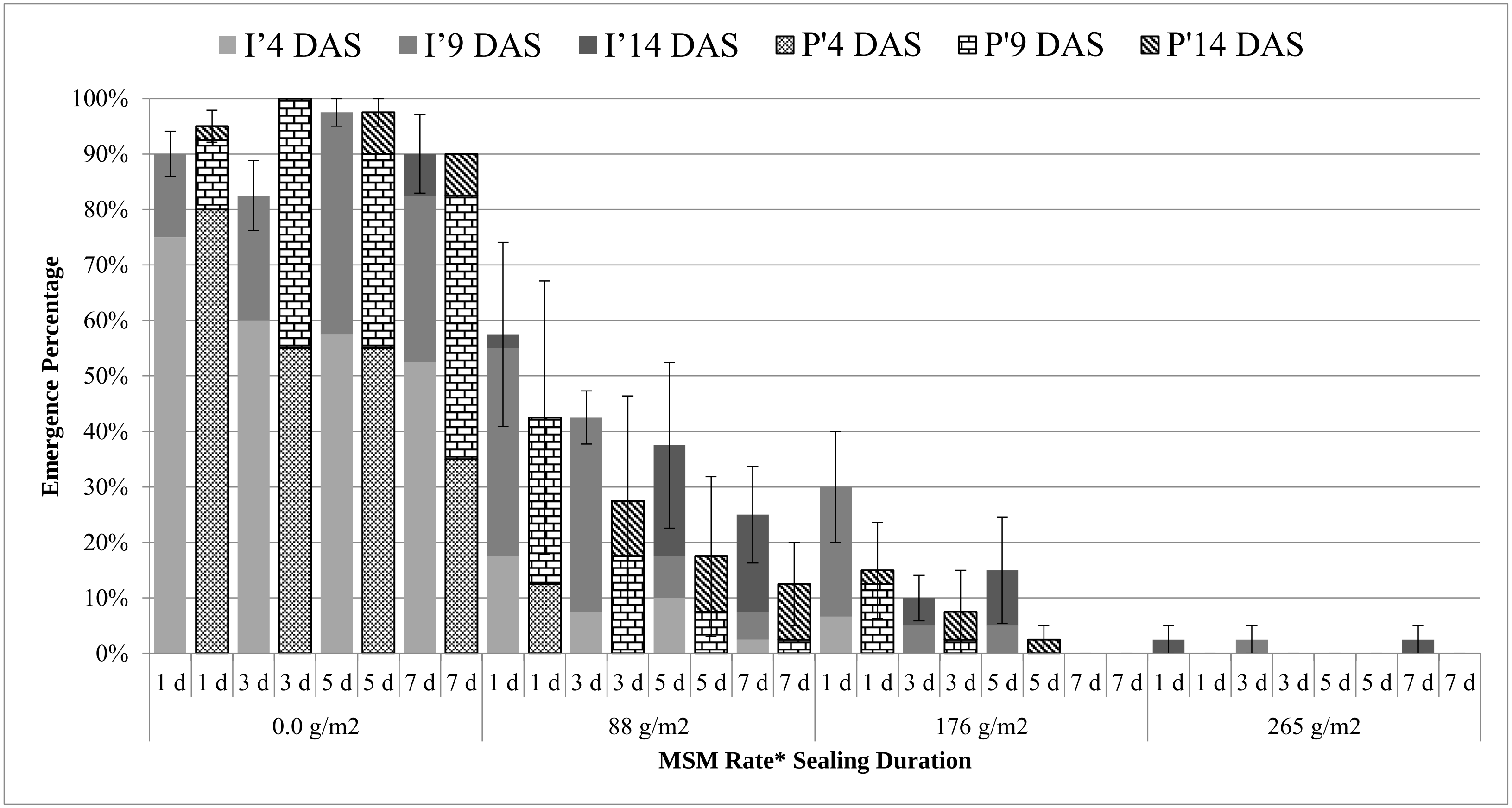
Table 63. Effects of different types ('IdaGold' and 'Pacific Gold') and rates (0 to 265 g/m^2) of mustard seed meal (MSM) and sealing durations (1 day, 3 days, 5 days, 7 days) on emergence index (± standard error) of 'Buttercrunch' lettuce seedlings at 14 days after sowing.

		Emergence Index (%) of 'Buttercrunch' Seedlings			
		Sealing Duration			
MSM	**Rate**	**1 Day**	**3 Days**	**5 Days**	**7 Days**
IdaGold	**0.0 g/m^2**	138.4± 10.0	129.4 ± 14.6	132.5 ± 7.1	122.4 ± 14.5
	88 g/m^2	66.4 ± 24.4	40.4 ± 11.6	27.0 ± 15.7	10.7 ± 4.8
	176 g/m^2	31.9 ± 14.4	5.7 ± 3.6	5.9 ± 3.9	0.0
	265 g/m^2	1.7 ± 1.7	2.5 ± 1.8	0.0	0.6 ± 0.6
Pacific Gold	**0.0 g/m^2**	141.6 ± 4.5	137.0 ± 11.7	125.4 ± 12.8	103.6 ± 10.1
	88 g/m^2	49.6 ± 29.6	17.4 ± 14.0	5.7 ± 5.5	3.1 ± 2.2
	176 g/m^2	8.9 ± 5.2	3.0 ± 3.0	0.4 ± 0.4	0.0
	265 g/m^2	0.0	0.0	0.0	0.0

Table 64. 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 day, 3 days, 5 days, 7 days) on fresh weight (± standard error) of 'Buttercrunch' lettuce seedlings at 18 days after sowing.

		Fresh Weight (g) of 'Buttercrunch' Seedlings			
		Sealing Duration			
MSM	**Rate**	**1 Day**	**3 Days**	**5 Days**	**7 Days**
IdaGold	**0.0 g/m^2**	0.36 ± 0.03	0.37 ± 0.04	0.40 ± 0.01	0.46 ± 0.04
	88 g/m^2	0.07 ± 0.04	0.06 ± 0.03	0.07 ± 0.04	0.02 ± 0.01
	176 g/m^2	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
	265 g/m^2	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Pacific Gold	**0.0 g/m^2**	0.38 ± 0.05	0.40 ± 0.04	0.39 ± 0.04	0.42 ± 0.05
	88 g/m^2	0.20 ± 0.12	0.11 ± 0.08	0.05 ± 0.05	0.03 ± 0.02
	176 g/m^2	0.05 ± 0.03	0.02 ± 0.02	0.01 ± 0.01	0.00 ± 0.00
	265 g/m^2	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00

Figure 12. Effects of different types (I'- 'IdaGold' and P'- 'Pacific Gold') and rates (0 to 265 g/m^2) of mustard seed meal (MSM) and sealing durations (1 day, 3 days, 5 days, 7 days) on emergence percentage of 'Buttercrunch' lettuce seedlings at 4, 9 and 14 days after sowing (DAS). Bars represent standard error of EP at 14 DAS.



The effects of the interaction among three main factors (MSM type and rate and sealing duration) and the interaction between MSM type and sealing duration were not significant on EP, EI and FW of ‘Black’ seedlings (Table 65). Also, the effects of MSM type and sealing durations and the interactions between MSM rate and sealing duration were not significant on FW of ‘Black’ seedlings. All the other effects of interactions between the main factors and the main factor on EP, EI and FW of ‘Black’ seedlings were significant. When there was no MSM incorporated into the germination mix, sealing durations did not affect EP at 14 days after sowing (DAS), EI or FW of ‘Black’ seedlings (Tables 66 and 67, Figure 13). At 88 g/m^2 of ‘IdaGold’, the EP at 14 DAS and EI of ‘Black’ seedlings were up to 102.7 percentage points lower when sealed for 3, 5 and 7 days than for 1 day, and there was no difference in EP at 14 DAS and EI at 88 g/m^2 of ‘Pacific Gold’ among all sealing durations (Table 66 and Figure 13). At 88 g/m^2, there was no difference in EP at 14 DAS of ‘Black’ seedlings between ‘IdaGold’ and ‘Pacific Gold’ when sealed for 1 and 3 days, while EP at 14 DAS was 29.2 percentage points lower in ‘Pacific Gold’ than ‘IdaGold’ when sealed for 7 days (Figure 13). However, there was no difference in EI of ‘Black’ seedlings between ‘IdaGold’ and ‘Pacific Gold’ under all sealing durations (Table 66). For both MSM types at 176 g/m^2, there was no difference in EP at 14 DAS and EI of ‘Black’ seedlings among all sealing durations, but EP at 14 DAS was up to 32.5 percentage points lower in ‘Pacific Gold’ than ‘IdaGold’ when sealed for 1 and 3 days, respectively (Table 66 and Figure 13). There was no difference in EP at 14 DAS between ‘IdaGold’ and ‘Pacific Gold’ when sealed for 5 and 7 days (Figure 13). Also, the EI of ‘Black’ seedlings was 24.0 percentage points lower in ‘Pacific Gold’ than ‘IdaGold’ when sealed with 176 g/m^2 of MSM for 3 days, while there was no difference in EI between 'IdaGold' and 'Pacific Gold' when sealed for 1, 5 and 7 days (Table 66). At 265 g/m^2 of MSM, the EP at 14 DAS and EI of 'Black' seedlings were zero with 'Pacific Gold' under all sealing durations, and there was no difference in EP at 14 DAS and EI among all sealing durations with 'IdaGold' (Table 66 and Figure 13). There was no difference in FW of 'Black' seedlings among all sealing durations at 88 and 176 g/m^2 under the same MSM type, respectively, and there was also no difference in FW between 'IdaGold' and 'Pacific Gold' at 88 and 176 g/m^2 under the same sealing durations, respectively (Table 67). The FW of 'Black' seedlings was too small to measure when sealed with 265 g/m^2 of 'IdaGold', although EP at 14 DAS and EI were not zero (Tables 66 and 67, Figure 13).

Table 65. ANOVA of emergence percentage (EP), emergence index (EI) and seedlings fresh weight (FW) of 'Black Seeded Simpson' lettuce seedlings exposed to different types ('IdaGold' and 'Pacific Gold') and rates (0 to 265 g/m^2) of mustard seed meal and sealing durations (1 day, 3 days, 5 days, 7 days).

Source	**EP**	**EI**	**FW**
	Pr > F	**Pr > F**	**Pr > F**
Rate	<.0001	<.0001	<.0001
Sealing Duration	<.0001	<.0001	0.7856
Type	<.0001	<.0001	0.3693
Type*Rate	0.0075	0.014	0.019
Rate*Sealing Duration	0.0044	0.0056	0.2436
Type*Sealing Duration	0.0812	0.1467	0.5261
Type*Rate*Sealing Duration	0.7064	0.7302	0.9884

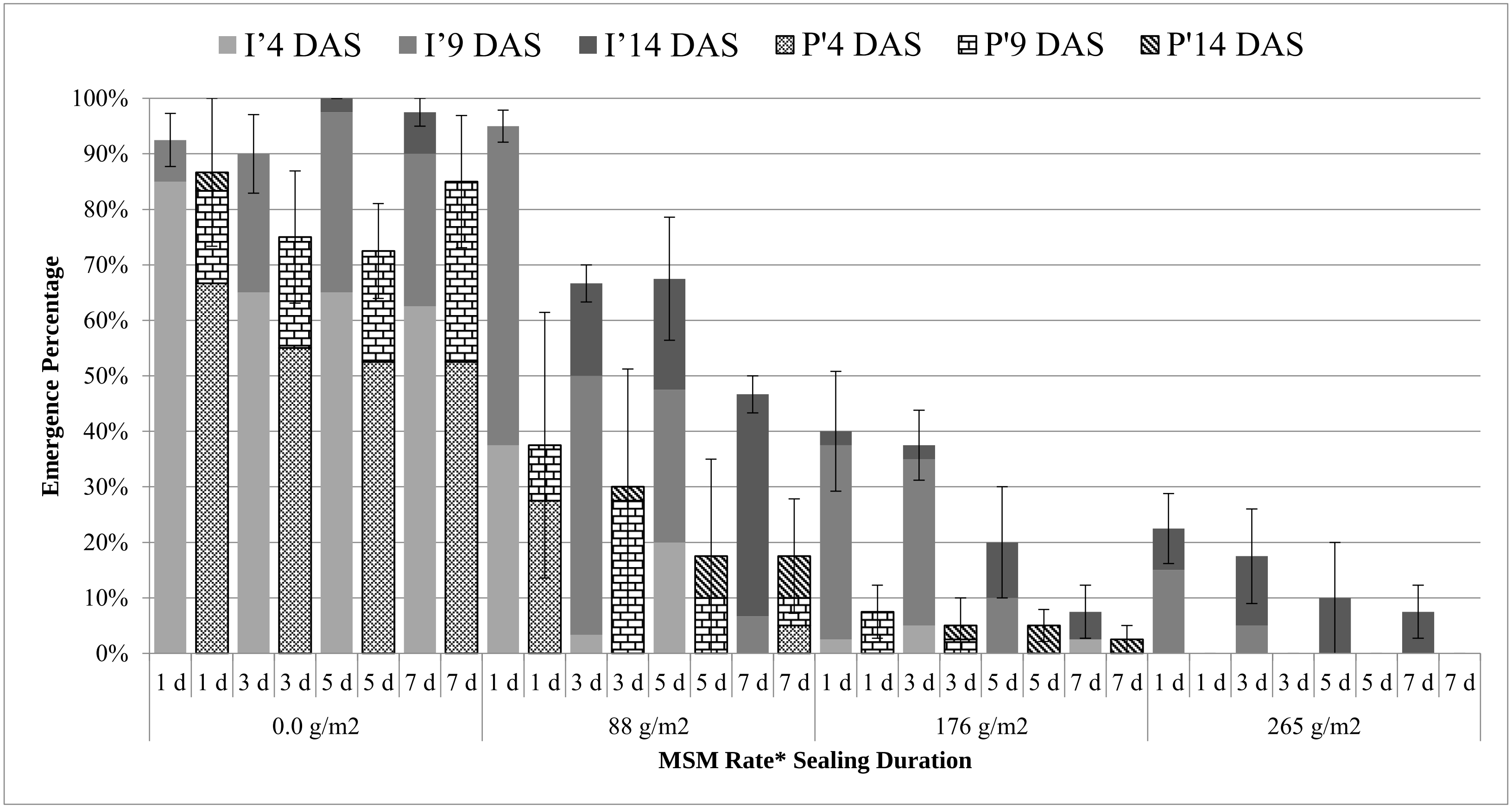
Table 66. Effects of different types ('IdaGold' and 'Pacific Gold') and rates (0 to 265 g/m^2) of mustard seed meal (MSM) and sealing durations (1 day, 3 days, 5 days, 7 days) on emergence index (± standard error) of 'Black Seeded Simpson' lettuce seedlings at 14 days after sowing.

		Emergence Index (%) of 'Black Seeded Simpson' Seedlings			
		Sealing Duration			
MSM	**Rate**	**1 Day**	**3 Days**	**5 Days**	**7 Days**
IdaGold	**0.0 g/m^2**	147.2± 9.4	135.7 ± 13.7	139.0 ± 3.1	133.1 ± 8.4
	88 g/m^2	119.6 ± 3.9	49.8 ± 5.4	62.4 ± 21.3	16.9 ± 1.1
	176 g/m^2	34.6 ± 12.8	26.2 ± 5.4	9.2 ± 6.8	7.1 ± 5.3
	265 g/m^2	11.3 ± 2.9	7.1 ± 3.3	2.0 ± 2.0	1.4 ± 0.8
Pacific Gold	**0.0 g/m^2**	126.0 ± 22.8	109.9 ± 21.7	103.4 ± 21.0	115.0 ± 19.2
	88 g/m^2	50.7 ± 33.1	20.8 ± 14.3	7.6 ± 7.6	11.6 ± 10.6
	176 g/m^2	6.1 ± 3.6	2.2 ± 2.2	0.8 ± 0.5	0.6 ± 0.6
	265 g/m^2	0.0	0.0	0.0	0.0

Table 67. 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 day, 3 days, 5 days, 7 days) on fresh weight (± standard error) of 'Black Seeded Simpson' lettuce seedlings at 18 days after sowing.

		Fresh Weight (g) of 'Black Seeded Simpson' Seedlings			
		Sealing Duration			
MSM	**Rate**	**1 Day**	**3 Days**	**5 Days**	**7 Days**
IdaGold	**0.0 g/m^2**	0.40 ± 0.04	0.39 ± 0.06	0.46 ± 0.05	0.48 ± 0.04
	88 g/m^2	0.13 ± 0.05	0.07 ± 0.02	0.10 ± 0.04	0.06 ± 0.03
	176 g/m^2	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.01
	265 g/m^2	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Pacific Gold	**0.0 g/m^2**	0.31 ± 0.03	0.33 ± 0.06	0.32 ± 0.04	0.38 ± 0.04
	88 g/m^2	0.22 ± 0.14	0.14 ± 0.11	0.05 ± 0.05	0.06 ± 0.05
	176 g/m^2	0.05 ± 0.03	0.02 ± 0.02	0.01 ± 0.01	0.01 ± 0.01
	265 g/m^2	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00

Figure 13. Effects of different types (I'- 'IdaGold' and P'- 'Pacific Gold') and rates (0 to 265 g/m^2) of mustard seed meal (MSM) and sealing durations (1 day, 3 days, 5 days, 7 days) on emergence percentage of 'Black Seeded Simpson' lettuce seedlings at 4, 9 and 14 days after sowing (DAS). Bars represent standard error of EP at 14 DAS.



The EP at 14 DAS, EI and the FW of lettuces 'Buttercrunch' and 'Black Seeded Simpson' seedlings were significantly correlated ($P < 0.01$) with MSM rate under each combination of MSM type and sealing duration (Tables 68, 69 and 70; Tables 71, 72 and 73). The significant linear, quadratic and cubic correlation indicated that increasing MSM rate under each combination of MSM type and sealing duration decreased the EP at 14 DAS, EI and the FW of the lettuces 'Buttercrunch' and 'Black Seeded Simpson' seedlings. The EP at 4 and 9 DAS showed similar trends as the EP at 14 DAS (Figures 12 and 13).

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 63 and Figure 12). 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 days) or higher rate (176 and 265 g/m^2) of MSM for shorter durations (1 and 3 days) (Table 66 and Figure 13). Meyer et al., (2011) found that 0.5% 'IdaGold' seed meal did not reduce lettuce (*Lactuca sativa*) seed germination, but all seed meal treatments containing 'Pacific Gold' significantly reduced germination when applied right after planting. Although the seed meals 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 days after seed meal treatments (Rice et al., 2007).

Table 68. Regression analysis of emergence percentage at 14 DAS of 'Buttercrunch' lettuce seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealing durations (1 day, 3 days, 5 days or 7 days).

Regression Analysis of Emergence Percentage at 14 DAS				
	Model		**P-value**	**R-Square**
IdaGold Sealed 1 Day	**Linear**	$Y=0.88-0.58X$	<.0001	0.7928
	Quadratic	$Y=0.89-0.7X+0.08X^2$	<.0001	0.7957
	Cubic	$Y=0.9-0.88X+0.45X^2-0.17X^3$	0.0004	0.7971
IdaGold Sealed 3 Days	**Linear**	$Y=0.75-0.55X$	<.0001	0.8739
	Quadratic	$Y=0.83-1.03X+0.33X^2$	<.0001	0.9361
	Cubic	$Y=0.83-0.76X-0.2X^2+0.23X^3$	<.0001	0.9397
IdaGold Sealed 5 Days	**Linear**	$Y=0.85-0.63X$	<.0001	0.7662
	Quadratic	$Y=0.96-1.31X+0.45X^2$	<.0001	0.8444
	Cubic	$Y=0.98-1.78X+1.35X^2-0.4X^3$	<.0001	0.8514
IdaGold Sealed 7 Days	**Linear**	$Y=0.73-0.58X$	<.0001	0.7284
	Quadratic	$Y=0.89-1.59X+0.68X^2$	<.0001	0.9292
	Cubic	$Y=0.9-1.78X+1.05X^2-0.17X^3$	<.0001	0.9306
Pacific Gold Sealed 1 Day	**Linear**	$Y=0.85-0.63X$	0.0001	0.6679
	Quadratic	$Y=0.94-1.19X+0.38X^2$	0.0003	0.716
	Cubic	$Y=0.95-1.38X+0.75X^2-0.17X^3$	0.0013	0.717
Pacific Gold Sealed 3 Days	**Linear**	$Y=0.82-0.64X$	<.0001	0.6832
	Quadratic	$Y=0.98-1.62X+0.65X^2$	<.0001	0.8242
	Cubic	$Y=1-2.24X+1.85X^2-0.53X^3$	<.0001	0.8349
Pacific Gold Sealed 5 Days	**Linear**	$Y=0.76-0.62X$	<.0001	0.6731
	Quadratic	$Y=0.95-1.78X+0.78X^2$	<.0001	0.8869
	Cubic	$Y=0.98-2.6X+2.35X^2-0.7X^3$	<.0001	0.9066
Pacific Gold Sealed 7 Days	**Linear**	$Y=0.68-0.57X$	<.0001	0.6882
	Quadratic	$Y=0.87-1.73X+0.78X^2$	<.0001	0.9471
	Cubic	$Y=0.9-2.55X+2.35X^2-0.7X^3$	<.0001	0.9709

Table 69. Regression analysis of emergence index (EI) of 'Buttercrunch' lettuce seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealing durations (1 day, 3 days, 5 days or 7 days).

Regression Analysis of Emergence Index				
	Model		**P-value**	**R-Square**
IdaGold Sealed 1 Day	**Linear**	$Y=1.26-0.89X$	<.0001	0.7706
	Quadratic	$Y=1.37-1.54X+0.43X^2$	<.0001	0.8052
	Cubic	$Y=1.38-2.03X+1.41X^2-0.44X^3$	0.0003	0.809
IdaGold Sealed 3 Days	**Linear**	$Y=1.07-0.83X$	<.0001	0.7447
	Quadratic	$Y=1.28-2.12X+0.86X^2$	<.0001	0.9031
	Cubic	$Y=1.29-2.47X+1.54X^2-0.3X^3$	<.0001	0.9053
IdaGold Sealed 5 Days	**Linear**	$Y=1.04-0.84X$	<.0001	0.7055
	Quadratic	$Y=1.29-2.33X+1X^2$	<.0001	0.9054
	Cubic	$Y=1.32-3.42X+3.08X^2-0.93X^3$	<.0001	0.9248
IdaGold Sealed 7 Days	**Linear**	$Y=0.9-0.75X$	0.0003	0.6242
	Quadratic	$Y=1.18-2.44X+1.12X^2$	<.0001	0.9026
	Cubic	$Y=1.22-3.85X+3.82X^2-1.2X^3$	<.0001	0.9382
Pacific Gold Sealed 1 Day	**Linear**	$Y=1.2-0.93X$	<.0001	0.7061
	Quadratic	$Y=1.41-2.18X+0.83X^2$	<.0001	0.8185
	Cubic	$Y=1.42-2.48X+1.42X^2-0.26X^3$	<.0001	0.8198
Pacific Gold Sealed 3 Days	**Linear**	$Y=1.03-0.85X$	0.0002	0.6501
	Quadratic	$Y=1.32-2.6X+1.17X^2$	<.0001	0.8947
	Cubic	$Y=1.37-4.07X+3.98X^2-1.25X^3$	<.0001	0.9263
Pacific Gold Sealed 5 Days	**Linear**	$Y=0.9-0.76X$	0.0004	0.6057
	Quadratic	$Y=1.2-2.55X+1.19X^2$	<.0001	0.9019
	Cubic	$Y=1.25-4.27X+4.48X^2-1.46X^3$	<.0001	0.9517
Pacific Gold Sealed 7 Days	**Linear**	$Y=0.74-0.63X$	0.0004	0.5995
	Quadratic	$Y=0.99-2.14X+1.01X^2$	<.0001	0.9068
	Cubic	$Y=1.04-3.61X+3.84X^2-1.26X^3$	<.0001	0.9609

Table 70. Regression analysis of fresh weight of 'Buttercrunch' lettuce seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealing durations (1 day, 3 days, 5 days or 7 days).

Regression Analysis of Fresh Weight				
	Model		**P-value**	**R-Square**
IdaGold Sealed 1 Day	**Linear**	Y=0.28-0.23X	<.0001	0.6917
	Quadratic	$Y=0.35-0.66X+0.29X^2$	<.0001	0.9059
	Cubic	$Y=0.36-0.88X+0.71X^2-0.19X^3$	<.0001	0.9162
IdaGold Sealed 3 Days	**Linear**	Y=0.28-0.23X	<.0001	0.6765
	Quadratic	$Y=0.36-0.7X+0.31X^2$	<.0001	0.914
	Cubic	$Y=0.37-1X+0.88X^2-0.25X^3$	<.0001	0.9318
IdaGold Sealed 5 Days	**Linear**	Y=0.31-0.25X	<.0001	0.7068
	Quadratic	$Y=0.39-0.74X+0.33X^2$	<.0001	0.9383
	Cubic	$Y=0.4-1.04X+0.9X^2-0.25X^3$	<.0001	0.9541
IdaGold Sealed 7 Days	**Linear**	Y=0.33-0.28X	0.0003	0.6228
	Quadratic	$Y=0.44-0.94X+0.44X^2$	<.0001	0.9258
	Cubic	$Y=0.46-1.55X+1.62X^2-0.52X^3$	<.0001	0.9746
Pacific Gold Sealed 1 Day	**Linear**	Y=0.35-0.26X	0.0004	0.6052
	Quadratic	$Y=0.39-0.46X+0.13X^2$	0.0014	0.6365
	Cubic	$Y=0.38-0.33X-0.12X^2+0.11X^3$	0.0054	0.6389
Pacific Gold Sealed 3 Days	**Linear**	Y=0.33-0.26X	0.0001	0.6541
	Quadratic	$Y=0.4-0.67X+0.27X^2$	<.0001	0.7951
	Cubic	$Y=0.4-0.86X+0.65X^2-0.17X^3$	0.0002	0.8012
Pacific Gold Sealed 5 Days	**Linear**	Y=0.3-0.24X	0.0002	0.6343
	Quadratic	$Y=0.38-0.75X+0.34X^2$	<.0001	0.8734
	Cubic	$Y=0.39-1.16X+1.13X^2-0.35X^3$	<.0001	0.9034
Pacific Gold Sealed 7 Days	**Linear**	Y=0.31-0.26X	0.0003	0.6156
	Quadratic	$Y=0.41-0.85X+0.39X^2$	<.0001	0.8973
	Cubic	$Y=0.42-1.37X+1.39X^2-0.44X^3$	<.0001	0.9377

Table 71. Regression analysis of emergence percentage at 14 DAS of 'Black Seeded Simpson' lettuce seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealing durations (1 day, 3 days, 5 days or 7 days).

Regression Analysis of Emergence Percentage at 14 DAS				
	Model		**P-value**	**R-Square**
IdaGold Sealed 1 Day	**Linear**	Y=1.02-0.53X	<.0001	0.7592
	Quadratic	$Y=0.97-0.23X-0.2X^2$	<.0001	0.7808
	Cubic	$Y=0.93+1.26X-3.05X^2+1.27X^3$	<.0001	0.8784
IdaGold Sealed 3 Days	**Linear**	Y=0.9-0.49X	<.0001	0.8525
	Quadratic	$Y=0.91-0.55X+0.04X^2$	<.0001	0.8536
	Cubic	$Y=0.9-0.31X-0.42X^2+0.2X^3$	<.0001	0.8564
IdaGold Sealed 5 Days	**Linear**	Y=0.97-0.63X	<.0001	0.8246
	Quadratic	$Y=1.02-0.93X+0.2X^2$	<.0001	0.8407
	Cubic	$Y=1-0.15X-1.35X^2+0.7X^3$	<.0001	0.8611
IdaGold Sealed 7 Days	**Linear**	Y=0.87-0.62X	<.0001	0.8512
	Quadratic	$Y=0.99-1.4X+0.52X^2$	<.0001	0.9634
	Cubic	$Y=0.98-0.95X-0.32X^2+0.37X^3$	<.0001	0.9693
Pacific Gold Sealed 1 Day	**Linear**	Y=0.74-0.56X	0.0009	0.5852
	Quadratic	$Y=0.87-1.21X+0.42X^2$	0.0017	0.6531
	Cubic	$Y=0.87-1.15X+0.32X^2+0.04X^3$	0.007	0.6532
Pacific Gold Sealed 3 Days	**Linear**	Y=0.65-0.5X	0.0006	0.5814
	Quadratic	$Y=0.75-1.1X+0.4X^2$	0.001	0.6558
	Cubic	$Y=0.75-1.1X+0.4X^2+0X^3$	0.0041	0.6558
Pacific Gold Sealed 5 Days	**Linear**	Y=0.58-0.46X	0.0005	0.5886
	Quadratic	$Y=0.71-1.21X+0.5X^2$	0.0002	0.7277
	Cubic	$Y=0.73-1.76X+1.55X^2-0.47X^3$	0.0008	0.7413
Pacific Gold Sealed 7 Days	**Linear**	Y=0.67-0.54X	0.0001	0.6575
	Quadratic	$Y=0.83-1.52X+0.65X^2$	<.0001	0.848
	Cubic	$Y=0.85-2.14X+1.85X^2-0.53X^3$	<.0001	0.8625

Table 72. Regression analysis of emergence index of 'Black Seeded Simpson' lettuce seedlings in response to application rate of 'IdaGold' or 'Pacific Gold' mustard seed meal under sealing durations (1 day, 3 days, 5 days or 7 days).

Regression Analysis of Emergence Index				
	Model		**P-value**	**R-Square**
IdaGold Sealed 1 Day	**Linear**	$Y=1.52-0.99X$	<.0001	0.8876
	Quadratic	$Y=1.53-1.05X+0.04X^2$	<.0001	0.8879
	Cubic	$Y=1.47+0.82X-3.53X^2+1.59X^3$	<.0001	0.9397
IdaGold Sealed 3 Days	**Linear**	$Y=1.19-0.83X$	<.0001	0.823
	Quadratic	$Y=1.33-1.79X+0.64X^2$	<.0001	0.9157
	Cubic	$Y=1.36-2.73X+2.4X^2-0.77X^3$	<.0001	0.9297
IdaGold Sealed 5 Days	**Linear**	$Y=1.23-0.92X$	<.0001	0.8008
	Quadratic	$Y=1.4-1.95X+0.68X^2$	<.0001	0.8849
	Cubic	$Y=1.39-1.62X+0.02X^2+0.3X^3$	<.0001	0.8866
IdaGold Sealed 7 Days	**Linear**	$Y=1.05-0.83X$	<.0001	0.7173
	Quadratic	$Y=1.29-2.41X+1.06X^2$	<.0001	0.9366
	Cubic	$Y=1.33-4.07X+4.17X^2-1.36X^3$	<.0001	0.9747
Pacific Gold Sealed 1 Day	**Linear**	$Y=1.05-0.81X$	0.0009	0.5828
	Quadratic	$Y=1.27-1.89X+0.69X^2$	0.0013	0.6716
	Cubic	$Y=1.26-1.76X+0.46X^2+0.1X^3$	0.0052	0.6718
Pacific Gold Sealed 3 Days	**Linear**	$Y=0.85-0.7X$	0.0004	0.5979
	Quadratic	$Y=1.07-2X+0.87X^2$	<.0001	0.7841
	Cubic	$Y=1.1-2.84X+2.49X^2-0.72X^3$	0.0002	0.7985
Pacific Gold Sealed 5 Days	**Linear**	$Y=0.75-0.63X$	0.001	0.5509
	Quadratic	$Y=0.99-2.06X+0.95X^2$	<.0001	0.7987
	Cubic	$Y=1.03-3.36X+3.44X^2-1.11X^3$	<.0001	0.8364
Pacific Gold Sealed 7 Days	**Linear**	$Y=0.85-0.71X$	0.0005	0.5885
	Quadratic	$Y=1.11-2.25X+1.03X^2$	<.0001	0.834
	Cubic	$Y=1.15-3.54X+3.49X^2-1.09X^3$	<.0001	0.8652

Table 73. Regression analysis of fresh weight of ‘Black Seeded Simpson’ lettuce seedlings in response to application rate of ‘IdaGold’ or ‘Pacific Gold’ mustard seed meal (MSM) under sealing durations (1 day, 3 days, 5 days or 7 days).

Regression Analysis of Fresh Weight				
	Model		**P-value**	**R-Square**
IdaGold Sealed 1 Day	**Linear**	Y=0.33-0.26X	<.0001	0.7483
	Quadratic	$Y=0.4-0.67X+0.27X^2$	<.0001	0.9048
	Cubic	$Y=0.4-0.73X+0.39X^2-0.05X^3$	<.0001	0.9055
IdaGold Sealed 3 Days	**Linear**	Y=0.3-0.25X	0.0001	0.6636
	Quadratic	$Y=0.38-0.72X+0.31X^2$	<.0001	0.8752
	Cubic	$Y=0.39-1.01X+0.88X^2-0.25X^3$	<.0001	0.8904
IdaGold Sealed 5 Days	**Linear**	Y=0.36-0.29X	<.0001	0.702
	Quadratic	$Y=0.45-0.81X+0.35X^2$	<.0001	0.9029
	Cubic	$Y=0.46-1.11X+0.93X^2-0.26X^3$	<.0001	0.9152
IdaGold Sealed 7 Days	**Linear**	Y=0.36-0.3X	0.0001	0.6635
	Quadratic	$Y=0.46-0.92X+0.42X^2$	<.0001	0.9248
	Cubic	$Y=0.48-1.45X+1.43X^2-0.45X^3$	<.0001	0.959
Pacific Gold Sealed 1 Day	**Linear**	Y=0.31-0.22X	0.0033	0.4718
	Quadratic	$Y=0.32-0.3X+0.05X^2$	0.0149	0.4767
	Cubic	$Y=0.31+0.02X-0.55X^2+0.27X^3$	0.0377	0.4923
Pacific Gold Sealed 3 Days	**Linear**	Y=0.29-0.22X	0.0012	0.5385
	Quadratic	$Y=0.33-0.48X+0.17X^2$	0.0025	0.6033
	Cubic	$Y=0.33-0.42X+0.06X^2+0.05X^3$	0.0092	0.6039
Pacific Gold Sealed 5 Days	**Linear**	Y=0.25-0.2X	0.0003	0.6208
	Quadratic	$Y=0.31-0.6X+0.26X^2$	<.0001	0.8316
	Cubic	$Y=0.32-0.91X+0.87X^2-0.27X^3$	<.0001	0.8566
Pacific Gold Sealed 7 Days	**Linear**	Y=0.29-0.24X	0.0002	0.6361
	Quadratic	$Y=0.37-0.72X+0.32X^2$	<.0001	0.8597
	Cubic	$Y=0.38-1.08X+1.02X^2-0.31X^3$	<.0001	0.8837

The different effects of MSMs in these experiments may have been due to several factors, including seed meal types, application rates and target plant species. Mustard plant species differ in types and amounts of GSLs. 'Pacific Gold' seed meal mainly contains sinigrin (2-propenyl GSL), while 'IdaGold' seed meal contains a large concentration of sinalbin (4-hydroxybenzyl GSL) (Borek and Morra, 2005; Rice et al., 2007; Hansson et al., 2008). The 2-propenyl-ITC was the dominant GSL hydrolysis product from 'Pacific Gold' seed meal, which is phytotoxic due to a non-specific and irreversible reaction with sulphur containing groups in proteins (Brown and Morra 1997; Bending and Lincoln, 1999; Rice et al., 2007). The ionic thiocyanate (SCN^-) in 'IdaGold', which is the primary toxic product from hydrolysis of unstable 4-hydroxybenzyl ITC, was relatively water soluble, so the volatile 3-butenyl-ITC may be responsible for inhibition of weed and vegetable seed emergence in our petri dish experiments (Borek and Morra, 2005; Tollsten and Bergström, 1988). Other studies have reported that SCN^- was more persistent in 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). The fate of allyl-ITCs could be microbial degradation, sorption by organic matter or reaction with nucleophillic groups (Gimsing and Kirkegaard. 2009). On the other hand, SCN- produced by 'IdaGold' is translocated and accumulates in plant tissues, which might not kill seedlings for shorter sealing durations (Stiehl and Bible, 1989; Brown and Morra, 2005), but affect plant growth. Besides, maximum SCN^- (211 µmol/kg of soil) was measured at 5 days in 0-5 cm samples from plots amended with 'IdaGold' at 2 t/ha (200 g/m^2). Different responses of weed and vegetable seeds to the type, rate and sealing duration of MSM treatments observed in this experiment may also be due to different sensitivity to glucosinolate breakdown products that have been observed among plant species (Vaughn et al., 2006).

3.5 Conclusion

For two weeds species, ‘Pacific Gold’ had more suppressive effect on large crabgrass seedling emergence. However, increasing sealing duration from 1 to 7 days did not cause additional reduction in weed seedling emergence, and both MSMs suppressed Palmer amaranth emergence almost completely at 176 and 265 g/m^2 of MSM regardless of sealing durations (Tables 27 and 33, Figures 6 and 7). For onion seedlings, phytotoxicity (reflected by fresh weight) increased under sealing durations (Table 15), and ‘Pacific Gold’ had greater suppressive effects on onion seedlings than ‘Idagold’ in this experiment (Table 39 and Figure 8). For kale and mustard seedlings, ‘IdaGold’ and ‘Pacific Gold’ had similar suppressive effects on seedling emergence (Tables 45 and 51, Figures 9 and 11). However, ‘IdaGold’ had greater phytotoxcity on mustard seedlings (Table 52) and ‘Pacific Gold’ delayed emergence of kale seedlings at 88 g/m^2 when sealed for 3, 5 and 7 days (Table 45). For green seedlings, ‘IdaGold’ had more suppressive effects than ‘Pacific Gold’ on seedling emergence, while sealing delayed but did not decrease emergence at the low rate (88 g/m^2) of MSMs compared to 0.0 g/m^2 (Table 48 and Figure 10). ‘IdaGold’ had greater phytotoxicity on green seedlings than ‘Pacific Gold’ (Table 49). For ‘Buttercrunch’ seedlings, there were no different suppressive effects between ‘IdaGold’ and ‘Pacific Gold’ (Tables 63 and 64, Figure 12). For ‘Black Seeded Simpson’ seedlings, ‘Pacific Gold’ had more suppressive effects on lettuce seedling emergence than ‘IdaGold’ when sealed with the lower rate (88 g/m^2) for longer durations (7 days) or higher rate (176 and 265 g/m^2) for shorter durations (1 and 3 days) (Tables 66 and 67, Figure 13).

Based on these results, extending sealing duration at the medium MSM rate (176 g/m^2) could achieve the same weed control as applying MSM at the high rate (265 g/m^2) without sealing. For vegetable production with direct seeding, MSM application several days before direct seeding is necessary to suppress weed emergence and avoid or minimize phytotoxicity to vegetable crops. Further application of MSMs may consider different environmental conditions, soil type and crop sensitivity to MSM in organic farms.

CHAPTER IV

SUMMARY

Mustard seed meals (MSMs) are produced after crushing oil seeds to produce biofuel. The allelopathic properties from MSMs have the ability to inhibit seed emergence and growth. MSMs have been reported to have potential herbicidal, insecticidal, nematicidal, and fungicidal effects. In order to be useful as bio-herbicides for weed control in nursery containers and organic farming systems, rates and application method and timing of MSMs must be determined to maximize weed control and reduce crop injury. Our objectives were to compare the herbicidal efficacy on weed seedling emergence of two MSM types applied to petri dishes in a laboratory setting, containers in greenhouse and outdoor settings. Various rates and methods were employed to determine the effects of MSMs types, rates and sealing durations on vegetable and weed seedling emergence and biomass in petri dishes.

In chapter II, MSMs were applied at 0, 50, 100, 200 or 300 g/m^2 to the bottom of petri dishes and covered with germination mix. For each weed, there were 10 replications per MSM rate and weed type combination, and 5 of the 10 petri dishes were sealed with parafilm. In the greenhouse containers experiments, MSMs were applied on the surface of or incorporated into the germination mix at 0, 1.5, 3.0 or 4.5 g/pot in the top 2.5 cm layer. In the outdoor containers experiments, MSMs were incorporated into the germination mix at 0, 1.5 or 3.0 g/pot in the top 2.5 cm layer. In petri dishes, emergence of large crabgrass (*Digitaria sanguinalis*) and Palmer amaranth (*Amaranthus palmeri*) seedlings was greatly reduced in sealed vs. unsealed petri dishes, and 'Pacific Gold' had better suppressive effects than 'IdaGold' on both weeds. In the greenhouse containers experiments, 'IdaGold' exhibited better herbicidal efficacy on Palmer amaranth (broadleaf weed) seedling emergence, whereas 'Pacific Gold' was more effective on large crabgrass (grassy weed) seedling emergence. Also, applying MSMs on the surface of the germination mix in containers had better suppressive effects on weed emergence than incorporating MSMs into the germination mix in the top 2.5 cm layer. In the outdoor container experiments, 'Pacific Gold' had better suppressive effects than 'IdaGold' on large crabgrass seedling emergence, while there was no difference in emergence of Palmer amaranth seedlings between 'IdaGold' and 'Pacific Gold' seed meals.

In chapter III, six types of vegetable seeds (onion *Allium cepa* 'Texas Grano 1015Y', lettuces *Lactuca sativa* 'Black Seeded Simpson' and 'Buttercrunch', mustard *Brassica juncea* 'Green Wave', kale *B. oleracea* 'Vates Blue Curled', green *B. rapa* 'Mizuna') and two types of weeds, large crabgrass and palmer amaranth were sowed in a germination mix incorporated with MSMs ('IdaGold' and 'Pacific Gold') at 0, 88, 176 or 265 g/m^2 in petri dishes. Petri dishes were sealed for 1, 3, 5 or 7 days after sowing. For large crabgrass and Palmer amaranth, 'Pacific Gold' had more suppressive effects on large crabgrass seedling emergence, but increasing sealing duration from 1 to 7 days did not cause an additional reduction in weed seedling emergence. For onion seedlings, phytotoxicity (reflected by fresh weight) increased with sealing duration, and 'Pacific Gold' had greater suppressive effects on onion seedling emergence than 'IdaGold'. For kale and mustard seedlings, 'IdaGold' and 'Pacific Gold' had similar suppressive effects on seedling emergence, however, ‘IdaGold’ had greater phytotoxicity on mustard seedlings and ‘Pacific Gold’ delayed emergence of kale seedlings at 88 g/m^2 when sealed for 3, 5 and 7 days. For green seedlings, ‘IdaGold’ had more suppressive effects than ‘Pacific Gold’ on seedling emergence, while sealing delayed but did not decrease emergence at the low rate (88 g/m^2) of mustard seed meal compared to 0.0 g/m^2. ‘IdaGold’ had greater phytotoxcity on green seedlings than ‘Pacific Gold’. For ‘Buttercrunch’ lettuce seedlings, there were no different suppressive effects between ‘IdaGold’ and ‘Pacific Gold’. For ‘Black Seeded Simpson’ lettuce seedlings, ‘Pacific Gold’ had more suppressive effects on seedlings emergence than ‘IdaGold’ when sealed with a lower rate (88 g/m^2) for longer durations (7 days) or higher rates (176 and 265 g/m^2) for shorter durations (1 and 3 days).

In conclusion, ‘Pacific Gold’ and ‘IdaGold’ seed meals at 50 to 300 g/m^2 had suppressive effects on weed and vegetable seedling emergence and growth. Surface applied MSMs had better herbicidal effects on weed emergence than MSMs incorporated into germination mix in greenhouse containers. Longer (5 and 7 days) sealing durations may strengthen suppressive effects on weeds and vegetable seedling emergence. The suppressive efficacy of MSMs varied with MSM type, weed species (broadleaf or grassy weed), vegetable species and sensitivity to phytotoxins from MSMs. These results suggest that MSMs have potential to be used as bio-herbicides in nursery container and organic farms. Better herbicidal efficacy can be acquired by sealing MSM treated soil and applying on the soil surface. Mixing ‘Pacific Gold’ and ‘IdaGold’ seed meals may be more effective to control both broadleaf and grassy weeds. Inhibition of vegetable seedling emergence and growth may be relieved by applying MSMs several weeks before seeding and increasing seeding density in organic farms.

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