Soil solarization and soil additives as alternatives to preplant fumigation in annual plasticulture strawberry production

Sanghamitra Das

Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

In

Horticulture

Jayesh B. Samtani

Jeffrey F. Derr

Alex X. Niemiera

Mark S. Reiter

July 20, 2018

Virginia Beach, Virginia

Keywords: (paper pellet, mustard seed meal, corn gluten meal, plant, canopy, yield, temperature, weed)

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ABSTRACT

Fumigation before strawberry (*Fragaria×ananassa* Duchesne) planting was a common practice as they are susceptible to numerous pests. Methyl bromide, the colorless, odorless gas, was the chosen fumigant for growers until it was classified as an ozone-depleting substance and its use was gradually restricted and legally phased out in 2015. Fumigant use has constraints and thus research on other preplant alternatives for soil sterilization of strawberry annual plasticulture production is necessary. This research focused on soil solarization, products including paper pellets, mustard seed meal, and corn gluten meal. Two studies were conducted at the Virginia Tech Hampton Road AREC (Agricultural Research and Extension Center), and follow-up studies at the Flanagan Farm in Virginia Beach. The first study at the AREC evaluated three-week soil solarization with and without pelleted products. The second study evaluated different rates of paper pellets, paper pellets plus mustard seed meal, mustard seed meal alone and fumigated plots. The purpose of each study was to evaluate the sterilization-mulching effects on weeds, plant health and stand count, yield and fruit parameters (as size and sweetness). A container-grown plant study determined if there was any phytotoxic effect of paper pellets and mustard seed meal on pansies (*Viola tricolor*). Another study evaluated the effect of paper pellets and mustard seed meal on germination of different weed species. The paper pellet and soil solarization treatments showed decreased early season weeds but season-long weed control was not provided by the same treatment. In the study one, paper pellet improved yield in the first

season but not the second season. Paper pellet and mustard seed meal increased yield compared to the black plastic control in the second study. No phytotoxicity was observed on pansies in response to paper pellet and mustard seed meal rates. In the grower farm study, weed biomass was higher under the clear tarp than the black tarp perhaps due to more light transmission under the clear tarp. A new locally available paper pellet product was used at the grower farm and the plants in plots treated with this product, had lower health rating and yield compared to other treatments.

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ABSTRACT

The strawberry fruit is not a typical fruit but develops from the receptacle and is well known for the bright red color, fleshy fruit and characteristic aroma. Growing strawberries is challenging as they are susceptible to soil-borne pests. Preplant fumigation was commonly accomplished by the use of methyl bromide (MB) to ensure the soil-borne pests are adequately controlled; until MB use as a fumigant was phased out by the Montreal Protocol Act. Use of fumigants require maintaining a fumigant management plan, a buffer zone between the treatment area and high population zone areas, and worker safety practices. There is a need to evaluate alternative preplant pest control strategies as soil solarization and mulching treatments that would not compromise on berry yield and quality. Two experiments were conducted at the Virginia Tech Hampton Roads Agricultural Research and Extension Center, Virginia Beach.

One experiment conducted in 2014-15 and 2015-16 evaluated soil solarization (a method where moistened soil is covered with a clear tarp, traps solar radiation, and thereby heats up the soil), and mulching treatments (paper pellet mulch, mustard seed meal, and corn gluten meal) used alone or in combination with soil solarization and their effect on weed control, crop growth, crop yield, and fruit quality. In the second study rates of paper pellets, mustard seed meal (alone or in combination of these), and fumigated plots were evaluated to study the effect on strawberry plants. The most effective treatments from the two studies were used in an experiment at a grower's farm. A shorter duration of soil solarization (three week) with paper pellet showed

lower early weed density than black plastic control, but overall solarization did not have consistent beneficial effect on yield. Paper pellets disintegrate over time and the pellets being porous to water; they were not an effective tool for weed control. However, combination of paper pellets and mustard seed meal showed a beneficial effect on yield compared to the black plastic control treatments. The plots covered with black tarp had less weed biomass than those covered with clear tarp in the grower farm study.

DEDICATION

I dedicate this work to my family, friends and colleagues whose continuous support helped me to achieve my dream.

ACKNOWLEDGEMENTS

I would like to thank my advisor Dr. Jayesh Samtani for giving me this opportunity to fulfill my dreams. Thanks, Dr. Samtani for guiding me to go ahead in life, participate in several seminars, write grants, and giving me the platform to grow as a researcher. I would also like to thank all my committee members, Dr. Jeffrey Derr, Dr. Mark Reiter, Dr. Alex Niemiera for their continued support to be a better researcher, think critically and be a better writer.

I would like to thank Dr. Roger Harris for being extremely supportive whenever I visited him to discuss my academic progress or any concern and he taught me to look at the bigger picture. I have learned immensely from the classes and very grateful to all the professors. Each one of my teachers had a unique way of teaching and their guidelines would be invaluable to me when I start my career. I am grateful to the statistical department for helping me on several occasions.

My sincere thanks to all members of Hampton Roads Agricultural Station for their immense support throughout this journey, especially Dr. Jim Owen for discussing several methodologies. Thanks to Ava Borden for lifting my spirits during tough times. I am grateful to all students and interns who helped to collect data, Zachary Landis, Ethan Murdock, Ashley Sibley, Mikel Conway, Danyang Liu, Ellen Owen and a very special thanks to Jillian Rajevich without whose help this work would not have been possible.

I would like to thank Roy Flanagan and Jeremah Brackero for allowing me to conduct trials at their farms and would like to end with a very special thanks to my sister Sheena, for being supportive during good and bad times, urging me to believe in myself and continue to work hard.

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CHAPTER I

INTRODUCTION

The economically important strawberry (*Fragaria*×*ananassa* Duchesne) was an accidental hybrid between *F. chiolensis* and *F. virginiana* that arose in France in mid 1700s (Hummer and Hancock, 2005). Strawberries are known for their bright red, fleshy fruit and the characteristic aroma. The fruit is not a typical berry but an aggregate accessory fruit which develops from the receptacle of the plant. Commercially, the plants are grown in an annual plasticulture system or as matted rows. In Virginia, the annual plasticulture production system has gained popularity in the past few decades. In the plasticulture system, raised beds are formed every year, the soil of which is typically fumigated to control soil borne pests, and strawberry plants are planted through holes in the plastic. Strawberries are susceptible to black root rot, *Phytophthora* crown rot, and other preplant issues as weeds and nematodes (2018 Southeast Regional Strawberry IPM Guide). Planting on the same site repeatedly without preplant fumigation is not desirable due to weed and diseases (Poling, 2005). The most chosen fumigant fruit growers had been using is methyl bromide, but methyl bromide is no longer available to growers in Virginia. Methyl bromide is an ozone depleting substance and it was agreed by law that its use would be reduced from 1991 up to 2005, and be completely phased out by 2015 (Rosskopf and Chellemi, 2005). Alternative fumigants are less broad spectrum and more target specific and a combination with other fumigants or pesticides is often required to reach the level of pest control efficacy and yield response as methyl bromide (Noling, 2002). Using fumigants require many measures as buffer restrictions, maintaining a fumigant management plan (FMPs), and worker safety measures. There is an urgent need to integrate research and extension activities which look into evaluating and adopting alternative bio-based and thermal treatments for preplant control in strawberry production.

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Literature Review

1. Methyl bromide as a soil fumigant

1.1 History

Soil disinfestation by fumigation is done before planting to control a wide spectrum of pests. Carbon disulfide, CS_2 was the first chemical soil fumigant used for the control of *Phylloxera* in French vineyards (Katan et al., 2004). Next was chloropicrin (Pic) which was used post the first world war which ended in 1918 (Katan et al., 2004).

Methyl bromide (MB) was a very popular soil fumigant used in France in the 1930's and since then, it has been effectively used for the control of nematodes, fungi, bacteria, and weeds (Rosskopf and Chellemi 2005). Methyl bromide was discovered by Mr. Le Goupil, who was searching for alternatives to hydrogen cyanide and carbon disulfide which were used as fumigants in harbor, but were highly flammable and increased chance of fire and found that MB had insecticidal properties when used in a vacuum for 1.5 hours in a range of concentrations (Ducom, 2012). At that time it was not considered toxic for humans unless used in large doses (Ducom, 2012). As an agricultural fumigant MB gained popularity in the 1960s (Gullino et al., 2005).

1.2 Uses

Methyl bromide is an odorless, colorless gas with a high vapor pressure that spreads rapidly through the soil, dissipates quickly after application, and has been used on more than 100 crops (Rosskopf and Chellemi, 2005). Methyl bromide has been used for the production of many high value crops in the U.S, and elsewhere (Noling, 2002). The largest consumer of MB has been the U.S. where it has been largely used as a soil fumigant for the production of *Solanum* *melongena* L.(eggplant), *Fragaria* L.(strawberries), *Solanum lycopersicum* L.(tomatoes), *Capsicum* L.(pepper), *Citrullus Schrad*.(watermelon) and nursery crops. Beyond agriculture, other sources such as oceans, burning of forests, and exhaust from automobiles also contribute MB to the environment (Cicerone, 1994). Ocean plankton release MB due to their biological activities (Khalil et al., 1993). Approximately 30% of the MB in the atmosphere is accounted for by forest fires or burning of waste materials (White, 1994).

The production of strawberries and fresh market tomatoes became highly dependent on fumigation with MB since 1960s (Ristaino and Thomas 1996). A mixture of MB and Pic have been used for many high value annual crops (Martin and Bull, 2002). This mixture has also been used for preplant uses including fruit crops such as *Malus* Mill. (apples), *Rubus* L.(blackberry), *Vaccinium* L.(blueberry), *Carya illinoinensis* (Wangenh.) K. Koch (pecan), *Rubus idaeus* L.(raspberry) (Johnson et al., 2012).

Strawberries are very susceptible to diseases especially black root rot, *Phytophthora*, *Pythium*, *Fusarium*, *Rhizoctonia* and Verticillium wilt. Other preplant issues include weeds, root and crown rot disorders and nematodes (2017 Strawberry IPM Guide). When sites are repeatedly planted with the same fruits without fumigant use, the yield may be lower and there may be an increase of plant pathogens and nematodes around the area of plant roots. Also when a grower has smaller acreage it may not be possible to practice crop rotations between the two growing seasons. In such circumstances it may often be necessary to fumigate (Mid-Atlantic Berry Guide for Commercial Growers 2013-14).

1.3 Methyl bromide disadvantages

Methyl bromide is expensive, toxic, and as it dissipates very quickly, MB may reach the soil surface and the ground water. Edible parts of the crop may contain bromide residues, MB may adversely affect beneficial organisms, and its application is complicated (Katan et al., 2004). Management practices, such as using deep injection of the fumigant, adding organic matter to soil before fumigation or using VIF (virtually impermeable film) may help to reduce the escape of the fumigant into atmosphere but there may be challenges associated with employing each practice. Injection of fumigant deep in the soil reduces emission to the atmosphere, but could also increase ground water contamination and inadequately control pests. The VIFs are much less permeable to MB but adds to the cost. Adding organic matter to soil enhances the capacity of the soil to degrade the fumigant before it is emitted to the atmosphere.

Soil fumigation may negatively affect soil biology. Where only the raised beds are fumigated, the furrows are a source of inoculum which may spread to the adjacent fumigated soil (Ristaino and Thomas, 1996). The microbial biomass is lower in fumigated soil compared to non-fumigated soil, and the mycorrhizal fungi are negatively impacted (Marois et al., 1983). In strawberry fields, soil bacteria are less severely affected by fumigation and recover quicker than fungi (Ristaino and Thomas, 1996). Beneficial nematodes play a role in nutrient cycling, but fumigation may reduce the diversity of nematodes and soil protozoa (Ristaino and Thomas, 1996).

Methyl bromide was used extensively as a fumigant until it was labelled as an ozone depleting substance. By 1985 bromine was found to be causing ozone depletion (Gullino et al., 2005). Bromine was found to be 50 times more reactive than chlorine, and it not only destroyed the ozone but also freed chlorine to react with the earth's ozone layer (Gullino et al., 2005). Ozone absorbs the ultraviolet radiation from the sun, and moderates the climate on earth (Ristaino and Thomas, 1996). Ozone is very reactive and has three atoms of oxygen per molecule. Most of the ozone occurs in the lowest two layers of the atmosphere, the troposphere and the stratosphere, with maximum concentrations occurring in the 25 km above the earth's surface. There can be many negative environmental impacts in a lowered ozone concentration such as crop damage, skin cancer, eye damage and others (Ristaino and Thomas, 1996). As MB was found to be an ozone depleting substance, by law the use and imports of MB was agreed to be reduced from 1991 up to 2005 and be completely phased out by 2015 (Rosskopf and Chellemi, 2005). However with certain commodities, such as dry cured ham, California strawberries, and dates, MB would be allowed under the critical use exemptions (CUE) (USDA 2014). In addition to the U. S., other countries have phased out MB use. Fumigation with MB was eliminated in the Netherlands in 1992, followed by Denmark and other Scandinavian countries in 1998 due to concern for ground water contamination (Thomas, 1996). Other countries with similar trends of reduction or regulatory action of use of MB for agriculture are the European Union, Canada, Indonesia, and Colombia (Thomas, 1996). In the absence of MB, finding chemical or non-chemical alternatives to MB, became important.

2. Alternatives: chemical or non-chemical

Alternative fumigants are less broad spectrum and more target specific and a combination is often required to reach a certain level of pest control efficacy and response to yield (Noling, 2002). In the absence of MB, strawberry growers in the Mid-Atlantic and Southern U.S. have been using combinations of 1,3-D (1,3-Dichloropropene) and chloropicrin. The former is effective in controlling soil borne nematodes but provides inconsistent weed control (Noling, 2002). The risk of cancer is increased with the exposure of 1,3-D to humans (Carter et al., 2005). Pic is used for broad-spectrum control of fungi, microbes, insects and other harmful pests, but is ineffective against nematodes and weeds. For humans, Pic may cause irritation of the throat and nose and may cause tears and it is advisable to wear loose fitting clothes, socks, shoes and a full face shield when applying the fumigant (Fan et al., 2004). These alternative fumigants are much more variable and not so consistent as MB in response and need uniform application, distribution and conditions in a field which may not be feasible at every location (Noling, 2002). Unlike MB, the weather conditions before and after application of alternative fumigants may have a role in the efficacy of the product and may result in reduced efficacy and yields when plots are treated with alternative fumigants relative to MB (Noling, 2002).

Fumigants that may be used in the annual plasticulture strawberry production in southeastern states are Telone II (1,3-D), Telone EC, Telone C17 (1,3-D + chloropicrin), Telone C35 (1,3-D + chloropicrin), InLine (1,3-D + chloropicrin), Pic-Clor 60 (chloropicrin + 1,3-D), Pic-Clor 60 EC, Metam potassium, Metam sodium, Chloropicrin, Paladin (dimethyl disulphide), Paladin EC, and Dominus (allyl isothiocyanate). Research has shown that combinations of these fumigants may be required as none are as broad spectrum as MB.

To find an alternative chemical to replace MB is difficult; rather a diverse cultural and management set of practices would give the growers more options (Ristaino and Thomas, 1996). These practices could include new techniques for soil injection and fumigant distribution, reduction of emissions from the fields, incorporation of herbicides due to lack of weed control, and adoption of new tillage and irrigation practices (Noling, 2009).

In land where intensive agriculture is practised and a crop is repeatedly produced on the same land, there is a possibility of having a pest population buildup that would cause root diseases. So adopting measures to ensure crop productivity is necessary (Katan et al., 2004). The different cropping systems would need different solutions and the same alternatives to MB cannot be used under all circumstances (Katan et al., 2004). The different alternatives vary in their degree of efficacy, cost, environmental effect, and other parameters (Katan et al., 2004).

For strawberry growers, non-chemical approaches include crop rotation, flooding, sanitation, fallowing, resistant cultivars, soil solarization, steaming, biological control, biofumigation, and others (Ristaino and Thomas 1996; Katan et al. 2004). Methods such as crop rotation and sanitation are not as effective as MB but they do help to reduce inoculum in soil so that there is a reduction in the use of drastic and expensive disinfestation methods as fumigation (Katan et al, 2004). In biofumigation, organic amendments added to soil and covered with a tarp, prevent the escape of the volatile compounds generated from these amendments, thus increasing the effectiveness of the method. Soil solarization combined with chicken compost have been effective in increasing the yield of lettuce (*Lactuca* L.) by controlling the root knot nematode (*Meloidogyne* spp.) (Gamliel and Stapleton, 1997). When the strategy is to combine methods, the phenomenon of weakening is used, when the pest propagule is weakened and becomes more vulnerable as a result of the synergic effects associated with combined treatments (Katan et al., 2004). In general, controlling soilborne pests is more difficult than the foliar ones as all soil niches have to be reached and also the pest population has to be reached and density reduced considerably (Katan et al., 2004). In addition, the control agent should have minimal harmful effect on the beneficial soil organisms and itself should be able to withstand all processes of the soil (Katan et al., 2004). Many non-chemical approaches may need additional measures simply because adequate pest control is not sufficient without it (Noling, 2002). The complexity of the issue of pest management in agriculture requires an integrated management approach (Noling, 2002). The shift from MB to other management strategies may also cause a shift in pest diversity and density (Noling, 2002).

3. Soil Solarization

3.1 History and Application

Solar radiation or soil solarization (SS), using the sun's energy to fumigate soil, was used as early as 1939 to control diseases in tobacco (*Nicotiana tabacum* L.) (Grooshevoy, 1939). In ancient civilization in India, solar energy was used to control biotic agents in soil and plant material (Raghavan, 1964). Though the exact nature of the plant pathogen was not known, here plants were exposed to heat. In Hawaii, SS was adopted to control nematodes (Phylum Nematoda) in pineapple (*Ananas comosus* (L.) Merr.) production (Hagan, 1933). Soil solarization is carried out in the warmer months (Katan et al., 1987). There are two belts of SS, one in each hemisphere, the northernmost site being Wellsbourne, UK, at 52 ^{o} N latitude and the southernmost being Victoria, Australia at 38 ^{o} S latitude (Katan et al., 1987). Soil solarization has been applied in many countries, including Israel, Japan, and USA. In Japan, SS has been widely adopted for the greenhouse vegetable industry where during summer months the greenhouses could be effectively heated by keeping them closed and then planted in fall (Stapleton, 1996). Soil solarization was first described in 1976 as a preplant treatment of soil to control weeds and pathogens (Katan et al., 1987). In the initial publications, the main emphasis was on the control of *Verticillium wilt* in solanaceous crops (Katan et al., 1987). The scientists at University of California at Davis also reported the control of *Verticillium* in cotton field, thus emphasizing the wide applicability of the method, and its role in control of diseases in the field. The findings from a study done in 1973-74 and the potential of SS in controlling disease and weeds under field conditions when the field is covered with clear plastic during hot summer months was first presented in a meeting of The Phytopathological Society of Israel in February 1975.

3.2 Factors influencing soil solarization.

Preplant SS treatment is achieved by covering soil with a clear polyethylene tarp during the summer season when soil temperatures are higher. The clear plastic film or tarp allows radiation to pass through, and traps heat which increases the soil temperature to a level that is often lethal to pathogens, insects, and weeds. The method of soil heating is termed passive, as the solar energy is transported through soil by thermal diffusion. Several factors such as soil structure, color, moisture, air temperature, and radiation determines the success of the process (Yates et al., 2011). In California climactic conditions, SS resulted in higher temperatures at the upper soil surface compared to the deeper in the soil, and a reduction of soil biota were achieved in the upper soil surface; but the upper surface could be also be subject to daily temperature fluctuations (Stapleton and DeVay, 1986). In another study, soil temperature was lower at 46 cm depth (about 32º to 37º C) compared to a depth of 5 cm (about 42º C to 55º C) (Elmore et al., 1997). In this process of treatment application, soil water content should be at least 70 % of field capacity, the soil should lack air pockets and there should be good contact between the soil and the tarp (Elmore et al., 1997; Marquez and Wang, 2014). The higher the OM (organic matter) content in soil, the higher the efficacy of SS (Minguez-Medina, 2000). Using organic amendments with SS improves pest control due to the formation of toxic compounds, and increases soil temperature by 1-3º C (Rubin et al., 2007). In SS treatments there is an effect called the "border effect" where soil temperature gradually decreases from the middle towards the edge of the plastic mulch (Grinstein et al., 1995). Plant growth is also retarded towards the edge of the plots, showing the partial efficacy of the process. This could be due to heat loss at the edges to non-solarized plots, indicating less effect of solarization at the edges. This border effect was first shown by Jacobsohn et al. (1980) where in a study, *Orobranche* L.(broomrape) was not sufficiently controlled towards the edges, and *Daucus carota* L.(wild carrot) near the edges were stunted. (Grinstein et al., 1995). Another explanation for the border effect would be heat loss at the border and reinfestation of the border with pests from non-solarized areas (Grinstein et al., 1995). The border effect is less pronounced when solarization is combined with fumigants (Grinstein et al., 1995).

3.3 Efficacy of soil solarization on soil borne pests and crop yield.

To achieve a certain level of control of pests, soil temperature needs to be more than 40º C for several hours (Yates et al., 2011), though organisms vary in their requirement of temperature and exposure time and many soil pests are killed above 30º C to 33º C (Elmore et al., 1997). Soil solarization is good for shallow rooted crops like strawberries and other small fruits as the clear tarp can be left after treatment of soil bed and plug plants can be planted later on in the season. This may be helpful for weed control, and also root development in the early season (Pinkerton et al., 2002). Soil solarization controls annual weeds better than perennial weeds, and its effectiveness depends on factors like weed species, type of plastic used, duration of exposure, day length, and depth of seed in the soil. In a study in California, solarization was seen to be effective in controlling annual weeds though not as effective as MB and Pic (Hartz et al., 1993). In the same study, strawberry yield in solarized plots were 12% greater than nonsolarized plots. In a strawberry trial, SS did not control weeds as well as MBPic or steam (Samtani et al., 2008). In a Calla Lily (*Calla pallustris*) trial, compared to black plastic control, SS had better control of weeds such as yellow nutsedge (*Cyperus esculentus L.*), common chickweed (*Stellaria media* (L.)Vill.), prostrate knotweed (*Polygonum aviculare*) and little mallow (*Malva parviflora*) (Railbot et al. 2008). Steam and steam + SS treatments effectively controlled weeds similar to that of MBPic, but SS alone (four week period) was not effective in controlling weeds, or reducing hand weeding time as MBPic (Samtani et al., 2012). Plots treated with SS for 45 to 50 days had 10 ^{0} C higher temperature compared to nonsolarized plots and was effective in controlling many weeds as common purslane, annual bluegrass, redroot pigweed, wild radish and wild chamomile; horseweed was not controlled (Boz, 2004). In Victoria, Australia, a decrease in the inoculum level of pathogens mostly in the upper surface between 0-10 cm occurred in naturally and artificially inoculated soils and this resulted in better root growth (Porter and Merriman, 1985). Soil solarization delayed the development of disease. There has been conflicting reports of control of nutsedge species and root knot nematode by SS (Chellemi, 2002). In general purple nutsedge (*Cyperus rotundus*) has been seen to be resistant to SS (Elmore, 1991). In Washington and Oregon, SS has potential to control plant pathogenic fungi, nematodes, weeds, and bacteria in small fruit crops (Pinkerton et al., 2009). In raspberry and strawberry production, SS showed promise for controlling root diseases including the ones caused by *Phytophthora fragariae* var. *fragariae* and *P. fragariae* var. *rubi* (Pinkerton et al., 2002). In New York, raspberry root rot control has been possible by applying a fungicide and gypsum to raised beds (Maloney et al., 2005). The effectiveness of such practices may be enhanced by SS (Pinkerton et al., 2009). One destructive fungal pathogen of strawberry is *Phytophthora cactorum* (Lebert & Cohn) Schrot which causes leather rot on fruits and wilt and crown rot of foliage and wilt in plants (Porras et al., 2007). In Spain, combinations of SS and *Trichoderma* treatment reduced *P. cactorum* populations in soil and also increased yield (Porras et al., 2007) indicating that SS could be a part of integrated management to manage *P. cactorum* in strawberry. Efficacy of SS can be improved by addition of pesticides, organic fertilizers and biological agents, particularly in cooler areas (Elmore et al., 1997). There have been some variations and adaptations to SS too, as using a clear tarp, then painting it white and using it as a mulch, or integrating it with pesticides or cruciferous residues or fertilizers with ammonium nitrogen (Stapleton, 1996).

3.4 Major constraints for soil solarization

The major constraint of SS is however, the long duration of the process and the dependence on weather (Rubin et al., 2007). For field applications, a minimum of about 4 to 6 weeks of SS treatment is recommended (Elmore et al., 1997) so that soil is heated to the greatest depth. Longer treatment periods of SS may not be feasible treatment for all berry growers in the southern region of the U.S. due to limited land and labor resources. Berry growers that rely on pick-your-own operations prefer to grow strawberries near road stands or where they can provide best access at their farms to consumers. These growers tend to use the same land for multiple seasons. Most growers depend on family help during the picking season in May-June and are not practically prepared to transition to earlier site preparation in mid-to- late July to ensure a long duration of SS. Another disadvantage is that land is under treatment and vacant of crops for long period of time in summer. Solarization may be unpredictable in areas where there is high temperature with cloud cover and precipitation (Ajwa et al., 2003).

3.5 Effect of soil solarization on soil nutrients and soil microorganisms

There have been mixed findings on the effect of SS on soil properties and the mineral nutrients in the soil (Seman-Varner et al., 2008) and the discrepancies are often due to the different ways of sampling, including sampling depth and assay procedure (Stapleton et al., 1985). In Italy, there was no change in total soil C, N and P due to soil solarization, compared to the black plastic control plots, however, over time SS led to the availability of some mineral nutrients due to the mineralization of the organic material in soil. This could lead to over exploitation of agricultural soils, thus addition of organic amendments may be necessary for SS treated plots (Gelsomino et al., 2006). Success may again depend on the type of soil, moisture level, and the biological communities present in soil. There have been studies where increases in availability of K, Ca, Mg have been observed after solarization (Grunzweig et al., 1999). Results from California and Israel have shown differences in soil nutrient assays but this could be due to a different soil type, assay procedure, or depth of sampling (Stapleton et al., 1985). But Stapleton et al. (1985) did not find any differences in leaf tissue nutrient concentration in Chinese cabbage (*Brassica rapa*) and this could be due to dilution of nutrients. As availability of nutrients take place due to mineralization of organic matter, the nutrient concentration may be diluted with increased biomass (Seman-Varner et al., 2008). Other studies have found increases in water extractable K, N, Ca, Mg and Na in solarized soil (Grunzweig et al., 1999). Seman-Varner et al. (2008) found increased N, K and Mn in solarization treatments which were reflected in tissue analysis and also by increase in okra (*Hibiscus esculentus* L.) biomass.

Soil solarization affects many soil pest and organisms, mainly the ones which are mesophyllic but does not affect thermotolerant fungi and *Bacillus* species (Stapleton and DeVay, 1981). The enhanced plant growth as a result of SS may be due to changes in microflora (Pinkerton et al., 2002). *Trichoderma* spp. have been reported to be the dominant colonizer of heated roots (Katan, 1981). The same was found of many fluorescent pseudomonads (Stapleton and DeVay, 1984). This could be of value, as the recolonization may provide protection to the plant roots against surviving pathogens and also the beneficial organisms could prolong the effect of the solarized treatments (Stapleton and DeVay, 1984). The predominant gram-positive bacteria that survived after SS are the *Bacillus* spp., which are beneficial for plant growth. This along with other thermotolerant microorganisms and thermophilic fungi may produce antibiotic metabolites, especially, in soils that have organic matter to colonize (Stapleton and DeVay, 1984). The *Pseudomonas* population and *Bacillus* sp. increased in a lettuce rhizosphere when grown in solarized soil compared to non-solarized control, which could be integral in suppressing pathogens and increasing plant growth in solarized soil (Gamliel, 1993). Stevens et al. (2003) reported similar findings for tomato and sweet potato. In another study a shift in the microbial community was seen when SS is applied alone or with chicken litter (Stevens et al., 2003). Chicken litter combined with SS proved to be very pesticidal and reduced diseases of sweet potato and controlled southern root knot nematode and increased lettuce yield for two years (Gamliel and Stapleton, 1993). Solarized soils supported indigenous vesicular arbuscular fungi (VAM) fungi populations compared with soil fumigated with MB (Afek et al., 1991). The VAM fungi are beneficial to plants in many ways, not only does they increase plant growth but also facilitates uptake of nutrients in many plants (Afek et al., 1991). A study by Afek et al. (1991) showed that there was great benefit of VAM inoculation and solarization. In the same study it was found that in solarized and tarped soil, roots of cotton, onion and pepper were longest compared to control plants that were VAM-inoculated and non-inoculated (Afek et al., 1991). Instead of considering SS as effective as MB, consider it as an effective tool that may be used at places where use of conventional fumigants is restricted (Hartz et al., 1993). There is also potential to evaluate the role of other bio amendments with SS. Though mainly used as a preplant method, SS has also been used in existing orchards of *Pistacia vera* L.(pistachio) to control *Vertcillium* (Ashworth, 1982).

4. Paper

4.1 History of use of paper mulch in agriculture and gardens

The first use of paper for mulching was in Florida by Mrs. E. W. Berger for her roses (*Rosa* L.) (Berger, 1915). She found the newspaper very effective in controlling weeds. C. F. Eckart, a manager of a sugar plantation in Hawaii, began experimenting with asphalt paper in 1914 and found that this method proved to be very effective in controlling weeds and it improved plant growth (Eckart, 1923). It proved to be so effective that the pineapple industry adopted the same method, and by 1927, 90 % of the crop was grown in this manner (Hutchins, 1933). In the U.S., perhaps L. H. Flint of the United States Department of Agriculture was the person who found there were advantages of using paper in vegetable production as it increased yields, decreased weeds, increased size and quality in some crops, prompted early crop maturity, and often increased germination percentages (Flint, 1928). When the Society of Manufacturing of Roofing Paper conducted experiments in Germany with paper mulches on more than twenty different crops, they found that the soil temperature was increased to 4^o to 5^o F and also better soil structure prevailed (Smith, 1931). *Cucumis* L. (melons), *Cucumis sativus* L. (cucumbers), and tomatoes showed an increase in crop yield with the paper treatment compared to the control. In field conditions in Hawaii, more soil nitrate was found in paper mulched plots possibly due to rapid degradation of the nutrients and the harvested pineapple were 30 to 40 per cent heavier from black plastic control plots (Smith, 1931). Flint worked with paper mulch in Rosslyn, Virginia, and found a stimulation in plant growth (Smith, 1931).

4.2 Advantages of paper mulch

Paper may influence vegetable production by having an effect on environmental factors, such as soil temperature and moisture. As some landfills do not accept waste paper due to limited space, paper could be applied on cultivated land as a mulch or a soil amendment (Unger, 2001).There may be conservation of moisture by preventing evaporation, increased nitrification under paper, increases in soil temperature, as well as soil texture and flora being affected. The effect on yield has been variable. Most cases however have reported a beneficial effect on plant growth. Paper is biodegradable and increases organic matter content of soil (Upadhyaya and Blackshaw, 2007).

In a study with shredded newspaper, wheat straw and bare soil with *Zea mays L*. (sweet corn), field corn, *Glycine max* (soybean), and *Solanum lycopersicum* L. (tomatoes), the soil was cooler and more moist due to the mulches compared to bare soil, and also many annual and some perennial weeds were suppressed (Munn, 1992). Soil temperature was cooler for straw and newspaper compared to the bare soil, but this was mostly seen in the cooler month of June in Ohio, but in warmer months there were no significant differences among treatments. Using rates of newspaper mulch as high as 35867 kg ha^{-1} did not have a detrimental effect on growth of soybeans and corn, and also there was no accumulation of heavy metal in the soil (Munn, 1992). The yield was higher and plants were larger with newspaper mulch compared to bare soil (Munn, 1992). One of the advantages of using newspaper is that it is free of weed seed whereas straw may introduce different weed seeds (Munn, 1992). In several projects with newspaper as compost and mulch, there was no increase in polychloroaromatic hydrocarbons (PAH) and heavy metals (McGrath, 1991). Various chemicals containing benzene may be present in the ink of newspaper but an experiment conducted with wheat did not show any detectable level of complex PAHs, though less toxic PAHs were found at the rate of 80 parts per billion. Similar level was also found in wheat grown in peat. Any country with an industrial background may have some chemicals including PAHs in soil (McGrath, 1991). Compared to the control, black paper increased yield between 20 to 25 per cent and increased soil temperature between 3 to 4.5° F (-16.1° C to -15.3° C) at a depth of 8 cm (Smith, 1931). At Davis, California, it was found that the nonperforated black paper conserved moisture the most at a depth of 0.1 m under dry, nonirrigated conditions. Yield in paper mulch treated *Sorghum* Moench (sorghum) and potatoes was higher than the control treatment. The greater the surface area covered by paper, the more positive effect it had on soil moisture, temperature, and yield (Smith, 1931). Moisture conservation due to paper mulch did not extend beyond a depth of 10 cm (Smith, 1931). In paper mulched plots, Smith did not find higher nitrates in soil, though plants contained higher nitrate levels by the Hoffer test compared to bare soil plants. An increase in yield of *Brassica oleracea* L. (cabbage), tomatoes and *Capsicum* L. (peppers), and an increase in earliness and yield of beans, cucumbers and sweet corn occurred when grown in a fertilized sandy loam soil, but no influence was seen on yield for lettuce when mulch paper was used (Edmond, 1929). The highest increase in yield was seen with cucumbers and the least in sweet corn (Smith, 1931). In Spain, a two-year study conducted with polyethylene plastic, biodegradable plastic, and four different papers showed that the paper mulched plots gave good weed control of all weed species including purple nutsedge (Cirujeda et al., 2012). The paper mulches had yields similar to that of polyethylene or biodegradable plastic and as long as paper mulch was able to resist pressure and did not tear, the nutsedge plants were not able to break through it and thus developed yellow leaves (Cirujeda et al., 2012). In the paper mulched plots the weeds grew where there was a tear or at the planting holes but were not able to pierce the paper (Cirujeda et al., 2012).

In Quebec, *Lactuca* L. (lettuce) was grown on different mulches including paper (830 kg ha^{-1}) and polyethylene and compared with a non-mulched control. Improved weed control was achieved with polyethylene or paper mulch that had at least one side black, and about 25% more marketable yield and heavier heads were achieved under paper or polyethylene mulches than the unmulched lettuce (Jenni and Brault, 2004). Paper mulch may be suitable for cool season crops as it does not heat the soil as much as clear or infrared transmitting polyethylene (Jenni and Brault, 2004). Paper can also be easily disked into soil. Paper may also help the water to reach roots more easily as it is more porous compared to polyethylene to rain and irrigation water (Jenni Brault, 2004). In Florida, experiments were conducted with hydramulch, a paper like material, applied as a slurry on soil, which not only remained intact, but also suppressed broadleaf weeds and grasses, except purple nutsedge (Warnick et al., 2006). The soil temperature under the hydramulch was 1-4 º C less, than the temperature under the black polyethylene mulch, and perhaps suitable for the fall crops (Warnick et al., 2006). As an alternative to black plastic, brown paper sheets with and without vegetable oil has been evaluated with transplanted basil (Miles et al., 2005) and they found that paper mulch resulted in effective weed control. Paper has also been used in *Lactuca L*. (lettuce), *Brassica oleracea* var. *italica* (calabrese) and *Brassica rapa* (Chinese cabbage) in the UK (Runham and Town, 1995) and paper controlled weeds as good as black plastic mulch and the crops matured at a similar time to other treatments and had comparable or better yield than plots treated with herbicides (Runham and Town, 1995). In the Netherlands, black and brown paper mulches applied on soil surface have been used in the salad and flower crops (Upadhyaya and Blackshaw, 2007) and was effective in controlling weeds though tearing of brown paper remained an issue. As paper mulches age, the optical properties may change, allowing for more light to pass through resulting in weed growth (Upadhyaya and

Blackshaw, 2007; Brault and Stewart 2002). For weed suppression, the mulch should adequately cover the surface and light transmission in the PAR (photosynthetically active radiation) region should be low. Weed germination depends on the type of light wavelength and the total amount of light transmitted (Ngouajio and Ernest, 2004). The use of paper pellets as a mulch did not affect *Sorghum* Moench (sorghum) yield, nor conserved soil water. Many storms in the southern Great Plain over the growing season provided little moisture, which the paper pellets intercepted and caused less entry of water to soil and increased evaporation loss from pellets (Unger, 2001) The incorporation of paper pellets at a shallow depth may be better than surface application as it would hasten the decomposition and help to improve the conditions of the soil (Unger, 2001). Soil C concentration, physical condition of the soil, and crop productivity is increased when paper pellets are decomposed (Unger, 2001).

4.3 Challenges with paper mulch

A major problem is that paper mulch begins to degrade during the growing season, though a lot depends on soil and temperature conditions (Stewart et al., 1995). Paper loses strength when wet and rapidly degrades after field application. To increase its strength, a number of coatings have been used, such as tar (Rivise, 1929), wax, polyethylene (Vandenberg and Tiessen, 1972), latex (Brault et al., 2002), polyesters (Rangarajan, 2000) and vegetable oil (Anderson et al., 1995). Though kraft (strong paper made from chemical pulp by the kraft process) paper coated with soybean or linseed oil and cured in the sun and air are as good as polyethylene mulches for growing watermelon (Shogren and Hochmuth, 2004) and cottonwood trees (Shogren and Rousseau, 2005), the whole process is cumbersome. One problem of using newspaper is acidification of the soil that may occur as the newspaper breaks down. Color printed magazines could be toxic. The penetration of paper fibres by bacteria and fungi is slowed by coating the paper with oil as it acts as a barrier (Shogren, 1999). Weed growth is very rapid for uncoated paper compared to coated paper. Oil-coated paper is resistant to water vapor transmission though less than that of polyethylene (Shogren, 2000). In Florida for watermelon production, paper coated with vegetable oil was a good substitute for polyethylene mulch but oil saturated paper mulch was difficult to apply when it is handled in the field, it has a higher cost than polyethylene mulch, and has a relatively long application time and depending on weather and soil conditions, the rate of degradation may vary (Shogren and Hochmuth, 2004). Kraft paper coated with resin made from epoxidized soybean oil and citric acid and then thermally cured, proved to be more durable and takes more time to biodegrade than the uncoated paper (Shogren, 1999; Shogren, 2000).

5. Corn Gluten Meal

Corn gluten meal (CGM) is a dry, concentrated byproduct, obtained when corn is processed to extract corn starch and syrup. It is also a natural fertilizer as it is 10% total nitrogen by weight. Different processor source of corn gluten meal did not show any difference in activity (Nonnecke and Christians, 1996). Corn gluten meal application could have a dual function, controlling small weed seedlings and providing nitrogen slowly when added to soil.

5.1 Effect on weeds

Corn gluten meal does not affect established plants but prevents weed seed germination by preventing normal root development under dry conditions. If the soil remains wet, root development may be resumed and its effectiveness may be reduced (Christians, 1993). In 1986, an experiment at Iowa State University with food grade corn meal led to the patenting of this natural, organic product for the control of annual weeds (Christians, 1986). In 1991, CGM was patented as a preemergent weed control tool (Christians, 1986). Corn gluten meal has shown to be effective in controlling weeds such as purslane (*Portulaca oleracea* L.), giant foxtail (*Setaria faberi),* common lambsquarters (*Chenopodium album L.*), creeping bentgrass (*Agrostis palustris Huds*.), curly dock (*Rumex crispus* L.), redroot pigweed (*Amaranthus retroflexus* L.), and smooth crabgrass (*Digitaria ischaemum* (Schreb.) Screb.ex Muhl.) (Bingaman and Christians, 1995) and used for turfgrass, small fruits, and vegetables grown in residential and commercial plots (Chalker-Scott, 1990). The CGM needs to be applied when weed seeds are germinating and may be applied in early spring when forsythia (*Forsythia* spp.), crocus (*Crocus* L.), daffodils (*Narcissus* L.) and tulips (*Tulipa* L.) bloom. In fall recommendation is to apply between mid-August and mid-September (Cox, 2005). Though CGM is produced as a fine yellow powder for easy application to soil, it may be easily converted to pellets. Using CGM with transplants may be feasible but direct seeding of some vegetables in soil where CGM is added is not advisable (McDade and Christians, 2000). A greenhouse study with increasing rates of processed corn grain as corn fiber, corn germ, corn gluten meal and starch were used and creeping bentgrass was seeded on top. The CGM rates used were 0, 6,800, 13,600 and 27,200 kg ha^{-1}. The inhibitory action was due to the corn gluten meal (Christians, 1986) and inhibited root formation in many grasses and broadleaf species including crabgrass (*Digitaria* Haller). Microbial activity and excessive periods of wetness can reduce the effectiveness of CGM (Christians, 1986). The drawbacks of CGM are that it may not provide complete weed control and may cost more than synthetic pesticides (Christians, 1986). This product provided better broadleaf weed control than narrow leaf weeds control in sandy soil (Abouziena et al., 2009). Amongst grasses, CGM provided control of *Lolium multiflorum* (annual ryegrass), *Dactyloctenium* Willd. (crowfoot grass) and *Acrachne* Chiov. (goosegrass), substantial control of *Setaria viridis* (green foxtail) and moderate (less than 77%) controls of *Sorghum halepense* (L.) pers. (Johnsongrass) and *Cyperus esculentus* L.(yellow nutsedge) in sandy soil (Abouziena et al., 2009). Corn gluten meal efficacy was affected by media type; the same weeds had different rates of control in a commercial potting mix and a sandy soil. Direct seeding of many vegetables is not advisable on soils treated with CGM, as it led to reduction of seedling survival (McDade and Christians, 2000). Using CGM with transplants may be better as the herbicidal effect as well as the nitrogen is beneficial. Using CGM as a herbicidal spray may be difficult due to its inability to dissolve in water (Liu et al., 1994). Enzymatically hydrolyzed CGM has been more herbicidal than CGM in greenhouse and growth chamber studies. The EPA has classified this as a 'minimum risk pesticide' and does not require registration (Cox, 2005). Corn and its byproducts may cause allergies to some people (Cox, 2005), and thus exposure to CGM should be avoided in some cases. Most CGM products recommend application twice a year, once in spring and once in fall at a rate of 556 to 1000 kg ha^{-1} of lawn (Cox, 2005). In a greenhouse study, CGM at 0, 3,240, 6,490, and 9,730 kg ha^{-1} was tested as a soil surface preemergence weed control product and its efficacy was evaluated on twenty two weed species; of which black nightshade (*Solanum nigrum* L.), common lambsquarters (*Chenopodium album* L.), creeping bentgrass (*Agrostis stolonifera* L.), curly dock (*Rumex crispus* L.), purslane (*Portulaca* L.) and redroot pigweed (*Amaranthus retroflexus*) were most susceptible at the CGM rate of 3,240 kg ha^{-1} (Bingaman and Christians, 1995). Plant survival rate and root growth of these species were reduced by ≥75% when CGM was used at a rate of 3240 kg ha^{-1}. When CGM was incorporated into soil, the effectiveness increased perhaps because it was in contact with the germinating seedlings. Broadleaf weed species were found to be more susceptible than the grasses (Bingaman and Christians, 1995). A greenhouse study that compared the herbicidal effect of CGM and MSM (mustard seed meal which is a byproduct of the oil extraction process) on emergence and dry weight of five broadleaf species and two grass species, found that at the application rates of 2,240, 4,480 and 6,720 kg ha^{-1}, MSM was more effective or equal to CGM in controlling weeds (Yu and Morishita, 2014). In 'Jewel' strawberry (*Fragaria* L.) plots, CGM was evaluated alongside the herbicide dimethyl tetrachloroterephthalate (DCPA) to see the effect on weed control and growth and development of strawberry plants (Nonnecke and Christians, 1996). There were two experiments in subsequent years; in the first year, CGM rates were 0, 1,000, 2,000, 3,000 kg ha^{-1} and in the second year rates were 980, 1,960, 2,940 kg ha^{-1}. In both seasons DCPA was used at 11.2 kg ha^{-1}. Application of CGM was made several times a year. The plots that received DCPA had the least number of grass weeds, whereas the CGM-treated plots had similar or fewer number of broadleaf weeds than the DCPA plots. Plots with four applications of CGM reduced total yield and average fruit weight possibly due to excessive nitrogen and also did not show any better weed control than plots receiving two applications of CGM, one at renovation during July, and the other at flower development during August (Nonnecke and Christians, 1996). Tests conducted in University of California showed only marginal efficacy of CGM as a herbicide. There remains use of such products as long as there is a market for 'natural' herbicides (Wilen and Shaw, 2000). When synthetic herbicides are used, more than 80% control is expected, a level which is not obtained when CGM is used. The cost of CGM is also high, about $ 418/A compared to synthetic herbicide which can be as little as $30/A (Wilen and Shaw, 2000). Cities as San Francisco, where pesticide use is limited, find it useful to control roadside weeds using CGM (Wilen, pers. comm.). If weed control is not adequate prior to application, the nitrogen in CGM may help the desired plants as well as the weeds to grow (Chalker Scott, 1990). Corn gluten meal is selective in turf, and greenhouse studies indicated greater effectiveness with increasing rates and cost. Reducing chemical inputs and adopting sustainable approaches is welcome to many growers especially as cranberry, is grown in wetlands and areas of suburbanization. Corn gluten meal did not effectively control weeds over black plastic control plots in cranberry (*Vaccinium macrocarpon* Aitum) production (Sandler and Ghantous, 2014).

About five dipeptides along with alaninyl-alanine have been separated from CGM which have inhibitory properties. The inhibitory action is mainly on roots. A study was conducted to see there were morphological and anatomical differences observed in perennial ryegrass when treated with alaninyl-alanine, a dipeptide. At all concentrations, root length was reduced by at least 42% and the root tips did not have nuclei and mitotic structures. Cell wall abnormalities were also observed which included breakage and uneven thickening at epidermal and subepidermal layers (Unruh et al., 1997).

5.2 Corn gluten meal integration with other products

The effectiveness of CGM (4000 kg ha^{-1}) could be improved by spraying in conjunction with 5% citric acid and 2% garlic or 30% acetic acid (Abouziena et al., 2009). In production systems where synthetic herbicides are not used, CGM may be used with other cultivation techniques (Dilley et al., 2002). Using CGM in broccoli (*Brassica oleracea* L.), and cauliflower (*Brassica oleracea*) production did not show any detrimental effect on dry root or shoot weight of transplants (McDade, 1999). It can also be used in combination with synthetic herbicides for weed control at lower label rates. About 75-85% reduction in crabgrass has been reported when combined with reduced rates of pendimethalin (Wilen and Shaw, 2000).

5.3 Corn gluten meal as a nitrogen source

In organic production, supplying nitrogen can be an issue which is attained by adding of manure and following legume-based crop rotations (Forcella et al., 2010). But rotation, Rhizobially fixed nitrogen require time and thus any additional nitrogen source, like protein rich products, may be beneficial for their crops. Corn gluten meal is of interest as it releases nitrogen over a period of 1 to 4 months when added to soil. When CGM was applied to nitrogen deficient turf at rates of 488.2 kg ha^{-1} and 976.5 kg ha^{-1}, it improved the appearance of turf, and the turf was able to resist weed invasion, but this effect was not apparent in well fertilized turf (Wilen and Shaw, 2000). Cranberry plants which received CGM showed considerable growth, probably due to the fertilizer effect of CGM (Sandler and Ghantous, 2014).

6. Mustard seed meal

6.1 Mode of action

Mustard seed meal (MSM) is a by-product of the mustard oil extraction process. Certain plant species of Brassicaceae family possess allellopathic properties and this ability is used in some cases to inhibit weed germination, emergence, and growth (Rice et al., 2007). These allelopathic properties can be attributed to sulfur-containing glucosinolate compounds that occur as secondary plant products. Glucosinolates may be of three types:- aliphatic, aromatic, and indolyl of which the former two liberate isothiocyanates on hydrolysis (Matthiessen and Kirkegaard, 2006). They commonly occur with a hydrolytic enzyme, myrosinase (Rosa, et al., 1997). On the disruption of cellular tissue, the hydrolysis reaction takes place, releasing a variety of compounds including isothiocyanates and are the most active broad spectrum biocide compared to glucosinolate degradation products (Brown and Morra, 1997). Isothiocyanate production occurs at warm temperatures, neutral pH, and dilution with water (Matthiessen and

Kirkegaard, 2006). One advantage of using MSM is that the myrosinase enzyme is preserved during crushing (Brown and Morra, 1996) and due to the low moisture content of meal, the glucosinolates are stable for a long time (Rice et al., 2007). Proper measures (as having a few days gap between incorporating and planting the crop) need to be taken while using MSM as it is non-selective and as a herbicide may harm the crop and the weed (Webber et al., 2003).

6.2 Mustard seed meal activity on soil borne pests

In a greenhouse study on apples (*Malus* Mill.) where *Brassica juncea*, *B. napa* and *Sinapsis alba* seed meals were evaluated for suppression of soilborne pathogens contributing to the replant disease, the seed meal enhanced growth of apple compared to the untreated (Mazzola et al., 2007).When MSM was applied at rates of 1,130, 2,250, and 4,500 kg ha^{-1} in containers, it controlled annual bluegrass, common chickweed, and when applied on soil surface at 2,250 kg ha^{-1}, MSM controlled creeping woodsorrel (*Oxalis corniculata* L.) (Boydston et al., 2008). Mustard seed meal controlled weeds better in tarped conditions than in untarped ones. Under tarped conditions in a greenhouse, MSM controlled annual bluegrass, broadleaf plantain, white clover, and common chickweed when used at a rate of 1,680 kg ha^{-1} but the result was less consistent under untarped conditions (Earlywine et al., 2007). For early season weed control, there may be some efficacy of MSM, but it does not last throughout the growing season (Rice et al., 2007; Al-Khatib et al., 1997). Seed meal from *S. alba* was more herbicidal than *B. juncea* or canola (*B. napus L.*) when applied at similar rates (Brown et al., 2006; Hoagland et al., 2008). Brown et al. (2006) found reduced weed biomass and emergence by *S. alba* seed meal compared to the untreated in strawberry production when used at a rate of 2,000 kg ha^{-1}. Usually MSM pellets is in the form of large irregular parts, which perhaps need to be made into smaller parts for more efficacy. The meal should be put near the germinating seedlings of weeds and uniform coverage is necessary to be effective (Boydston et al., 2008). In strawberry production, increasing the rate of MSM from 560 kg ha^{-1} to 4,484 kg ha^{-1} did not have any effect on grass (as tall fescue (*Festuca arundinacea*) or ryegrasses (*Lolium* spp.) or nutsedge, but did have better control on broadleaf weeds (Deyton and Sams, 2010). Though the reason for a yield increase is not known, plots treated with MSM between 2,240 to 4,480 kg ha^{-1} increased berry yield 20 to 29%. In 2004, using MSM applied at 1120 kg ha^{-1} to 4480 kg ha^{-1} increased fruit size around 7%. The yield increase was seen in both seasons with use of MSM (Deyton and Sams, 2010). In California, several non-fumigant treatments as MSM, furfural, steam and *Muscodor albus* were evaluated in strawberry production (Samtani et al., 2011) and they observed that MSM (at a rate of 2242 kg ha^{-1}) was either moderately effective or ineffective in controlling weeds. Though weeds were not controlled, at least in one growing season, in 2007-2008 there was higher yield in Watsonville, CA in strawberry yield for MSM treatments. The following growing season there was no yield differences between treatments (Samtani et al., 2011) though for weed control there were significant treatment differences. In the Pacific Northwest, MSM at 644 kg ha^{-1} and with low glucosinolates, controlled broadleaf weeds and MSM with high glucosinolates aided in controlling both the broadleaf and the grass weeds (Miller et al., 2013). High glucosinolate MSM (at the rate of 644 kg ha^{-1}) also decreased the berry yield and fruit weight at one location (Miller et al., 2013). The low glucosinolate MSM treatment did not influence weeding time or berry yield but did help in increasing the vegetative area (number of runners and daughter plants in strawberry) (Miller et al., 2013). Mustard seed meal has been used to control weeds in onion, potato, peppermint, and turf and the range has been extensive, starting from common chickweed (*Stellaria media* (L). Vill.), large crabgrass (*Digitaria sanguinalis* L. Scop.), prickly lettuce (*Lactuca serriola* L.), wild oat (*Avena fatua* L.), Italian ryegrass (*Lolium perenne*

L. spp. multiflorum Lam. Husnot.), kochia (*Kochia scoparia* (L) Schrad.), green foxtail (*Setaria viridis* (L). Beauv.), redroot pigweed (*Amaranthus retroflexus* L.), common lambsquarters (*Chenopodium album* L.), barnyard grass (Echinochloa crus-galli L. Beauv.), buckhorn plantain (*Plantago lanceolata* L.), annual sowthistle (*Sonchus oleraceous* L.) to name a few. While using MSM, some additional measures would be needed as some weeds would escape, there would be lack of control on some perennial weed species and some weeds would emerge in mid-season to late season (Webber et al., 2003).

6.3 Role of allelochemicals in agriculture

Although soil-applied organic amendments have shown some promise for weed control in greenhouse and container applications, they have not been widely applied in field scenarios as they did not attain a level of efficacy and consistency that is required for widescale adoption (Mazzola et al., 2007). Allelochemicals affect many physiological processes (Farooq et al., 2011). The allelochemicals are usually byproducts of the main metabolic pathway and can be synthesized in any plant part and under favorable environmental conditions; are released into the environment and affect adjacent plants (Farooq et al., 2011). The Austrian plant physiologist Molish first used the term 'allellopathy' meaning the interaction between plants and microorganisms (Farooq et al., 2011). The isothiocyanates obtained naturally from Brassica plants are detrimental to many soil borne pathogens and may be used as natural fumigants or biofumigants (Ntalli and Caboni, 2017). Isothiocyanates are also very toxic to root-knot nematodes. Methyl isothiocyanate, which is a fumigant, is also a naturally occurring product of glucosinolate which occur in crops as cabbage, canola, mustard, rape and broccoli (Ntalli and Caboni, 2017). The glucosinolates are found not only in the Brassicaceae, but also other families as Poaceae, Capparaceae and Caricaceae (Ntalli and Caboni, 2017). In open-field pepper production, biofumigation with rapeseed meal and chemical fumigation with dazomet were compared to the effect on soil microbial community. Biofumigation increased bacterial diversity and fungal diversity was decreased and it increased total soil N, available P and K (Ntalli and Caboni, 2017; Wang et al., 2014). Disease incidence had a negative correlation with bacterial diversity, and a positive correlation with fungal diversity (Ntalli and Caboni, 2017). With isothiocyanates in soil, several saprophytes increase in soil which have an antagonistic effect on parasitic organisms, thus prolonging the disinfestation effect in soil (Ntalli and Caboni, 2017). The isothiocyanates are released very slowly in soil, and may be volatile, may degrade or be adsorbed to soil with high organic matter (Ntalli and Caboni, 2017). Biofumigation works best when integrated with other approaches as crop rotation, solarization, biocontrol agents or chemical applications to increase its efficiency. With selection of varieties with more biofumigation potential and more effective ways of incorporating them in the soil, its efficacy in field applications would increase (Smith et al., 2001). In most oilseeds, oil is extracted by a process of cleaning, drying, dehulling, size reducing, flaking, cooking and tempering (Dunford, 2008). The last two of these are very important and is also called conditioning in which proteins are denatured, by which oil is released and enzymes are inactivated. Once a specific temperature is reached, seeds are pressed to yield the oil and the residue is known as the meal, which can be used as animal feed (Moore, 2011). The oilseed meals are rich in macro and micronutrients and have a low C:N ratios (about 5:1 to 15:1) and this makes it readily decomposable to plant available forms after application in the field. This property makes it attractive to organic growers (Moore, 2011). In 2008, many growers in the US were unable to afford P or K fertilizers (Moore, 2011). The biofuel products as ethanol and biodiesel have seed meal byproducts that may be used in agriculture. The biofuel byproducts can often be a viable option for growers if fertilizer cost seems to be too high. In Asia, fertilizer from rapeseed oil cake has been used for many years though the concept of using oilseed meal as a fertilizer is relatively new in the United States (Moore, 2011). Most organic sources of fertilizers are composts, cover crops and the animal manures. Some of the limitations of manures are that they are not easily available in certain regions and some growers and international markets may not accept it readily (Moore, 2011). Most of the oilseed meals are certified as organic sources of fertilizer in OMRI (Organic Materials Review Institute) (Moore, 2011). There are some concerns though if these meals are GMOs. Organic growers can take the benefit of the pesticidal and fertilizer potential of the MSM, but while applying it in fields, some caution should be exercised as it cannot be applied at the same time as planting, as it can harm the small plants if enough time is not given for the isothiocyanates to break down in soil (Moore, 2011). Most of the research has indicated an increase in yield when biofuel byproducts are used. In one study, seed meal treatments from canola and brassica at 0, 4483 and 13450 kg ha^{-1} were tested and Brassica meal treatments increased fruit yield in all but the highest rate where it was reduced by 42 % and some summer germinating and winter annuals were less in number in mustard than the canola or the control treatments (Bañuelos and Hanson, 2010). In the same study, experiments carried out in growth chambers showed reduction in berry yield with high application rate of meals. Mustard seed meal was also more effective in weed control than the canola meal but not in all cases. With Brassica seed meal, the weed control was variable among treatments, in some cases biomass and emergence was reduced but in other cases there could be a fertilizer effect and reduction was not so evident (Bañuelos and Hanson, 2010). But many nutrients as P, Ca, and Mn were increased in berries both in growth chamber and field studies. Type of GLS in the seed meal, and their effect on the microbial biomass and N mineralization, may have an effect on the nutrient uptake by the plant (Bañuelos and Hanson, 2010).

Objective

The objectives of the work were:

1. To evaluate treatment time of SS alone and with various amendments including CGM, MSM, and PPM and determine the effect on weed control, crop health, and crop yield in annual strawberry plasticulture production.
2. To evaluate effect of paper pellets at different dose rates alone and also in combination with mustard seed meal in annual strawberry plasticulture production.
3. To evaluate the best treatments from the previous studies at a grower's site.
4. To determine if there is any phytotoxic effect of paper pellet mulch, mustard seed meal and their combinations in container-grown *Viola tricolor* (Pansy).
5. To determine the effect of corn gluten meal, mustard seed meal and various rates of paper pellet mulch on several weed seed species in greenhouse conditions.

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Chapter II

Soil solarization, paper pellets, corn gluten meal, and mustard seed meal as preplant treatments for annual plasticulture strawberry in the Mid-Atlantic United States

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Abstract. Soil-borne pests including weeds can be a major problem in the annual strawberry (*Fragaria×ananassa*) plasticulture production system. There is a need to look at alternative strategies to preplant fumigation due to challenges in fumigant use. A field study was conducted in the 2014-15 and 2015-16 growing seasons at the Hampton Roads Agricultural Research and Extension Center, Virginia Beach, Virginia. to evaluate the effects of a three-week period of soil solarization (SS), corn gluten meal (CGM), mustard seed meal (MSM), and paper pellet mulch (PPM) on weed control, crop health, and crop yield. A total of eight treatments included: i) Corn gluten meal (CGM) at 1,709 kg ha^{-1} ii) CGM + mustard seed meal (MSM) at 1,709 + 1,121 kg ha^{-1} iii) MSM at 1,121 kg ha^{-1} iv) MSM at 1,121 kg ha^{-1} +SS v) paper pellet mulch (PPM) at 3,662 kg ha^{-1} vi) PPM at 3,662 kg ha^{-1} +SS vii) SS viii) control (black plastic). The soil solarization treatment started 19 September, 2014 and 3 September, 2015. Each replicate field plot was 3.1 m long and 0.7 m wide. In the 2014-15 growing season, plots with PPM, PPM+SS, and MSM had higher marketable yield than CGM plots, but no difference was observed during the 2015-16 growing season. Paper pellet mulch showed lower early weed density in combination with SS compared to the control (control) and did not have any detrimental effect on strawberry plants, however the effect was not consistent on crop yield and weed control throughout the season. A reduced period of SS with the amendments evaluated is not a practical preplant option for strawberry growers under coastal Virginia climactic conditions.

Keywords: fumigant, weed, berry, organic, pellets

Introduction

In Virginia about 250 acres of strawberries are grown of which 30 acres are grown in Virginia Beach (Strawberry Fact Sheet, 2014). Methyl bromide:chloropicrin (MBPic) was the fumigant of choice for soil disinfestation by fruit growers, but methyl bromide (MB) is no longer available for use as a fumigant. Methyl bromide was found to be an ozone depleting substance; by law the use and imports of MB was agreed to be reduced from 1991 to 2005 and be completely phased out by 2015 (Rosskopf and Chellemi, 2005). In the absence of MB, a common alternative is the combination of 1,3-D (1,3-dichloropropene) and chloropicrin (Pic). The 1,3-dichloropropene provides good control of nematodes and a few soil insects but is less effective for weeds and other soilborne pathogens and is often combined with chloropicrin to increase effectiveness (Noling and Becker; 1994; Lembright 1990; Munnecke and Van Gundy 1979; Radewald et al., 1987). California's Proposition 65 mentions a list of chemicals including 1,3-D, that increase the cancer risk and therefore there are limits to regulate the exposure to 1,3-D (Carter et al., 2005). The high vapor pressure of 1,3-D not only enables it to diffuse in soil but also helps to transfer from soil to air, posing an inhalation risk for those nearby, such as bystanders and agricultural workers (Ashworth and Yates, 2007). Chloropicrin is used for broad-spectrum control of microbes, insects and other harmful pests, but is ineffective against nematodes and weeds. Chloropicrin is volatile and there are health concerns about inhalation exposure to humans (U.S. Environmental Protection Agency, 2008). The use of fumigants necessitates the maintenance of buffer zones (a minimum distance between residential areas, schools and the land where fumigation is done), following farm worker safety precautions for health safety reasons, and creating a fumigant-management plan. Compared to the major agronomic crops in U.S., few herbicides are available for specialty crops and prospects of developing new herbicides for horticultural crops are bleak (Fennimore and Doohan, 2008). Many strawberry growers no longer fumigate their soils due to health and regulatory concerns, and they have a desire to cater to consumer needs of growing foods using more benign products (personal communication J. Samtani). Lack of MB availability as a fumigant, complications using available fumigants, evaluating bio-based alternatives becomes necessary to enable growers to combat pest issues and sustain yields in lieu of soil fumigation in strawberry production.

Solar radiation was used as early as 1939 to control *Thielaviopsis basicola* by heating the soil with sunlight (Grooshevoy, 1939). In Hawaii, soil solarization (SS) controlled nematodes (Phylum Nematoda) in pineapples [*Ananas comosus* (L.) Merr.] (Hagan, 1933). Soil solarization is usually done during the summer months by covering soil with a clear polyethylene tarp, which allows radiation to pass through but traps heat in the soil, thereby increasing soil temperature. During the SS process, the soil water content should be at least 70% of field capacity in the upper surface and moist to a depth of 60 cm (Elmore et al., 1997). For SS to be effective, the soil should be free of air pockets, and good contact between the soil and the tarp is required (Marquez and Wang, 2014). The increased soil temperature is often lethal to pathogens, insects, and weeds. In California climactic conditions, higher temperatures via solarization are achieved to a soil depth of 5 cm (Stapleton and DeVay, 1986). In vitro studies of many microorganisms have shown that within a few hours a temperature of 50º C or above can be lethal (Stapleton and DeVay, 1986). Many plant pathogens, insects and weeds, are killed when exposed to 65º C for 30 min (Pullman et al., 1981). Sublethal heating may decrease the ability of a propagule to cause disease (Pullman et al., 1981). The greatest reduction in soil pests occur near the surface, though the surface (15 to 30 cm) could also be subject to daily temperature fluctuations due to day and night (Stapleton and DeVay, 1986). In the deeper layers, temperature is lower compared to the surface but more constant (Stapleton and DeVay, 1986). When there is more organic matter content in soil, SS is more effective (Minguez-Medina, 2000). Although many soil pests are killed above 30º C and 33º C, some are resistant to these temperatures and may require additional measures for more effective control (Elmore et al., 1997). Gases and other products released from residue biodegradation and organic amendments could have a biofumigation effect, acting as fumigants on soil-borne pathogens (Bello et al., 1999). Soil solarization offers better control of annual weeds than perennial weeds (Hanson and Shreshtha, 2006), and its effectiveness depends on factors such as weed species, polyethylene mulch type, soil exposure duration, day length, and seed depth in the soil (Stapleton and Devay, 1986). In a strawberry study in coastal California, SS did not control weeds, primarily common purslane (*Portulaca oleracea*) and yellow nutsedge (*Cyperus esculentus L*.), as effectively as MBPic or steam. Compared to the untreated control SS was more effective for control of common knotweed (*Polygonum plebeium* R. Br.) (Samtani et al., 2012). In a Central coast of California study, steam was injected into raised beds preplant to achieve soil temperatures ≥ 70° C for 20 min to a depth of 25 cm. Steam and steam + SS treatment effectively controlled weed biomass and density, killed weed seeds and tubers of yellow nutsedge, and at 15 cm depth controlled microsclerotia of *V. dahlia*, and strawberry yield in steam-treated plots was comparable to MBPic-treated plots. The four-week period of SS without steam was not as effective in controlling weeds or reducing hand weeding time as MBPic (Samtani et al., 2012). The major constraint of SS is the long duration required for the process and the dependence on weather (Rubin et al., 2007). Soil solarization is an attractive method for small fruit production as the clear tarp can be left after treatment of soil beds, and plug plants can be planted (post-treatment) through the plastic, that not only help in weed control but also early season root development due to increased soil temperature (Pinkerton et al., 2002). For field applications, about four to six weeks of SS treatment is recommended (Elmore et al., 1997) so that soil is heated to the greatest possible depth. In Virginia climactic conditions, at least a six-week SS period is required to provide consistent weed control compared to the untreated control (Samtani et al., 2017). Six weeks or more duration of SS may not be feasible for many berry growers, as ones in the southern region of the U.S. can have limited land and labor resources. Depending on family help during the picking season in May-June and transitioning to a new growing season in mid to late July when the soil needs to be prepared and covered by a clear tarp, ensuring a long duration of soil solarization, may not be a feasible option. A longer period of eight to ten weeks SS period keeps the land vacant of crops which is a disadvantage, and cloud cover and frequent rainfall may diminish the effect of SS (Chase et al., 1999). Improved control of pathogens, weeds and nematodes have been seen by combining SS with pesticides, organic fertilizers and biological control agents and may be used in cooler regions for increasing long term benefit of solarization and against heat tolerant organisms (Elmore et al.,1997). Using organic amendments as cover crop residues or animal manure with SS improves pest control due to the formation of toxic compounds and increases soil temperature by 1-3^{o}C (Rubin et al., 2007; Gamliel et al., 2000).

Corn gluten meal (CGM) is a dry, concentrated byproduct when corn is processed to yield corn starch and syrup (Cox, 2005). This material is also an organic fertilizer. Corn gluten meal is 60% protein and 10% nitrogen by weight (Christians, 1993). This meal does not affect established plants but prevents normal root development during germination. Though there is some variation in sensitivity, CGM inhibits root formation in many grasses and broadleaf species (Christians, 1993). The recommendation is to apply CGM prior to weed germination (Christians, 1993) under dry soil conditions. However, if the soil remains wet, root formation may occur and effectiveness may be reduced (Christians, 1993). Corn gluten meal has been effective in controlling weeds such as smooth crabgrass [*Digitaria ischaemum (Schreb.) Schreb. ex Muhl.*.], purslane (*Portulaca oleracea* L.) giant foxtail (*Setaria faberi),* common lambsquarters (*Chenopodium album L.*), and creeping bentgrass (*Agrostis palustris Huds*.) (Bingaman and Christians, 1995) and is used for turfgrass, small fruits, and vegetables grown in residential and commercial plots (Chalker-Scott, 1990). Non-genetically modified CGM may be used by organic growers for integrated weed management in combination with methods as crop rotation and cover cropping. A field study with cranberry showed that CGM was not effective for preemergence weed control but despite the lack of weed control for organic crop growers this may still be used as a source of fertilizer (Sandler and Ghantous, 2014). Some dicot weed species can be controlled by CGM and CGM may be used in combination with other cultivation techniques where synthetic herbicides are not used (Dilley et al., 2002). Corn gluten meal can inhibit survival rate of seedlings of vegetables grown from seed as even at low rate of CGM (1000 kg ha^{-1}) (McDade and Christians, 2000), but CGM can be used in soils where transplants need to be established for crop production (McDade and Christians, 2000).

Mustard seed meal (MSM) is a byproduct of the mustard seed oil-extraction process. Some plants of the family Brassicaceae exhibit allelopathic properties that may inhibit weed germination, emergence, and growth (Rice et al., 2007). These allelopathic properties can be attributed to sulfur-containing glucosinolate compounds that occur as secondary plant products. Glucosinolates commonly occur in various parts of a plant as root, stem, leaf, seed with a hydrolytic enzyme, myrosinase (Rosa et al., 1997). When the plant tissue is wounded, the hydrolysis reaction occurs, overcoming the barrier between myrosinase and glucosinolate, releasing a variety of compounds, including isothiocyanates that have been considered broad-spectrum biocides since the early twentieth century (Brown and Morra, 1997). Isothiocyanate production occurs at warm temperatures, neutral pH, and high dilution with water (Matthiessen and Kirkegaard, 2006). At drier conditions, acid pH and lower temperature, nitriles are mainly formed, which are less active biologically (Rosa et al., 1997). One advantage of using MSM is that the myrosinase enzyme is preserved during crushing (Brown and Morra, 1996), and because of the meal's low moisture content, the glucosinolates are stable for a long time (Rice et al., 2007). Under tarped conditions in a greenhouse, MSM controlled annual bluegrass, broadleaf plantain, white clover and common chickweed when used at a rate of 1,680 kg ha^{-1} but the result was less consistent under untarped conditions (Earlywine et al., 2007). Mustard seed meal applied preplant, tilled into soil, and covered with polyethylene mulch between 1,120 kg ha $^{-1}$ to 4,480 kg ha $^{-1}$ increased yield of strawberries by about 12 % (Dayton and Sams, 2010). While using MSM, some additional control measures would be needed as certain perennial weeds would not be controlled and some weeds and some weeds would emerge in mid-season to late season (Webber et al., 2003).

Paper mulch covered with tar or asphalt was placed over seed cane (a section of cane with bud, used for vegetative propagation) in the early 20th century in Hawaii, for sugarcane (*Saccharum officinarum* L.) production (Coolong, 2012). This process helped prevent weeds from penetrating the mulch, but cane shoots pierced through and continued to grow (Stewart et al., 1926). Paper mulch has been used for a variety of vegetables from the Solanaceae and Brassicaceae families, but the effects on soil conditions and plant growth have not been consistent and depend on climate, crop species, agricultural practices, and the mulching material (Haapala et al., 2014). Paper mulch is free of weed seeds, decreases soil temperatures during sunny days, retains soil moisture, increases organic content as the mulch is biodegradable, and controls weeds (Pellett and Heleba, 1995; Salokangas, 1973). Radics and Bognar (2004) evaluated different mulch types, including plastic, paper mulch, straw mulch, and grass clippings used in a dry (2000) and a wet (2001) year for weed control and tomato (*Solanum lycopersicum* L.) and bean (*Phaseolus* L.) yield. The weedy, herbicide-treated, and hoed plots were treated as control plots. In both dry and humid weather conditions best weed control was seen in plastic and paper covering treatments for both beans and tomatoes. In dry weather yield of tomato was significantly higher in the plastic and paper covered treatments compared to herbicide and hoed control treatments but the same observation was not seen in the humid year (Radics and Bognár 2004). The effects of paper on yield is variable and depends on the crop species and the mulch effect may be different in different weather conditions (Haapala et al., 2014). Daugovish and Mochizuki (2010) found that in raised-bed California strawberry plasticulture production, paper between two plastic layers increased yellow nutsedge (*Cyperus esculentus*) control.

Paper pellet mulch (PPM) used in this study was mostly made of recycled newsprint (92%) and sold as dry pellets containing starter fertilizer (6.5%) and moisture cell technology (made of absorbent polymers that absorb water and release the water back to the soil) (1.5%). Paper pellet mulch was first marketed in 1995 and is used extensively for newly established turf grass and to our knowledge have not been used in strawberry production. The pellets expand by absorbing water then release it back to the soil. An advantage of PPM mulch is that it does not blow away, and unlike straw it does not contain weed seeds. The mulch helps to keep the root zone moist and delivers a starter fertilizer (0.7 N:1 P_2O_5: 0.4 K_2O) that promotes root development and enhances germination. The objective of this study was to evaluate a relatively shorter duration of SS alone and with additives - corn gluten meal, mustard seed meal, and paper pellet mulch - and observe their effects on crop health, crop yield, and weeds in a coastal Virginia annual strawberry plasticulture production system.

Materials and Methods

Field studies were conducted as a randomized complete block design with four replications at the Hampton Roads Agricultural Research and Extension Center, Virginia Beach (36º 9′ N, 76º 2′ W; 3.7m elevation) in the 2014-15 and 2015-16 growing seasons. Each replicate was a bed approximately 4.9 m in length, 0.7 m wide on top, and 0.14 m in height, oriented in the east-west direction. Prior to this study in 2014, the site was primarily under grassy vegetation that was maintained by mowing. Soil tests were conducted in both seasons in mid-July by the Virginia Tech Soil Testing Laboratory in Blacksburg, Virginia. Soil at the site was a Tetotum loam (USDA-NRCS, 2004), with 0 to 2% slope, with pH 5.2 in 2014-15, and 6.2 in 2015-16. Since the soil pH was 5.2 in the 2014-15 growing season, limestone was applied at a rate of 6,725 kg ha^{-1} prior to bed formation. The center 3 m length of each plot, was used for strawberry transplanting and data collection. Fertilizers were incorporated after prebedding as per the recommended rates of the soil test, and rates were adjusted for N, P_2O_5, and K_2O according to each treatment as CGM, MSM, and PPM provided some nutrients. Nitrogen was applied at 62 kg ha^{-1} [recommended rate of fertilizer as per soil test report, Maguire and Heckendorn (2017)] in both seasons. The grade of fertilizer used was 10 N: 0 P_2O_5: 20 K_2O (urea and muriate of potash, Southern States Cooperative, Virginia Beach, Virginia) and adjusted per plot (for example, the untreated or black plastic control plots received 0.34 kg 10 N:0 P_2O_5:20 K_2O that provided 0.034 kg N and 0.057 kg K). No preplant P_2O_5 applications were recommended for either growing season. The CGM and MSM+CGM plots which required only K_2O, the grade of fertilizer used was 0 N-0 P_2O_5-60 K_2O (muriate of potash, Southern States Cooperative, Virginia Beach, Virginia). Recommended rate for K_2O was 84 kg ha^{-1} in the 2014-15 growing season based on soil test report. In 2015-16 growing season, no preplant K_2O application was recommended.

However, in the southeastern states the standard recommended rate for N is 67.3 kg ha $^{-1}$, 67.3 kg ha^{-1} for P_2O_5 and 134.5 kg ha^{-1} for K_2O (Poling, 2005). Appendix C provides an approximate amount of N, P_2O_5 and K_2O from each product, fertilizer and total amount applied per plot. In the 2014-15 growing season, there were nine treatments, which included SS for a three-week period, MSM (1,121 kg ha^{-1}, MPT Mustard Products & Technologies Inc., Saskatoon, Canada), CGM (1,709 kg ha^{-1}, Grain Processing Corporation, Muscatine, Iowa, USA), and PPM (3,662 kg ha^{-1}; Lebanon Seaboard Corporation, Lebanon, Pennsylvania, USA) alone and in combination with a 3 wk SS and control (black plastic).

In our study, we selected a 2,242 kg ha^{-1} rate for MSM. We used CGM at rate of 1,709 kg ha^{-1} and for PPM, the recommended rate of 3,662 kg ha^{-1} for turf was used. Soil solarization with CGM at 1,709 kg ha^{-1} had to be abandoned soon after treatment initiation, as the plots were damaged by raccoons (*Procyon lotor* (L.) in the 2014-15 growing season. The remaining eight treatments were repeated in time for the 2015-16 growing season. Due to rainfall and equipment failure in 2014-15, SS was carried out for 20 days (19 September through 8 October, 2014) for two replications and 15 days for the other two replications (24 September through 8 October). All mulch treatments were applied prior to laying clear plastic. In the 2015-16 growing season, the three-week SS period began 5 September and ended 25 September, 2015. Soil solarization was performed by using a clear, 1 mil embossed polyethylene tarp (Robert Marvel Plastic Mulch, LLC, Annville, PA, 17003), and for the non-solarization treatments, a black, 1.25 mil. standard polyethylene tarp (TriEst Ag Group, Inc, Greenville, NC, 27835) was used.

Mustard seed meal and CGM treatments were broadcast after prebedding and incorporated with a bedder (to make a raised bed) to a depth of 15 cm prior to the final bed formation. Paper pellet mulch was surface applied after prebedding. During bed formation, the appropriate plastic was used (clear tarp in case of soil solarized plots and black tarp in case of other non-solarized plots) Temperature probes (Hobo data loggers, Onset Computer Corporation, Bourne, Massachusetts) were inserted at depths of 5 cm and 15 cm to record temperatures at ten-minute intervals in a single solar (SS) plot and a single black plastic control plot. A 15 mil single drip line with a 0.3-meter emitter spacing and flow rate of 1.7 l per minute was used to irrigate and fertigate the beds (Berry Hill Irrigation, Inc., Buffalo Junction, VA 24529). Italian ryegrass (*Lolium multiflorum* Lam.) was seeded on 1 October, 2014 and 18 September, 2015 at 44.8 kg ha^{-1} in the furrows for improving drainage, providing a grass walkway, and suppressing weed species. In 3 m long plots, ‘Chandler’ strawberry plants were transplanted in two rows with 0.4 m between the plants within the row. Strawberry plants were transplanted on 9 October, 2014 and 30 September, 2015. The first 0.9 m length of each plot was for weed data collection only and demarcated by field paint in the case of SS plots. In the non-SS plots, the black tarp was replaced with a 1 mil clear tarp on the bed top to create a 0.9 m (length) weed-viewing area (window). There were a total of 16 strawberry plants in two rows for each plot. Five were in the window, and the remaining eleven outside the window, from which yield data were collected.

For each night temperatures that was forecasted to be around 35 º F (1.7 º C) or lower, strawberry plants were protected with a 40 g m^{-2} floating row cover (Atmore Industries, Inc., Atmore, AL 36502). A critical temperature of 30 º F (-1.1 º C) may cause damage to open blossoms in strawberry (Perry and Poling, 1986). In both spring growing seasons, liquid fertigation (a normal practice) was carried out at the recommended nitrogen rate of 1.12 kg ha^{-1}/day. Calcium nitrate ($CaNO_3$) and potassium nitrate (KNO_3) were used in alternate weeks. In 2014-15, liquid fertigation started on 25 March and ended 10 June. In the following growing season, fertigation started 26 March, 2016 and ended 16 June, 2016. For the 2014-15 growing season, weeds were recorded by species on 21 October, 1 December, 9 February, and 21 April. For the 2015-16 growing season, weeds were recorded by species on 9 November and 8 January. After each weed count, weeds in the whole bed were uprooted by hand and discarded. Only the weeds in the bed top were recorded. The strawberry plant stand count was collected monthly, beginning in November 2014 until June 2015 for the 2014-15 growing season, and from October 2015 until June 2016 for the 2015-16 growing season. Total plant stand count in the whole plot, as well as in the three-feet window area was recorded. Until the harvest season, a plant health rating was recorded once a month on a scale of 0-10, on which 0 represented dead plants and 10 vigorous plants. Canopy diameter measurements were taken on six of the eleven plants (alternating between plants) that were outside the weed-viewing area on 7 April, 2015 and 23 March, 2016. Two canopy diameter measurements were taken on each plant and readings were averaged. To control diseases, each season fungicide was sprayed according to the Strawberry IPM (Integrated Pest Management) Guide.

For the 2014-15 growing season, yield data was collected from 4 May to 19 June, in 2015 and from 21 April to 24 June. Berries were separated into marketable and nonmarketable yield, with the marketable fruit comprised of fruit weighing 10 g and higher, without blemish or disease. Non-marketable fruit comprised of misshapen, diseased, and small berries (less than 10 g weight). Fruit size was recorded once a week by measuring five randomly selected marketable berries using a digital Vernier caliper (Neiko®01407A, Taiwan) and an average for each plot was calculated. In the 2015-16 growing season, fruit size was measured four times from 12 May through 6 June. However, due to lower yield in 2015-16, only three fruits per plot were analyzed for fruit size. After measurement of fruit size, fruits were kept frozen at 4^{o} C for determining the total soluble sugars (TSS). Berries were removed from the freezer, thawed, and crushed in a pestle and mortar. Berry pulp was sieved through a fine mesh and the juice was collected in a beaker. When the temperature of the juice was around 20 ºC, the ºBrix reading was recorded with a refractometer (MA871 Milwaukee Refractometer, Rocky Mountain, North Carolina).

At the end of the 2015-16 growing season, three plants were uprooted from each plot from three blocks, washed to remove soil and debris, and fresh biomass of roots determined on a digital scale (Valor 2000W, OHAUS, Parsippany, NJ). Additionally, root length was determined by Winrhizo software (Scanner STD 4800, Regent Instruments Inc., Canada). When uprooting plants, care was taken to ensure that crop plants were healthy, free from disease, and taken from the plot center.

Data analysis. Data were analyzed by SAS v 9.4 (SAS Institute Inc, Cary, NC, USA) and were subject to analysis of variance (ANOVA) with growing season and treatments considered as fixed effects. Prior to running ANOVA, data were checked for normality of residuals and log-transformed where necessary. A two-way interaction between growing season and treatment effect was determined. When the interaction was significant, each growing season was analyzed individually. When the interaction was insignificant, main effects for growing season and treatment were evaluated.

Weed-density and yield were cumulative for the season. For the early- season weed density and total weed density, weed counts were combined for all species, log10 (x+50) transformation was used for normality of residuals. Plant health ratings and stand counts were averaged by plot over the entire season and subjected to ANOVA. Mean separation was calculated using LSD (least significant difference) at alpha 0.05. Paired t-test was used for soil solarization temperature data and for others PROC GLM was used.

Results and Discussion

Weed density. For cumulative total weed density (sum of all species), treatment by growing season interaction was insignificant (P=0.8167), and season variation was seen (P= 0.003) with higher densities in 2014-15 (427.8 per plot) over the 2015-16 (132.8 per plot) growing season but treatment did nothing. In the 2014-15 growing season, dominant broadleaf weed species were common chickweed (*Stellaria media* (L.) Vill.), Carolina geranium (*Geranium carolinianum L.*), speedwell (*Veronica* spp. L.), henbit (*Lamium amplexicaule L.*), cudweed (*Gnaphalium* spp. L.), and wild garlic (*Allium vineale* L.). In the 2015-16 growing season, the main broadleaf weed species were common chickweed, wild garlic, cudweed, and speedwell. Low buttercup (*Ranunculus bulbosus* L.) density (about 11 per plot in 2014-15 and 6 per plot in the next season) was observed from January to April in both seasons. For common chickweed (62 in 2014 and 11 in 2015 per plot) and speedwell (35 in 2014 and 12 in 2015 per plot), there was no growing season by treatment interaction, and only the main effect of growing season was significant. Bermudagrass (*Cynodon dactylon* (L.) Pers.), large crabgrass (*Digitaria sanguinalis* (L) Scop.), and goosegrass (Eleusine indica (L.) Gaertn.) were seen in the early season, from October to December, and in both seasons, volunteer Italian ryegrass (*Lolium multiflorum* Lam.) was found in the cooler months from December to February.

When the cumulative early season weed count (sum of all species count from October to December) was analyzed, there was no treatment by season interaction, but the main effects of the growing season and treatment were significant. Early season weed density was lower in PPM+SS plots compared to the black plastic control plots (Table 2.3). Few weeds in the early season may be beneficial for better establishment of the transplants and also if plots are to be hand weeded. Weed suppression is often affected by environmental conditions and the depth at which the weed seed may be buried. In 2014-15 numerically the lowest number of weeds in the early season were in the PPM+SS plots. During the 2015-16 growing season, air temperature was higher for the months of September, November, December, January, February, and March than in the 2014-15 growing season (Table 2.2). Soil solarization was also initiated earlier in the 2015-16 growing season, which may have led to a higher soil temperature during the SS period that would reduce early weed density in PPM+SS compared to black plastic control plots. Early season common chickweed density showed no growing season by treatment interaction, though there was the significance of the growing season, chickweed was less in 2015-16 (4 per plot) compared to 2014-15 (24 per plot). Early season wild garlic density was low in PPM+SS, MSM+SS and SS plots compared to PPM, CGM and CGM + MSM plots, though not significantly different from the black plastic control plots. Fewer weeds in the early season may allow for better establishment of young strawberry plants. As the season progresses and temperatures begin to drop, fall-emerging weeds, such as Italian ryegrass, wild garlic, white clover, common chickweed, and purple cudweed, began to emerge, so the early effect of SS treatments on weeds may not continue and effectiveness of SS may not be seen throughout the whole season. It is desirable to find less expensive sources of PPM as it may be expensive [SS is estimated between 375 to 750 $/hectare and PPM cost is estimated at 3662 $/hectare (Lebanon Seaboard Corporation, Lebanon, Pennsylvania, USA)].

The main weed species during the midseason (January to March) were common chickweed, wild garlic, Italian ryegrass, and speedwell. There was no growing season by treatment effect for midseason weed density, and only the main effect of growing season was significant (In 2014-15 there were about 119 weeds and in 2015-16, the number was 51 per plot). For individual weed species, as speedwell, there was no growing season by treatment or treatment effect and only a growing season effect was seen (22 in 2014-15 and 2 in 2015-16 per plot). For common chickweed, however, the growing season and treatment main effect were significant. In midseason, common chickweed density was lower in the MSM plots (8) compared to the black plastic control plots (18) and common chickweed was more in number in 2014-15 (22 per plot) than in 2015-16 (7 per plot).

Deyton and Sams (2010) found that in the first season, there was no effect of MSM on weeds, and there were numerous broadleaf weeds especially common chickweed and henbit in MSM-treated plots. Most of the grass in their plots were tall fescue (*Festuca arundinaceae*) and ryegrasses (*Lolium* spp.) but MSM did not reduce grass or nutsedge species.

The thickness at which mulch is applied plays an important role in weed control in particle mulches (Ozores-Hampton, 1998). In our study, using higher rates of the amendments to achieve a greater thickness of application would be cost prohibitive (at least twice as much or more as fumigation), and the rate used for PPM was not thick enough to suppress weeds. The gaps in between pellets and also the fertilizer effect may have aided in weed emergence in PPM plots.

Plant stand count and health ratings. The visual rating though subjective, allows for rapid evaluation of overall health or plant condition. A monthly inspection of plants also helps to determine if plants need immediate attention in field. There was a significant growing season by treatment interaction on plant health ratings (P=0.0092) so data for the two growing seasons are presented separately (Table 4). Paper pellet mulch-treated plants had a significantly higher health rating than in SS, MSM + CGM, and CGM but not significantly different from the black plastic control plants for the 2014-15 growing season. No treatment differences were found for the 2015-16 growing season (Table 4). Lower ratings of plants in SS, MSM + CGM, and CGM plots were due to slightly smaller plant size in 2014-15 (Table 5). At a study in California, strawberry plants transplanted after incorporation of mustard seed meal were stunted initially as well as discolored but this effect did not last in spring and had no effect on productivity or growth (Bañuelos and Hanson, 2010). This effect could be due to phytotoxicity from allelopathic compounds. In our study, the plants of plots treated with MSM were a little stunted initially compared to black plastic control plots but this had no effect on yield in 2014-15 (data not shown). A study at Iowa State University, with three strawberry day neutral cultivars (‘Tribute’, ‘Tristar’ and ‘Seascape’) and four rates of CGM (0, 500, 1,000 and 2,000 kg ha^{-1}) between 2002-2005, showed that in 2005, the Seascape plants had the least leaf area, leaf dry weight and root dry weight, and less total yield (Nonnecke et al., 2006). In our study, the plants in plots treated with CGM had the least health rating, canopy reading and marketable yield in one season (2014-15). The plants in soil solarized plots not faring well could be that as the season progresses, the bed is covered with weeds, which may be detrimental for the plants. The plants in CGM and SS plots had lower marketable yield compared to PPM plots in 2014-15. The plants of MSM+CGM plots had lower health rating compared to PPM plots in 2014-15 (Table 2.4) but the marketable yield was comparable to that of PPM plots (2.6). The growing season by treatment interaction and the main effects of the growing season and treatment had no influence on crop plant stand count (data not shown).

Canopy reading. For canopy reading, the growing season by treatment interaction was significant (P=0.04), and data for the two seasons are presented separately (Table 2.5). In 2014-15 growing season, canopy of plants treated with PPM were greater than plants of CGM, MSM+CGM, and SS plots but not from those of control (black plastic) (Table 2.5). The PPM treated plants having greater canopy also had a higher health rating. For the 2015-16 growing season, PPM plots had the numerically largest canopy which was significantly different from the black plastic control and the PPM+SS plots (Table 2.5). In 2014-15 there was a correlation (0.92) between canopy size and marketable yield per plant per treatment but not in 2015-16. Flint (1928) found stimulation in vegetative growth of tomato, green beans, and potatoes with impervious paper mulch.

Crop yield and fruit quality parameters. For marketable fruit yield, the two-way growing season by treatment interaction was significant (P=0.0088) (Table 6). In the 2014-15 growing season, yield in PPM was higher than CGM and SS plots but similar to PPM+SS, MSM+SS, MSM, MSMCGM, and black plastic control plots. Paper mulches increased pineapple (*Ananas comosus*) production by increasing soil moisture and nitrate level (Stewart, 1926). Deyton and Sams (2010) found a 12% increase in strawberry yield with MSM-applied preplant (tilled in bed) at 1,120 kg ha^{-1} to 4,480 kg ha^{-1} over control (black plastic) plots in one season. The following season, there was on an average increase of 20% in plots treated with MSM compared to black plastic control plots in their research. They concluded that using a rate of 2,240 kg ha^{-1} to 4,480 kg ha^{-1}, the yield increase of 20 to 29 % may be possible in strawberry fields. In our study, using 1,121 kg ha^{-1} resulted in a numerical 14% increase in marketable yield per plant in MSM plots in 2014-15 compared to the black plastic control plots, but the increase was not statistically significant. When SS was carried out from late July through September, a 12% higher yield than black plastic control plots was seen at Irvine, California (Hartz et al., 1993). In our study, the PPM+SS plots showed a numerical increase of 20% yield over black plastic control plots in the 2014-15 season; however, no such difference was seen in the following season. Precipitation was higher in the 2015-16 growing season (Table 2.2), causing the beds to remain wet for a longer time and perhaps contributing to the leaching of nutrients. Compared to 2014-15 growing season, in 2015-16 precipitation was especially high in the months of October, November (when the plants were established), January, February, and May (during harvest). One reason for the paper mulch not performing well (low yield) in 2015-16 could be that with excessive rainfall, rapid decomposition of the pellets could have taken place. Excessive moisture retained on the beds following precipitation may also render some fruits non-marketable since the fruits turn soft and subsequently rot. The drier period in May in the 2014-15 growing season may have resulted in fewer fruit rots, contributing to a greater marketable yield. With 10g as a standard fruit size in our study, smaller berries were included in the non- marketable category. In the 2015-16 growing season, there was a spring frost in the first week of April. A number of open blooms at our study site were damaged in the first week of April 2016 when a row cover was not used as the air temperature was supposed to be around 2.8^{o} C (37^{o} F). Spring frost damage may have contributed to overall lower yield for the 2015-16 growing season compared to the first season. The black plastic control plots had numerically lower marketable yield compared to some of the treatments, but the difference was not always significant. Fruit size or total soluble solid content was unaffected by any treatments in both growing seasons (data not shown).

Strawberry Root biomass. In the 2015-16 growing season, root biomass differences were not significant (P=0.08). Numerically SS plots had the greatest biomass, and the black plastic control plots had the least root biomass. With okra (*Abelmoschus esculentus*), four-week SS increased the whole plant dry biomass by more than three times, and by four times for the six-week solarization period over non-SS treatments of the same duration (Seman-Varner et al., 2008). Increase in dried root and shoot biomass was found in strawberry plants that were grown in solarized and pasteurized soils compared to those grown in non-solarized soils (Pinkerton et al., 2002). Root biomass in SS was 43% higher than the control (black plastic) in this study. An increase in plant biomass due to SS generally indicated improved crop health. However, in our study, no improved yields with SS were observed compared to the control (black plastic). Three week SS may not have been effective for increasing crop yield even when bio-based amendments were used to supplement the SS process.

Soil and air temperature. In both seasons, soil temperature, both mean and maximum were higher in SS (solar treatments with clear tarp) than in the non-solar (black tarp) treatments at both depths (Table 2.1). In 2014, the maximum temperature at 5 cm (P=6.059e-10), 15 cm (P=2.665e-09), mean temperature at 5 cm (P=1.832e-09) and 15 cm (P=4.214e-09) were significantly different between the two treatments. Similarly in 2015, the maximum temperature at 5 cm (P=2.104e-09), 15 cm (0.004736), mean temperature at 5 cm (P=1.145e-10) and 15 cm (P=1.611e-09) were significantly different between the solar and black plastic control treatments. Since many soil borne pests are adversely affected by temperature ≥ 40 °C (Stapleton, 1995), the total hours ≥40 °C is important for solarization (Table 2.1). In 2014-15, the highest temperature at the 5 cm depth was 44.2 °C for soil solarization with clear tarp, but the following season, at the same depth, the highest temperature was 47.2° C for the soil solarization treatment. Time ≥40° C at a 5 cm depth was higher in clear tarp treatments than in black tarp treatments in both seasons. At a 15 cm depth for clear and black tarp treatments, temperatures ≥ 40° C were not achieved in the 2014-15 season; however, there were accrual of temperatures ≥40 °C even at the 15 cm depth in the clear tarp and the black tarp treatments in the 2015-16 growing season. At the 15 cm depth, the temperature accrual was much lower compared to the 5 cm depth for both clear and black treatments. At a 15 cm depth for the clear tarp temperature was 37.4° C in the 2014-15 growing season and 43.2° C in the 2015-16 season, and for the black tarp at the same depth, temperature was 32.3° C in 2014-15 and 38.3 °C in 2015-16. These differences may be because SS in 2015-16 growing season was initiated earlier in the calendar year on 3 September compared to 19 September in 2014-15 growing season. In 2014-15 growing season, SS was carried out for 20 days in replicate one and two and 15 days in replicate three and four, but the following growing season, soil solarization was carried out for 21 days in all replicates. Average air temperature in September was higher in 2015-16 (24.3 ^{0} C) than in 2014-15 (23.2^{o} C) (Table 2.1). These factors may have led to higher soil temperatures in 2015-16 than 2014-15.

Conclusion

Higher soil temperature under the SS plots compared to black plastic control plots may have resulted in lower early season weed density in PPM +SS plots. Rainfall during the treatment period in both years made it difficult to provide a dry period for CGM to act on weeds. Mustard seed meal alone used at 1121 kg ha^{-1} did not provide improved weed control compared to black plastic control plots and a higher rate could be evaluated in future for improved weed control and yield. The PPM showed increased yield in one season compared to SS and CGM plots but not significantly different from the black plastic control plots and provided early-season weed control when used in combination with SS, but no benefit to yield was seen in the next season. A reduced period of SS with amendments does not appear to be a practical preplant option for conventional strawberry growers under coastal Virginia climactic conditions. The shorter duration of SS with PPM can be used by organic growers to achieve early season weed control, but a longer duration of SS may be more effective. Using PPM showed no detrimental effect on strawberry plants and could be evaluated further at different dose rates, alone as well as in combination with other strategies for strawberry annual plasticulture production system in Virginia.

Tables.

Table 2.1. Soil temperature in the 2014-15[a] and 2015-16[b] growing seasons collected at 5 cm and 15 cm depths during 3-wk soil solarization treatment periods, in beds with black tarp[c] or clear tarp in annual plasticulture strawberry production in Virginia Beach, Virginia.

Depth	Tarp	2014-15	2015-16	2014-15	2015-16	2014-15	2015-16
		Maximum Temperature		Mean Temp[d]		Time > 40 º C	
		-------ºC------		-------ºC------		---------hr------	
5 cm	Black	36.0	44.9	24.6	27.3	0	27.1
	Clear	44.2	47.2	27.0	28.2	30.7	45.7
15 cm	Black	32.3	38.3	24.3	26.8	0	2.1
	Clear	37.4	43.2	26.1	27.4	0	16.9

[a] In 2014-15, data was collected from 19 September to 8 October, 2014

[b] In 2015-16, data was collected from 3 September to 25 September, 2015

[c] Bed with a black tarp was one of black plastic control.

[d] The maximum and mean temperature of black and clear tarp were significantly different in respective years.

Table 2.2. Monthly average air temperature and monthly precipitation for Norfolk International Airport, Virginia in the 2014-15 and 2015-16 growing seasons

Monthly mean air temperatures (ºC) in the 2014-15 and 2015-16 growing seasons										
Year	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June
2014-15	23.2	17.9	9.5	7.6	4.3	0.3	8.6	15.1	21.4	25.9
2015-16	24.3	17.1	14.1	14.1	5.1	6.9	13.2	14.3	18.9	24.2
Monthly total precipitation (cm) in the 2014-15 and 2015-16 growing seasons										
Year	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June[a]
2014-15	23.3	4.0	8.7	9.4	9.2	6.5	6.8	11.7	3.8	11.8
2015-16	13.8	9.3	11.7	8.6	11.7	15.9	8.8	7.1	13.0	11.4

[a] Precipitation data for the month of June is the total until the harvest date, i.e. 19 June in 2014-15 and 24 June in 2015-16

Source: United States Department of Agriculture, Natural Resources Conservation Service, National Water and Climate Center (2017)

Table 2.3. Cumulative early-season weed density (0.63 sq m) collected during October-December in 2014-2015 and 2015-2016 in 0.9 m length of bed in Virginia Beach, Virginia as affected by preplant treatment in annual plasticulture strawberry production.[a]

Treatment	Grass species		Wild garlic[b]	Cumulative early weed density[b]
	2014-15	2015-16	2014-16	
Corn gluten meal	25.8 bc[b]	15.3 bc	53.4 a	149.8 abc
Mustard seed meal + corn gluten meal	30.8 bc	20.3 abc	52.6 a	155.8 ab
Mustard seed meal	24.5 c	25.5 ab	41.6 ab	143.4 abc
Mustard seed meal + Solarization	67.5 a	13.3 bc	17.6 c	145.4 abc
Paper pellet mulch	25.3 bc	25.3 ab	52.1 a	181.5 a
Paper pellet mulch + solarization	37.8 bc	8.0 c	19.3 bc	113.5 c
Solarization	44.8 b	9.0 c	22.8 bc	138.1 bc
Control (black plastic)	21.5 c	31.0 a	40.9 abc	167.9 ab
$P_r > F$ Treatment	0.0001[c]		0.01	0.03

[a] Means with the same letter within a column are not significantly different using least significance difference at P≤0.05. Data is from 0.9 m length of bed top.

[b] Growing season by treatment interaction was not significant for cumulative early-season weed count and garlic, and both treatment and year effect were significant.

[c] For grass species, the growing season by treatment effect was significant. The value mentioned here is that of treatment by year interaction. Grass species include bermudagrass, large crabgrass, and Italian ryegrass.

Table 2.4. Cumulative health rating in annual plasticulture strawberry production in 2014-15 and 2015-16 growing season in Virginia Beach, Virginia.

Treatment	Rate	Cumulative health rating 2014-15	Cumulative health rating 2015-16
	-----kg ha^{-1}-----		
Corn gluten meal	1709	6.3 d	7.8
Mustard seed meal+Corn gluten meal	1709 +1121	6.4 cd	7.9
Mustard seed meal	1121	6.9 ab	7.8
Mustard seed meal+Solarization	1121	6.9 ab	7.8
Paper pellet mulch	3662	7.0 a	7.8
Paper pellet mulch+Solarization	3662	6.8 ab	7.7
Solarization	-	6.6 bcd	7.7
Control (black plastic)	-	6.7 abc	7.9
Pr > F[a] Growing season by treatment		0.0092	

[a] Means with the same letter within a column are not significantly different using least significant difference at P ≤ 0.05. A rating of 0 is for dead plants and 10 vigorous plants in a plot.

Table 2.5. Late-season canopy diameter of strawberries in the 2014-15 and 2015-16 growing season in Virginia Beach, Virginia.

Treatment	2014-15 (April 2015)	2015-16 (March 2016)
	-------cm-------------	
Corn gluten meal	24.0 d	27.7 abc
Corn gluten meal+Mustard seed meal	24.9 cd	28.6 ab
Mustard seed meal	26.6 abc	28.4 abc
Mustard seed meal+Solarization	26.5 abc	29.2 ab
Paper pellet mulch	27.7 a	29.3 a
Paper pellet mulch + Solarization	27.0 ab	26.8 c
Solarization	25.4 bcd	28.1 abc
Control (black plastic)	26.7 abc	27.4 bc
Pr > F[a] Growing season by treatment	0.04	

[a]Means with the same letter within a column are not significantly different using least significant difference at P≤0.05.

Table 2.6. Cumulative marketable yield per plant in 2014-15 and 2015-16 growing seasons, collected at Virginia Beach, Virginia.

Treatment	Cumulative marketable yield		Ratio marketable/nonmarketable	
	2014-15	2015-16	2014-15	2015-16
	-----g-----			
Corn gluten meal	279.3 c	265.9 ab	2.1:1	0.9:1
Corn gluten meal+Mustard seed meal	356.1 abc	293.6 a	2.3:1	1:1
Mustard seed meal	411.0 ab	247.2 ab	2.1:1	0.9:1
Mustard seed meal + Solarization	394.3 abc	179.4 b	2.1:1	0.5:1
Paper pellet mulch	464.3 a	200.2 b	2.2:1	0.7:1
Paper pellet mulch + Solarization	434.6 ab	189.1 b	2.1:1	0.8:1
Solarization	324.5 bc	240.5 ab	2.0:1	0.9:1
Control (black plastic)	361.3 abc	206.2 ab	2.1:1	0.8:1
Pr > F [a] Growing season by treatment	0.0088			

Table 2.7 Effect of treatment on strawberry plant root biomass in the 2015-16 growing season in Virginia Beach, Virginia.

Treatment	Root biomass
	----g----
Corn gluten meal	125.3
Corn gluten meal+Mustard seed meal	125.0
Mustard seed meal	134.0
Mustard seed meal+Solarization	140.0
Paper pellet mulch	116.7
Paper pellet mulch+Solarization	152.0
Solarization	162.3
Control (black plastic)	113.0
Pr>F Treatment	0.08

Table 2.8 Total weed density in 2014-15 and 2015-16 growing season, an average of four reps (0.63 sq m), collected at Hampton Road AREC, Virginia Beach, Virginia.

Treatment	Total weed density 2014-15	Total weed density 2015-16
Corn Gluten Meal	412.3	136.5 ab
Corn gluten meal + Mustard seed meal	410.0	141.0 ab
Mustard seed meal	401.8	139.8 ab
Mustard seed meal+Solarization	418.5	110.8 b
Paper pellet mulch	498.0	151.5 a
Paper pellet mulch+Solarization	380.5	110.3 b
Solarization	432.5	116.8 b
Control (black plastic)	469.0	156.3 a
Pr≤0.5	0.5	0.03

In 2014-15 weed data were collected four times from October 2014 through April 2015. There was no significant difference in treatments in 2014-15.

In 2015-16 weed data were collected twice a year, once in October-November 2015 and once in January 2016.

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CHAPTER III

Paper pellet and mustard seed meal as fumigant alternatives in annual strawberry (*Fragaria*×*ananassa* Duch*)* plasticulture system

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Abstract. In strawberry (*Fragaria×ananassa*) annual plasticulture production, early-season weeds can impede crop establishment if not controlled. Biodegradable paper mulches play a role in retaining soil moisture, increasing organic content, and providing weed control. In previous studies involving horticultural crops, the effect of paper mulch on crop yield has been variable. Mustard seed meal (MSM) is a by-product of the mustard oil extraction process. The objective of this study was to determine if paper pellet mulch (PPM) at different rates and its combination with mustard seed meal (MSM) had any effect on weed density and crop yield and could be an alternative to traditional fumigation practices. A study was conducted at the Hampton Roads Agricultural Research and Extension Center with seven treatments. Treatments were PPM at 4,882, 6,103,7,324 kg ha^{-1} respectively, MSM at 2,242 kg ha^{-1}, PPM 6,103 kg ha^{-1} + MSM 2,242 kg ha^{-1} and 1,3-D + Pic (39% 1,3-dichloropropene + 59.6% chloropicrin) that was shank-1,3-D+Pic in beds at 152 kg ha^{-1} and covered with VIF (virtually impermeable film), and control (black plastic). Beds were 11.3 m in length, 0.7 m wide, and 0.14 m high. The center 4.6 m length of the bed was used for transplanting 'Chandler' strawberry plugs in two rows at 36 cm in-row spacing where data collection was done. Early season weed biomass as well as weed density was lowest statistically in 1,3-D+Pic treatments. Compared to the black plastic control treatment, marketable yield was higher in MSM and PPM+MSM treatments in the 2015-16 growing season but in the 2016-17 growing season; higher marketable yield was seen only in the 1,3-D+Pic and PPM+MSM treatment compared to black plastic control treatment. Total yield, in the 2015-16 growing season, was highest in PPM+MSM treated plots which was significantly higher than the black plastic control, but not different from the MSM and some PPM treatments. In 2016-17, the 1,3-D+Pic treatments had the highest total yield, followed by the PPM+MSM, MSM, and PPM (7,324 kg ha^{-1}) treatments. Fruits were larger in 1,3-D+Pic and PPM+MSM

treatments compared to control (black plastic) and were sweeter in the 2015-16 growing season than in the 2016-17 growing season. PPM pellets did not control weeds in our study but PPM+MSM showed increased marketable and total yield and needs further evaluation.

Introduction

In annual strawberry production, soil fumigation is often practiced to maximize yield when disease, nematode, or weed pressure is high or when crop rotation may not be feasible (Demchak ,2013). Strawberries are susceptible to diseases - especially black root rot, *Phytophthora*, *Pythium*, *Fusarium*, and Verticillium Wilt. Without fumigation, strawberry may be grown for 2 to 3 years on that land but after that, as high pest pressure could build up, growing the plants may not be possible. Non-fumigating the land may cause pathogens to reoccupy the land fast (White, 1994).

Methyl bromide (MB) is an odorless, colorless gas with a high vapor pressure that spreads rapidly through the soil, dissipates quickly after application, and has been used as soil fumigant on more than 100 crops (Rosskopf and Chellemi, 2005). Methyl bromide has been used for a variety of high-value crops, especially tomatoes and strawberries. The huge popularity of MB as a soil fumigant came to a halt after being labeled as an ozone-depleting substance. A lowered ozone concentration in the stratosphere (troposphere and stratosphere constitute the two lower layers of atmosphere) can have many negative environmental impacts such as crop damage, skin cancer, eye damage, and others (Ristaino and Thomas, 1997). A law was passed to phase out consumption of MB by the year 2015 (Rosskopf et al., 2005) though, for some commodities such as dry-cured ham, California dates, and strawberries, MB would be used under the critical use exemption (CUE) (USDA 2014). The transition from MB will not be easy or seamless and alternatives would require multiple approaches towards pest control (Noling et al., 2009). Alternatives to MB vary in their degree of efficacy, cost, environmental effect, and other parameters (Katan et al., 2004) and the many cropping systems would require a soil sterilization system suited to each system (Katan et al., 2004).

Some of the alternatives may have technical issues associated with them as phytotoxicity may be caused due to heavy rain and hurricane (Sydorovich et al., 2006). In the absence of MB, strawberry growers in the Mid-Atlantic and Southern U.S. have been using 1,3-D (1,3-Dichloropropene), Pic (chloropicrin) or their combinations. Commercial product formulations include Telone II (1,3-D 94%), Telone EC (drip application of Telone II, Rosskopf et al., 2005), Telone C17 (73 % 1,3-D + 17 % chloropicrin), Telone C35 (65 % 1,3-D + 35 % chloropicrin), InLine (drip application of Telone-C35, 1,3-D + chloropicrin), Pic-Clor 60 (chloropicrin + 1,3-D), or Pic-Clor 60 EC. Other fumigation products include metam potassium, metam sodium, dimethyl disulphide (Paladin), and allyl isothiocyanate (Dominus). Alternative fumigants are often less broad spectrum and more target specific compared to MB (Noling, 2002) and their performance can vary by region. In wet years fumigants can lead to phytotoxicity and yield decline (Sydorovych et al., 2006). A combination of fumigants is often required to reach a certain level of pest control efficacy and yield (Noling, 2002). For example, 1,3-D is effective in controlling soil-borne nematodes but is inconsistent in controlling weeds (Noling and Becker, 1994).These fumigants (1,3-D, Chloropicrin) are known to be harmful to human health. California’s Proposition 65 gives a list of chemicals including 1,3-D, that increase cancer risk and therefore there are limits to regulate the exposure to 1,3-D (Carter et al., 2005). Chloropicrin (Pic) is used for broad-spectrum control of fungi, microbes, insects and other harmful pests, but is ineffective against nematodes and weeds (Kabir et al., 2005). Chloropicrin vapor may cause illness due to inhalation and may cause tears, irritation of the throat and nose, therefore protective clothing at the time of application is needed (Fan et al., 2004). Fumigants may move off-site, thus posing hazards to humans and other organisms (The Mid-Atlantic Berry Guide for Commercial Growers 2013-14). Those administering fumigants should 1) have a fumigant management plan with all the procedures outlined prior to fumigating 2) a strategy in place to tackle any problem that may arise during the fumigation process, and 3) additional requirements include maintain buffer zones (a minimum distance between residential areas, schools, etc. and land where fumigation is applied) for health and safety reasons

Many growers no longer wish to fumigate their land for reasons concerning their health and the environment. For strawberry growers, some non-chemical preplant approaches to fumigation include crop rotation, soil solarization, flooding (an ancient practice to get the field rid of inoculum by flooding with water (Palti, 1981)), sanitation (measures which reduce disease inoculum in field and prevents introduction of inoculum), fallowing (a period between planting two successive crops, when land is being prepared, and left unseeded), using resistant cultivars, biofumigation, steaming, and others (Ristiano and Thomas, 1996; Katan et al., 2004).

Paper has been used in various forms of agriculture for a long time. An impervious form of asphalt paper (Eckart, 1923) was used in Hawaii as a mulch to control weeds and improve plant growth. Beneficial effects of using paper as a mulch have been increasing organic content in soil, improved plant growth in many instances, reducing evaporation, increased nitrification, and increased soil temperature. Paper can also be disked in the soil, and paper being porous to rain and irrigation water allows the water to reach roots directly (Jenni and Brault, 2004). However, there are issues with retaining its strength throughout the growing season especially when wet. To prevent degradation, paper has been coated with several substances such as tar

(Rivise ,1929), latex (Brault et al., 2002), wax (Vandenberg and Tiessen, 1972), or vegetable oil (Anderson et al.,1995). Kraft paper (made from 100% recycled fiber) coated with polymerized vegetable oil was more durable and gave better weed control compared to uncoated paper or paper covered with unpolymerized oil (Shogren, 2000). Lettuce grown with paper or polyethylene mulches had heavier heads and 25% more marketable yield than those grown in unmulched treatments (Jenni and Brault, 2004). Black and brown paper mulches have been used in the Netherlands for salad and flower crops and provided good weed control (Wilson, 1990). In Spain, a study, using processing tomato (*Solanum lycopersicum* L.) was conducted with polyethylene plastic, biodegradable plastic, and four different types of papers for two years for control of purple nutsedge (*Cyperus rotundus* L.). Paper-mulched treatments gave the best control of all weed species including purple nutsedge and yield was similar to that of polyethylene-mulched treatments (Cirujeda et al., 2012). In general, the weeds did not pierce the paper, however weeds did emerge through tears and planting holes (Cirujeda et al., 2012). The effect of paper mulch on crop yield has been variable (Haapala et al. 2014). Munn (1992) in a study, using sweet corn (*Zea mays* L.), field corn, soybean (*Glycine max* (L) Merr.) and tomatoes (*Lycopersicon esculentum* Mill.), soil plots treated with shredded newspaper, wheat straw mulch (*Triticum aestivum* L.) and bare soil found that the effect on yield, weed control, soil moisture and temperature were mostly similar in wheat straw and shredded newspaper mulched plots and significantly different from the bare soil plots. The soil was cooler, more moist and effectively suppressed various species of annual and perennial weeds under mulches compared to bare soil (Munn, 1992). Using high rates of newspaper mulch did not have detrimental effects on growth of soybeans and corn and also there was no accumulation of heavy metals in soil. In one season, for the three crops, yield was higher with newspaper mulch compared to bare soil.

Mustard seed meal (MSM) is a by-product of the oil extraction process from mustard seeds. Oilseed meals are rich in macro and micronutrients (Moore, 2001). They also have low C: N (carbon to nitrogen) ratios (5.1 to 12) and this makes them readily decomposable to plant available forms after application in the field. Most of the oilseed meals are certified as organic sources of fertilizer in OMRI (from Organic Materials Review Institute). Mustard seed meal may be used as a fertilizer or herbicide. Organic growers can take the benefit of the pesticidal and fertilizer potential of the MSM, but while applying MSM in fields, some caution should be exercised as it cannot be applied at the same time as planting. Small plants may be harmed if enough time is not given for the isothiocyanates to break down in soil (Moore, 2011). Seed meal treatments from canola (*Brassica napus*) and brassica (*Sinapsis alba*) at 0, 2,242, 4,483 and 13,450 kg ha^{-1} were tested in field and showed that the treatments increased strawberry fruit yield in all but the highest rate of mustard meal where yield was reduced 42 % compared to control treatments (Bañuelos and Hanson, 2010). Germination of summer and winter annuals were reduced by mustard more than the canola or the control treatments (Bañuelos and Hanson, 2010).With Brassica seed meal, the weed control was variable among replicates and in some cases weed biomass and emergence were reduced compared to the control, but in other cases, there could be a fertilizer effect and reduction was not so evident (Bañuelos and Hanson, 2010). When MSM was applied at rates of 1,130, 2,250 and 4,500 kg ha^{-1} in container grown plants, it controlled annual bluegrass (*Lolium multiflorum*) and common chickweed (*Stellaria media* (L.) Vill.), and when applied on a mineral soil surface at 2,250 kg ha^{-1} it controlled creeping woodsorrel (*Oxalis corniculata* L.) (Boydston et al., 2008). Mustard seed meal controlled weeds better in tarps than in untarped ones (Earlywine et al., 2007). Under tarps in a greenhouse, MSM controlled annual bluegrass (*Poa annua* L.), broadleaf plantain (*Plantago major*), white clover (*Trifolium repens* L.), and common chickweed when used at a rate of 1,680 kg ha^{-1} but the result was less consistent under untarped conditions (Earlywine et al., 2007). Rice et al. (2007) observed early season weed control with a single application of MSM (at 4,190 kg ha^{-1} and 12,575 kg ha^{-1}) relative to no-meal treatment but the effect was short-lived. Brown et al. (2006) showed reduced weed biomass and emergence in strawberry production when *S. alba* was used at 2000 kg ha^{-1}. Efficacy of the mustard meal is greater with uniform application and when the meal is placed near the germinating weed seedlings (Boydston et al., 2008). Single season data collected in strawberry production at the University of Tennessee showed that MSM (from Oriental mustard, *Brassica juncea*) did not control grasses or nutsedge but increasing the rate from 560 kg ha^{-1} to 4,484 kg ha^{-1} provided better broadleaf weed control compared to control treatments (Deyton and Sams, 2010). For the same study, fruit yield was higher from 20 to 29% in MSM plots compared to black plastic control treatments and fruit size was larger than the black plastic control treatments. In a study in California in the 2007-2008 and 2008-2009 seasons, several non-fumigant alternatives such as MSM, furfural, steam, and *Muscodor albus* (a fungus that is detrimental to many pests) were evaluated in strawberry production and compared to black plastic control and MB+Pic (MBPic) treatments (Samtani et al. 2011) MSM (at a rate of 2242 kg ha^{-1}) was either moderate or not effective in controlling weeds. In spite of the lack of weed control, at least in one growing season, the yield was high in MSM treated plots at Watsonville, CA in a strawberry field. In the Pacific Northwest at 644 kg ha^{-1} MSM, which had low glucosinolate concentration (from *Sinapsis alba* L., UI7012 G) with less than 2 µmole glucosinolate/gram, helped to control broadleaf weeds whereas at the same rate the MSM which had high glucosinolate concentration (*Sinapsis alba* L., IdaGold), with sinalbin and progoitrin at 173 and 7 µmole/gram aided in controlling both broadleaf and grass leaf weeds (Miller et al., 2013). But the high glucosinolate MSM (at the rate of 644 kg ha^{-1}) also decreased the berry yield and fruit weight at one location (Miller et al., 2013). Mustard seed meal has been used to control weeds in onion (*Allium* L.), potato (*Solanum tuberosum* L.), peppermint (*Mentha* x *piperita* L.), and turf and the range has been extensive, including common chickweed, large crabgrass (*Digitaria sanguinalis* L. Scop.), prickly lettuce (*Lactuca serriola* L.), wild oat (*Avena fatua* L.), Italian ryegrass (*Lolium perenne* L.spp. multiflorum Lam.Husnot), kochia [*Kochia scoparia* (L). Schrad.], green foxtail [Setaria viridis (L).Beauv.], redroot pigweed (*Amaranthus retroflexus* L.), common lambsquarters (*Chenopodium album* L.), barnyardgrass (Echinocloa crus-galli L.Beauv.), buckhorn plantain (*Plantago lanceolata* L.), and annual sowthistle (*Sonchus oleraceus* L.) (Boydston et al., 2011; Earlywine et al., 2010; Handiseni et al., 2011; Yu and Morishita, 2011). The species from which the MSM is derived is also important, as MSM from *Sinapsis alba L* was found to be as much or more phytotoxic than MSM from *Brassica napus L and Brassica juncea L* (Hoagland et al., 2008). Though MSM may provide early preemergence weed control, some additional measures would be needed as some weeds would avoid control, including some perennial weeds and some weeds would emerge in mid-season to late season (Webber et al., 2003).

Strawberries allocate their resources to the roots, crowns, and leaves in the fall and optimal conditions in fall and late winter minimize stress to the developing plant and helps to achieve maximum yield (Fernandez et al., 2001). For ‘Chandler’, this was also the time when the number of crowns increased (Fernandez et al., 2001). Growth of winter-planted strawberries is negatively impacted if the average temperature is at or below 12.8^{o} C (Voth and Bringhurst, 1962). When considerable growth occurs in winter, flowers are initiated and crowns develop (Voth and Bringhurst, 1962). In ‘Tristar’ strawberries optimal growth and development occurred between 17^{o} C (63^{o}F) and 29^{o} C (84.2^{o} F) (Biela et al., 1999).

The objective of this study was to determine if paper pellet mulch (PPM) application rate and its combination with mustard seed meal (MSM) had any effect on weed control and strawberry crop yield and could be an alternative to traditional fumigation practices.

Materials and Methods

Field studies were set up as a randomized complete block design with four replications at the Hampton Roads Agricultural Research and Extension Center, Virginia Beach (36º 9′ N, 76º 2′ W; 3.7m elevation) in the 2015-16 and 2016-17 growing seasons. Each replicate's bed was 11.3 m in length, 0.7 m wide and 0.14 m in height oriented in the east-west direction. The center 4.6 m of the bed was planted with 'Chandler' strawberry plugs in two rows at a 36 cm in-row spacing. Prior to initiation of this study in 2015, the site had been used for strawberry research for two prior years and before summer 2013, the site was primarily under grassy vegetation that was maintained by mowing. Soil tests were conducted in both seasons by sending representative soil samples in mid-July to the Virginia Tech Soil Testing Laboratory. Soil at the site was a Tetotum loam (sandy loam, deep, moderately well drained, parent material: loamy, fluvial and marine sediments) (USDA-NRCS, 2004), with 0 to 2% slope, with a 6.2 soil pH in 2015-16 growing season, and soil pH of 6.6 in the 2016-17 growing season. Fertilizers were applied after prebedding and rates were adjusted (for N, P_2O_5 and K_2O) according to each treatment as MSM (5 N:1 P_2O_5:1 K_2O) and PPM (0.7 N:1 P_2O_5:0.4 K_2O) provided some fertilizer. In 2015-16 growing season nitrogen was applied at 62 kg ha $^{-1}$ using 10 N: 0 P_2O_5: 20 K_2O (urea and muriate of potash, Southern States Cooperative, Virginia Beach, Virginia) and also potash [(In the southeastern states the standard recommended rate for N is 67.3 kg ha $^{-1}$, 67.3 kg ha^{-1} for P_2O_5 and 134.5 kg ha^{-1} for K_2O (Poling, 2005)] and in 2016-17 nitrogen was applied using 34 N: 0 P_2O_5: 0 K_2O at the same rate. No preplant phosphorus was recommended for either season according to soil test reports, but potash (0 N-0 P_2O_5-60 K_2O, muriate of potash, Southern States Cooperative, Virginia Beach, Virginia) was applied at 84 kg ha $^{-1}$ according to recommendation in the 2016-17 growing season. In both seasons there were seven treatments which included paper pellet mulch (PPM) at 4882 kg ha^{-1} (Lebanon Seaboard Corporation, Lebanon, Pennsylvania, USA), PPM at 6103 kg ha^{-1}, PPM at 7324 kg ha^{-1}, mustard seed meal or MSM (2242 kg ha^{-1}, MPT Mustard Products & Technologies Inc., Saskatoon, Canada), combination of PPM (6103 kg ha^{-1}) and MSM (2242 kg ha^{-1}), black plastic control, and a fumigation treatment using shank-applied 1,3-D + Pic (39% 1,3-dichloropropene + 59.6% chloropicrin) at 152 kg ha^{-1} and covered with 1.25 mil. VIF (Virtually impermeable film; TriEst Ag Group, Inc, Greenville, NC, 27835). The same tarp (VIF) was used for all treatments. Mustard seed meal and fertilizer were applied broadcast and incorporated before final bedding. The PPM was applied by making a slit in the tarp, covering the slit with a black tarp strip, and anchoring it with anchor pins. A 15 mil single drip line with 0.3 m emitter spacing and flow rate of 1.7 l per minute was used to irrigate and fertigate the beds (Berry Hill Irrigation, Inc., Buffalo Junction, VA 24529). Italian ryegrass (*Lolium multiflorum* Lam.) was seeded on 21 September 2015 and 18 September 2016 for each season respectively in the furrows to improve soil drainage, providing a walkway, and suppressing weed species. The first 1.5 m of the bed were marked as 'window' with field paint, and later the tarp in the 'window' area was replaced by clear 1 mil. embossed polyethylene tarp (Robert Marvel Plastic Mulch, LLC, Annville, PA, 17003), which was anchored by pins. Strawberries 'Chandler' were transplanted at a 36 cm spacing, in two staggered rows on 1 October, 2015 and 3 October, 2016. About twenty-five plants in two rows were transplanted in each treatment, nine being in the window area where the weed data was collected and sixteen plants being outside the window area where the horticultural data were collected. Winter protection of the strawberries was undertaken by using a 40 g m^{-2} floating row cover (Atmore Industries, Inc., Atmore, AL 36502) when temperature were forecast to fall below 1.7º C. In the spring of 2015-16 growing season, liquid fertigation was carried out at the N recommendation of 0.8 kg/ ha/day and in 2016-17, the rate was 1.12 kg/ ha/day based on tissue sample report. Plants were fertilized by fertigation was done using calcium nitrate ($CaNO_3$) and potassium nitrate (KNO_3) in alternate weeks. In 2015-16 growing season, liquid fertigation started on 29 March and ended 16 June, and the next growing season it started 22 March, 2017 and ended 26 May, 2017. A single one-time application of boron at 0.14 kg/ ha was made in 2016-17 on 11 April, 2017 through drip irrigation. Weeds in the window area of the treatments were recorded by species in December 2015 and in February 2016 for the 2015-16 growing season, and in November 2016, February-March 2017, and April 2017 for the 2016-17 growing season. Only weeds in the bed top were recorded. After each weed count, weeds in the bed top were uprooted by hand, put in paper bags and weighed. Time for hand weeding the treatments was recorded. The strawberry plant stand count was collected on a monthly basis beginning in October until June for both seasons. Total strawberry plant stand count in the whole treatment area as well as in the five-feet window area was recorded, though for plant stand count data analysis, only the number outside the window was used. Plant health rating was done once a month until the harvest season on a scale of 0-10, where 0 indicated dead and 10 indicated vigorous plants. Canopy diameter measurements were taken during the growing season on eight plants that were outside the 'window' on 27 November, 2015 and 22 March, 2016 and 19 April, 2017, but only the late season data was used for data analysis.

Fruit harvest began on 4 April and continued until 21 June in 2016 for the 2015-16 growing season and from 4 April until 30 May 2017 for the 2016-17 growing season. At harvest, berries were separated into marketable and nonmarketable categories, with the marketable fruit comprising of fruit ≥ 10 g, without blemishes and diseases. The non-marketable fruit category comprised of misshapen, diseased, and small berries (< 10 g weight). Diseased berries included those infested with Anthracnose or Botrytis. Five berries from the marketable category of each treatment were randomly selected and measured using a digital Vernier caliper scale (Neiko®01407A, Taiwan) and an average fruit size of each treatment was noted. In the 2015-16 growing season, fruit size was measured five times starting 13 May and ending 10 June, and in the 2016-17 growing season, fruit size was measured thrice during the harvest season starting 20 April and ending 1 May. After size measurement, fruits were stored in a freezer by treatments and by the date harvested in the freezer. To measure the total soluble solids (TSS) content, berries were taken out of the freezer, crushed with a pestle and mortar. The puree temperature was recorded, juice was sieved through a fine mesh, and a refractometer reading was noted. To protect the berries from diseases (*Anthracnose, Botrytis*) and insects (sap beetles), the instruction in Strawberry Integrated Pest Management Guide was followed.

Data analysis. Data were analyzed by SAS v 9.4 (SAS Institute Inc, Cary, NC, USA) and was subject to analysis of variance (ANOVA) with growing season and treatments considered as fixed effects. Prior to running the ANOVA, data were checked for normality of residuals and log-transformed where necessary. A two-way, growing season by treatment interaction was determined. When the interaction was significant, each growing season was analyzed individually. When the interaction was insignificant, main effects for growing season and treatment were evaluated.

Weed data and yield data were cumulatively assessed for the season for each treatment to determine total weed density during the season and total marketable and non-marketable yield for the season and subjected to ANOVA. Crop health reading, a rating between 0-10, which was collected monthly, was averaged over the entire season and subjected to ANOVA. Treatment stand counts were averaged for the season and average stand count was subject to ANOVA. Canopy measurements were done on eight plants per treatment and each plant was treated as a subsample. Mean separation was done using least significant difference (LSD) at alpha 0.05. Five fruits were collected from each treatment and treated as subsamples for fruit size. The average of the subsamples over the entire season for each treatment was then analyzed using SAS. For determining TSS, the fruits from a treatment were crushed together and pureed and data noted for each treatment. The average Brix reading for each treatment was calculated for the entire season and then analyzed.

Results and Discussion

Total weed density. Predominate weed species in the study in both seasons were white clover (*Trifolium repens* L.), cudweed (*Gnaphalium* spp. L.), yellow woodsorrel (*Oxalis stricta* L.), Italian ryegrass (*Lolium perenne* L.), common chickweed [*Stellaria media* (L). Vill.], and Carolina geranium (*Geranium carolinianum* L.). Total weed density data were log transformed (log10 (x+50)), and there was a significant growing season by treatment interaction (Table 2). In 2015-16 weeds were least in 1,3-D+Pic treatments compared to black plastic control. Numerically the most weeds (by density) in 2015-16 were seen in PPM treatments at 7,324 kg ha^{-1}, but not significantly different from MSM or other PPM only treatments. Overall weed density was higher in 2016-17 than in the 2015-16 growing season. Compared to 2015-16, precipitation was higher in 2016-17, especially in the months of October, March, and April and also cooler in the months of November and December (Table 1). As mostly winter annuals were seen at the site, these weeds may have been favored by a cool and moist environment in 2016-17, the result of which was a higher weed density in 2016-17. For the 2016-17 growing season, PPM + MSM had the lowest numerical weed density, but only significantly lower than the 1,3-D + Pic treatment. For yellow woodsorrel, and Carolina geranium, only the year effect was significant. Yellow woodsorrel was more in number in 2016 than in 2015, but for Carolina geranium weed density was higher in 2015 than in 2016. The year 2015-16 being drier compared to 2016-17 may have favored germination of Carolina geranium, unlike yellow woodsorrel which proliferate in moist conditions (Uva et al., 1997). Compared to other treatments, total weed density of common chickweed was lowest in fumigated plots (data not shown). For cudweed and ryegrass, the main effect of treatment was significant. Cudweed density was higher in the 2016-17 growing season than in 2015-16 growing season. Compared to the black plastic control treatments, cudweed as well as ryegrass density were lower in the 1,3-D+Pic treatments. For white clover, the growing season by treatment interaction was significant. White clover density was high in 2016-17 in the 1,3-D + Pic treatments. In a commercial raspberry (*Rubus idaeus* L.) study, several alternatives to MB (as Telone C-35, MIDAS, Pic Clor 60) were evaluated, all treatments including Pic Clor60 (at 410 kg ha $^{-1}$ under VIF or virtually impermeable film) were shown to enhance emergence of white clover (Zasada et al., 2010).

Early season weed density. For the cumulative early season weed density data, only the treatment effect was significant. The lowest weed density was in the Pic + 1,3-D treatment. Weed density in 1,3-D+Pic treatment was comparable to the weed density in PPM at 4,882 kg ha $^{-1}$ and PPM+MSM treatments. For grasses (which included ryegrass in 2015-16 and ryegrass and crabgrass in 2016-17), the treatment effect was significant. The lowest number of grasses occurred in the 1,3-D+Pic treatments. For common chickweed, both growing season and treatment effect were significant and lowest weed counts were seen in the 1,3-D+Pic treatments.

Common chickweed was more prevalent in the 2015-16 growing season than in the 2016-17 growing season. For white clover, only the treatment main effect was significant. White clover density was higher in 1,3-D+Pic treatments compared to the black plastic control. For cudweed and Carolina geranium, only the year effect was significant. Cudweed density was higher in 2016-17 (average number per plot was10) growing season than in 2015-16 season (average number per plot was 3). Carolina geranium was present in higher numbers in 2015-16 (average number per plot was 8) compared to 2016-17 (average number per plot was 3). For yellow woodsorrel, growing season by treatment was significant and hence the two seasons are presented separately in this report. The early weed density is presented in Table 3.

Mid-season weed density. There was a significant growing season by treatment interaction for the midseason weed density data (P=0.0059) (Table 4). The mid-season weed density count was high in the Pic +1,3-D treatments in 2016-17 especially due to the presence of white clover. Dominant weed species observed during the mid-season were common chickweed, cudweed, and white clover. In addition to these weed species, oxalis, bittercress, and swinecress were found in plots during the 2016-17 growing season. Only the treatment main effect was significant for chickweed density count and least weeds were seen in 1,3-D+Pic treatments. For white clover density, there was a growing season by treatment interaction (Table 4). In 2015-16 white clover count was high in MSM and 1,3-D + Pic over other treatments but in the 2016-17 growing season, white clover was high only in 1,3-D + Pic treatments. For cudweed only the treatment effect was significant. Cudweed was the least in number in 1,3-D + Pic treatments compared to the black plastic control treatments.

Weed biomass and hand weeding times. For total weed biomass collected over the whole season from November to April only the year effect was significant for time required for hand weeding.

More time was needed overall to weed the treatments in 2016-17 than in 2015-16 (data not shown).

Only the treatment main effect was significant for early season weed biomass. Compared to the black plastic control treatments, the lowest early season weed biomass was seen in 1,3-D+Pic treatment. Early season weed biomass in PPM+MSM treatments was comparable to that of 1,3-D + Pic treatments though not significantly different from the black plastic control treatments. The shortest weeding time was recorded in 1,3-D + Pic treatment (Table 5).

Plant stand count and health rating. There was a significant growing season by treatment interaction for health rating (P= 0.0001) and hence data for two seasons are presented separately (Table 3.6). In 2015-16, 1,3-D + Pic treated plants had the lowest health rating possibly due to smaller sized plants, but the next season 1,3-D+Pic treated plants had the highest health rating but statistically the health rating was similar to the plants of PPM + MSM, PPM at 6103 kg ha $^{-1}$ and PPM at 7324 kg ha^{-1} treatments. The MSM treated treatments were not significantly different from the black plastic control treatments in both seasons. In California, strawberry plants showed phytotoxicity after MSM incorporation but the effect was not long lasting and had no effect on productivity (Bañuelos and Hanson, 2010). The isothiocyanates released from glucosinolates could have a suppressive effect on plants (Moore, 2011). There was no effect of growing season, treatment or their interaction on strawberry plant stand count (data not shown).

*Canopy reading***.** For the canopy reading, there was growing season by treatment interaction (P=0.0001). In 2015-16 canopy of plants in the PPM+MSM treatments was significantly different from the canopy readings of 1,3-D + Pic and the black plastic control treatments. In 2016-17, the 1,3-D + Pic treatments had the largest canopy, followed by PPM at 7323.6 kg ha^{-1}, PPM+MSM, and MSM treatments. The lowest canopy reading in 2016-17 occurred in the black plastic control treatments, PPM at 4882.4 kg ha^{-1} and 6103 kg ha^{-1} treatments. The canopy reading was higher in the second growing season than the first, possibly because that data were taken in April in 2016-17 compared to March in 2015-16 and may not be related to the performance of the plants. For the cultivars ‘Chandler’, ‘Camarosa’, and ‘Sweet Charlie’ that were observed in an annual plasticulture system, the largest increase of biomass of leaves took place in the period just before and during fruiting from March to June (Fernandez et al, 2001) and in April a surge in biomass allocation to leaves took place. Small trials at Aurora Hills in Virginia with tomato, green beans (*Phaseolus* L.), and potatoes (*Solanum tuberosum* L.) have previously shown marked increase in vegetative growth with impervious paper mulch (Flint 1928).

Crop yield and fruit quality parameters. For marketable and total yield, the growing season by treatment interaction was significant (P=0.0001). In the 2015-16 growing season, marketable yield in PPM+MSM and MSM treatments was higher than the black plastic control but not different from the 1,3-D + Pic treatment. In 2016-17, the highest marketable yield was seen in the 1,3-D + Pic treatments followed by the PPM+MSM treatments which were both significantly higher than the black plastic control. Effect of MSM on yield may be variable. During 2007-08 growing season at Watsonville, California, yield was high in MSM treatments compared to the black plastic control when used at a rate of 2,242 kg ha^{-1} but the same effect was not seen the next season (Samtani et al., 2011). In Tennessee incorporation of mustard seed meal (applied preplant) at 2240 to 4480 kg ha^{-1} increased strawberry yield between 20 to 29 % compared to the control treatments (Deyton and Sams, 2010). In California (Bañuelos and Hanson, 2010), MSM applied seven days before planting in strawberry treatments at 2,242 kg ha^{-1} and 4,483 kg ha^{-1}

increased yield compared to control plots but a high rate of 13,450 kg ha^{-1} decreased berry yield by almost 42%. The increase in yield after application of MSM could be due to low carbon to nitrogen ratio that could make them readily decomposable and through mineralization provide substantial amount of plant available nitrogen (Brown and Morra, 2005). Paper mulches have shown to increase soil temperature and moisture, control weeds, and improve yield of pepper (*Capsicum* L.), muskmelon (*Cucumis melo* L.), and tomato (*Solanum lycopersicum* L.) (Thompson and Platenius, 1931). Lettuce (*Lactuca L.*) grown on paper or polyethylene mulch had higher marketable yield and heavier heads compared to unmulched lettuce (Jenni and Brault, 2004). In 2015-16, higher total yield was seen in PPM+MSM treatments which were significantly different from the black plastic control treatments but not from the treatments treated with medium (6103 kg ha^{-1}) and higher (7324 kg ha^{-1}) PPM rates and MSM treatments. In 2016-17, 1,3-D + Pic treatment had the highest total yield compared to black plastic control control. The treatments PPM + MSM, MSM, and PPM at 7324 kg ha^{-1} also had higher total yield over the nontreated control (Table 3.9). In our trial, PPM+MSM treatments showed higher yield than the nontreated control in both seasons which could be due to the allelopathic property of the meal and the beneficial effect of the paper.

For fruit size, both treatment and growing season were significant. Larger berries were seen in 1,3-D + Pic, PPM + MSM and MSM treatments which were significantly different than the black plastic control (Table 10). In 2016-17 the berries were larger than that of the 2015-16 treatments. For Brix there was growing season effect. Berries were sweeter in 2015-16 compared to 2016-17.

Air temperature and precipitation. Average air temperature in our study was higher in November and December 2015-16 than in 2016-17 (Table 1). In 2015-16, the average temperature was 14.1^{o} C (57.4^{o} F) in November (an increase of 2.8^{o} C compared to 2016-17) and 14.2 ^{o} C in December (an increase of 6.9 ^{o} C compared to 2016-17). Precipitation was high (10.2 cm) in November 2015-16, about 7.7 cm more than the next growing season (2.5 cm). Compared to 2015-16, rainfall was higher in the months of harvest in March, April, and May in 2016-17. An increase in diseases and reduced pollination in wetter years could cause a reduction in yield in strawberries and many other crops (Lobell et al., 2007).

Conclusion

Paper pellets alone did not control weeds in our study, perhaps because over the long strawberry season, paper mulch disintegrates. However, in PPM + MSM treatments early season weed biomass was lower compared to some other PPM treatments. Compared to black plastic control, plants in PPM+MSM treatments had increased marketable as well as total yield and needs further evaluation in the strawberry annual plasticulture production system.

Table 3.1 Monthly average air temperature and monthly precipitation in the 2015-16 and 2016-17 growing seasons.

Monthly average air temperature (º C) in 2015-16 and 2016-17 growing season									
Year	October	November	December	January	February	March	April	May	June
2015-16	17.1	14.1	14.2	5.1	6.9	13.3	14.3	18.9	24.2
2016-17	18.6	11.3	7.3	7.3	10.8	10	19.1	20.2	
Monthly precipitation (cm) in 2015-16 and 2016-17 growing season									
Year	October	November	December	January	February	March	April	May	June[a]
2015-16	9.4	11.7	8.6	11.7	16.0	8.9	7.1	13.0	13.0
2016-17	23.9	2.5	6.4	11.2	1.8	11.7	9.1	21.8	

[a] Precipitation data for the month of June is the total until the harvest date, i.e. June 21 in 2015-16 and May 30 in 2016-17

Source: United States Department of Agriculture, Natural Resources Conservation Service, National Water and Climate Center (2017)

Table 3.2 Cumulative total weed density of cudweed, ryegrass, and white clover collected in 1.5 m length of bed in 2015-16 and 2016-17 in Virginia Beach, Virginia[a,b]

Treatment	Rate	Cudweed[b]	Italian ryegrass[b]	White clover[b]		Total weed density	
	kg ha^{-1}	2015-17	2015-17	2015-16	2016-17	2015-16	2016-17
Paper pellet mulch	4,882	33.3 a	17.6 ab	25.3 b	214.5 b	155.8 ab	478.0 ab
Paper pellet mulch	6,103	18.3 ab	16.8 ab	24.5 b	167.5 b	154.8 ab	484.5 ab
Paper pellet mulch	7,324	15.4 bc	25.0 a	16.8 b	196.5 b	189.8 a	457.3 ab
Mustard seed meal	2,242	33.1 a	17.5 ab	49.5 a	218.8 b	172.5 ab	498.5 ab
Paper pellet mulch + Mustard seed meal	6,103+2,242	22.0 ab	14.1 b	21.3 b	242.0 b	133.3 b	422.8 b
1,3-D + chloropicrin	152	1.1 c	1.5 c	52.5 a	618.5 a	93.8 c	675.5 a
Control (black plastic)	-	29.4 ab	21.5 ab	27.5 b	246.8 b	170.5 ab	500.3 ab
$P_r > F$ Growing season by treatment		0.23	0.25	0.03		0.005	

[a] Means with the same letter within a column are not significantly different using least significance difference at P≤0.05. Data is from 1.5 m length of bed top.

[b] For cudweed and Italian ryegrass, treatment effect was significant. For white clover, the growing season of treatment was significant.

Table 3.3 Cumulative early season weed density of common chickweed, white clover, grass and yellow woodsorrel collected in a 1.5 m length of bed in 2015-16 and 2016-17 in Virginia Beach, Virginia [a].

Treatment	Common chickweed[b]	Grass[c]	White clover[d]	Yellow woodsorrel		Cumulative early weed density[e]
	2015-17	2015-17	2015-17	2015-16	2016-17	2015-2017
Paper pellet mulch	15.9 a[c]	17.8 a	7.3 b	5.3 ab	12.5 ab	96.8 abc
Paper pellet mulch	15.8 a	28.6 a	23.4 b	6.8 ab	12.5 ab	120.5 a
Paper pellet mulch	17.9 a	20.9 a	8.6 b	8.3 a	18.3 ab	116.9 ab
Mustard seed meal	18.6 a	15.4 a	18.9 b	6.0 ab	18.8 ab	109.4 ab
Paper pellet mulch + Mustard seed meal	12.9 a	11.5 a	11.5 b	8.0 a	8.3 b	82.8 bc
1,3-D + chloropicrin	1.1 b	0.9 b	37.8 a	2.8 b	29.5 a	68.8 c
Control (black plastic)	17.1 a	21.5 a	17.5 b	4 ab	15.0 ab	116 ab
P r> F Growing season by treatment	0.12	0.08	0.16	0.05		0.04

[a] Means with the same letter within a column are not significantly different using least significance difference at $P \leq 0.05$. Data is from 1.5 m length of bed top

[b] For common chickweed both the growing season and treatment were significant. For yellow woodsorrel, there was the significant interaction of growing season and treatment.

[c] Grasses included ryegrass in 2015-16 and ryegrass and crabgrass spp. in 2016-17

[d] For white clover treatment effect was significant.

[e] For cumulative early weed density, treatment effect is shown

Table 3.4 Cumulative mid-season density of common chickweed, white clover, and cudweed collected in 1.5 m length of bed in 2015-16 and 2016-17 in Virginia Beach, Virginia.

Treatment	Common chickweed	White clover		Cudweed	Cumulative mid-season weed density	
	2015-17	2015-16	2016-17	2015-17	2015-16	2016-17
Paper pellet mulch	11.0 a	14 b	109 b	17.4 a	62.5 ab	209.3 b
Paper pellet mulch	7.5 a	13 b	75.8 b	8.5 bc	59.0 ab	147.5 b
Paper pellet mulch	10.6 a	9 b	113.8 b	8.3 bc	71.8 a	213.8 b
Mustard seed meal	8.0 a	22 a	100.3 b	14.1 ab	64.8 a	195.3 b
Paper pellet mulch + Mustard seed meal	6.9 a	8.5 b	152.8 b	11.5 ab	49.5 bc	227.8 b
1,3-D+chloropicrin	0.8 b	27.3 a	460.3 a	0.8 c	45.8 c	465.3 a
Control (black plastic)	8.4 a	13.5 b	127.8 b	15.8 ab	59.5 abc	217.0 b
P r> F Growing season by treatment	0.02	0.002		0.0097	0.0059	

Table 3.5 Early season weed biomass and time to weed in 1.5 m length of bed in Virginia Beach, Virginia, in 2015-17 growing season[a].

Treatment	Early season[b] weed biomass	Time
	g	min
Paper pellet mulch	510.0 ab	26.3 a
Paper pellet mulch	648.9 a	25.1 a
Paper pellet mulch	628.6 a	28.2 a
Mustard seed meal	494.0 ab	24.6 a
Paper pellet mulch + Mustard seed meal	304.6 bc	21.9 ab
1,3-D + chloropicrin	82.1 c	14.8 b
Control (black plastic)	507.0 ab	23.6 a
Pr>F Growing season by treatment	0.52	0.95

[a] Means with the same letter within a column are not significantly different using least significance difference at P≤0.05. Data is from 1.5 m length of bed top

[b] Early season weed biomass did not show a growing season by treatment interaction, or a growing season effect, but the treatment effect was significant, so data were pooled for two seasons. For time taken to harvest weeds, there was no growing season by treatment effect but there was both treatment and season effect.

Table 3.6 Cumulative health rating in annual plasticulture strawberry production in 2015-16 and 2016-17 growing season in Virginia Beach, Virginia[a].

Treatment	Cumulative health rating 2015-16	Cumulative health rating 2016-17
Paper pellet mulch	8.0 a	8.0 bc
Paper pellet mulch	8.1 a	8.1 ab
Paper pellet mulch	7.9 ab	8.2 ab
Mustard seed meal	7.8 b	8.0 bc
Paper pellet mulch + Mustard seed meal	8.0 a	8.3 ab
1,3-D + chloropicrin	7.4 c	8.4 a
Control (black plastic)	7.7 b	7.7 c
Pr > F[a] Growing season by treatment	0.0001	

[a] Means with the same letter within a column are not significantly different from one another using least significant difference at $P \leq 0.05$

Table 3.7 Canopy diameter of strawberries in annual plasticulture production system in 2015-16 and 2016-17 growing season in Virginia Beach, Virginia[a].

Treatment	2015-16 (March 2016)	2016-17 (April 2017)
	------cm------	
Paper pellet mulch	28.1 ab	31.4 c
Paper pellet mulch	28.3 a	30.5 c
Paper pellet mulch	28.2 ab	33.8 b
Mustard seed meal	28.4 a	33.1 b
Paper pellet mulch + Mustard seed meal	29.0 a	33.6 b
1,3-D + chloropicrin	26.5 c	36.5 a
Black plastic control	26.9 bc	30.7 c
Pr > F[a] Growing season by treatment	0.0001	

[a] Means with the same letter within a column are not significantly different from one another using least significant difference at $P \leq 0.05$

Table 3.8 Cumulative marketable yield and total yield per plant collected in strawberry annual plasticulture production system in 2015-16 and 2016-17 in Virginia Beach, Virginia[a] .

Treatment	Cumulative marketable yield(g)		Cumulative total yield(g)	
	2015-16	2016-17	2015-16	2016-17
Paper pellet mulch	281.2 b	205.5 c	610.6 b	390.1 cd
Paper pellet mulch	327.1 ab	220.1 c	694.8 ab	389.0 cd
Paper pellet mulch	349.5 ab	238.9 bc	681.4 ab	433.0 bc
Mustard seed meal	380.9 a	261.8 bc	692.5 ab	434.2 bc
Paper pellet mulch + Mustard seed meal	414.2 a	326.5 b	777.3 a	545.4 b
1,3-D + chloropicrin	330.1 ab	602.8 a	583.0 b	869.6 a
Control (black plastic)	265.7 b	165.2 c	589.7 b	304.7 d
Pr > F[a] Growing season by treatment	0.0001		0.0001	

[a] Means with the same letter within a column are not significantly different from one another using least significant difference at $P \leq 0.05$

Table 3.9 Fruit size in strawberry annual plasticulture production system in 2015-17 in Virginia Beach, Virginia [a].

Treatment	Fruit size (mm)
Paper pellet mulch	29.9 bc
Paper pellet mulch	29.9 bc
Paper pellet mulch	30.5 abc
Mustard seed meal	30.7 ab
Paper pellet mulch + Mustard seed meal	31.4 a
1,3-D + chloropicrin	31.6 a
Control (black plastic)	29.4 c
Pr > F[a] Growing season by treatment	0.83

[a] Means with the same letter within a column are not significantly different from one another using least significant difference at $P \leq 0.05$

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CHAPTER IV

Flanagan Farms Study

Abstract. A split-plot study was set up at Flanagan Farms, Virginia Beach with two treatment factors- tarp as the whole plots and pelleted products as subplots. Whole plot treatments were zebra mulch (which is a soil solarization treatment) tarp (clear plastic at the top of beds and black plastic at the side of beds) and standard black polyethylene tarp. The subplot treatments were (i) paper pellet mulch with fertilizer at 6,103 kg ha^{-1}, (ii) paper pellet mulch without fertilizer at 6,103 kg ha^{-1}, (iii) mustard seed meal at 2,242 kg ha^{-1}, (iv) paper pellet mulch at 6,103 kg ha^{-1} and mustard seed meal at 2,242 kg ha^{-1} and (v) control (black plastic). Soil solarization was carried out for about four weeks (24 August, 2016 – 26 September, 2016). Three fumigated plots (Pic-Clor 60 at 134.5 kg ha^{-1}) were established adjacent to the study for comparison of the study treatments to a standard grower preplant treatment. The objectives of the study were to see how the treatments which showed numerical increased yield and reduced weed density relative to the black plastic control at the Hampton Road Agricultural Research and Extension Center (Chapter 3 study) performed at a grower site. An additional treatment in the conducted study included a locally available paper pellet mulch without fertilizer. The four-week period of soil solarization proved to be inadequate and did not result in improved crop health, weed control or yield over the black plastic control. The study was established (bed formation, application of fertilizer and mustard seed meal) on 24 August, 2016. The strawberry plug plants were established on 28 September, 2016. The plots with paper pellet mulch without fertilizer had the lowest health rating and total yield per plant. The fumigated plots (at one end, outside the study) had high health rating and total yield. A longer period of soil solarization and also increased depth of paper mulch may be evaluated in future studies.

Introduction.

The absence of methyl bromide as a preplant fumigant necessitates looking for alternative treatments that may be used for an annual plasticulture strawberry (*Fragaria*×*ananassa* Duch.) production system. Although solar radiation has been used as early as 1939 to control disease in tobacco (*Nicotiana tabacum* L.) (Grooshevoy, 1939), soil solarization as a preplant treatment to control weeds and pathogens was first described in 1976 (Katan et al., 1976). Soil solarization is achieved by using a clear tarp which allows the solar radiation to pass through and traps the heat, which in turn heats up the soil, and in the process proves to be detrimental for many pests. Paper mulch is beneficial in many aspects, by controlling weeds, increasing yield of some crops as lettuce (*Lactuca* L.) (Brault et al., 2002), tomato (*Solanum lycopersicum* L. var. *lycopersicum*) (Schonbeck and Evanylo, 1998), influencing soil temperature (Thompson and Platenius, 1931), decreasing evaporation, and adding organic matter to the soil. Mustard seed meal is a byproduct of the mustard seed oil extraction process. They contain compounds called glucosinolates that release isothiocyanates in the presence of water and may be used for biofumigation. The objectives of the study were to see how the treatments which showed increased yield and reduced weed density relative to the black plastic control plots at the Hampton Road Agricultural Research and Extension Center (Chapter 3 study) performed at a grower site.

Materials and Methods.

A study was initiated as a split-plot design on 24 August, 2016, at Flanagan Farms, Virginia Beach, Virginia. There were three blocks, each block having one bed under zebra mulch (Ginegar Plastic Products, Santa Maria, California) of about 30-micron thickness (where the top of the bed had clear plastic and the sides had black plastic) and one bed under a black polyethylene tarp (TriEst Ag Group, Inc, Greenville, NC, 27835) (1.25 mil thickness). The bed covered with zebra mulch was used for soil solarization treatment and all other beds were covered with black plastic. The tarps were the whole plot treatments and each bed had five subplots, each subplot having a separate pelleted product. Each subplot was 3.2 m in length with a buffer area of 0.9 m between the subplots. Preplant soil tests indicated a pH of 6.6 and limestone was not applied to the site. Fertilizers were applied (broadcast before final bedding) as per grower recommendations. Nitrogen was applied at 67.2 kg ha^{-1}, phosphate at 33.6 kg ha^{-1} and potash at 72.8 kg ha $^{-1}$. The grades of fertilizer used were 34 N-0 P_2O_5-0 K_2O (ammonium nitrate) for nitrogen, 0 N-0 P_2O_5-60 K_2O for potash and 0 N-44 P_2O_5-0 K_2O (triple superphosphate) for phosphate. About 67.2 kg ha $^{-1}$ N, 33.6 kg ha $^{-1}$ P_2O_5 and 72.8 kg ha^{-1} K_2O were applied in black plastic control plots and rates of fertilizer were adjusted in each plot according to each pelleted product treatment as most pelleted products had a preformulated rate of fertilizer incorporated. Pelleted product treatments consisted of (i) mustard seed meal (MSM; Biofence, 6 N:2 P_2O_5:0 K_2O, Southern States Cooperative, Virginia Beach, Virginia) at 2242 kg ha^{-1}, (ii) MSM at 2242 kg ha^{-1} and paper pellet mulch (PPM, 0.7 N:1 P_2O_5:0.4 K_2O, Pennmulch, Lebanon Seaboard Corporation, Lebanon, Pennsylvania, USA) at 6103 kg ha^{-1} [composed of recycled newsprint, starter fertilizer and moisture cell technology (absorbent polymers that absorb water and release water back to soil)], (iii) PPM at 6103 kg ha^{-1}, (iv) a paper pellet mulch without any fertilizer [Lesco seed starter 3 Cleveland, Ohio,] made of more than 83% cellulose fiber from newsprint, about 15% ground corn stalks, vegetable gum and biodegradable green dye @ 6103 kg ha^{-1} and (v) the black plastic control plots. The fertilizer and MSM were applied after prebedding and the PPM was applied before the plug plants were transplanted. Hobo temperature sensors (Hobo data loggers, Onset Computer Corporation, Bourne, Massachusetts) were placed at depths of 5 cm and 15 cm in two solarized (clear tarp) and two non-solarized (black tarp) beds at the time of initiation of the study. A month later after solarization on 26 September, 2016, PPM was applied at a depth of about a centimeter on bed tops by making a slit in the plastic along the length of the bed. After PPM application, the bed tops were resealed with a strip of plastic (approximately 15 cm width, either clear or black depending on the type of plastic covering the bed, placed in a manner to cover the gap caused by the slit) using anchor pins. There were three fumigated plots (Pic-Clor 60, at 135 kg ha^{-1}, Tri Est Ag Group, Greenville, NC) of similar length (3.2 m) adjacent to the replicated study to allow for comparison of the study treatments to standard fumigated preplant treatment. Fumigation occurred on 4 September, 2016. Sixteen strawberry plug plants per subplot of 'Chandler' were transplanted on 28 September, 2016, in a staggered manner in two rows per bed at 0.4 m spacing between plants. To reduce weed emergence and growth, bed tops of plots receiving soil solarization treatments (covered with zebra mulch) were painted black using a paint brush and black paint (Behr black paint, Santa Ana, California) in October 2016 after the solarization treatment period was over. In spring and early summer, strawberry plants were periodically fertigated (approximately every 10 days) with calcium nitrate (3.6 kg N per acre) and potassium nitrate (3.2 kg N per acre) from March 10 till May 20. Two times during this period on 29 March and 14 April, Jack's fertilizer (20 N-20 P_2O_5-20 K_2O; Jack's fertilizer, JR Peters Inc, Allentown, PA) was applied at 2.3 kg N per acre. Health rating of plants in a bed (0 to 10) and stand count were taken once a month during the growing season from 28 October, 2016 until 12 April, 2017. Health rating was recorded monthly (28 October 2016 to 14 April, 2017) on a scale of 0 (all plants dead) to 10 (plants growing vigorously). Weeds growing under the bed top were harvested by hand through the strawberry planting hole on 28 October, 2016, and 30 March, 2017. Fresh weed biomass was recorded and time to harvest weeds were noted for each subplot. Fruit harvest began on 12 April and continued till 13 June in 2017 by harvesting plots two times per week. Berries were separated into marketable and nonmarketable fruit, with the marketable fruit comprising of fruits weighing 10 g and above, without blemishes or diseases. Non-marketable fruit were comprised of misshapen, diseased and small berries (under 10 g weight). Fruit size and refractometer readings were recorded from 21 April to 15 May. Fruit size was recorded once a week on five randomly selected berries per sub-plot using a digital Vernier caliper (Neiko®01407A, Taiwan) scale. An average fruit size for each subplot was calculated. After measurement of fruit size, the same fruits were kept in the freezer at 4º C for measuring the total soluble solids (TSS) content. Berries were taken out from the freezer, thawed, and upon thawing, berries were crushed using a pestle and mortar. Berry juice was sieved through a fine mesh strainer, and when juice temperature was around 20º C the TSS content was noted (MA871 Milwaukee Refractometer, Milwaukee Instruments Inc., Rocky Mount, North Carolina, USA). Health rating, plant stand count, TSS and fruit size were averaged across the season. Marketable yield per plant, total yield per plant were added over the entire season and the cumulative reading was subjected to ANOVA.

Data analysis. Data were analyzed as a split plot and the tarp by pelleted product interaction, tarp effect and pelleted product effect were noted for each dependent factor. Mean separation was done using LSD at alpha 0.05. Data were analyzed by SAS v 9.4 (SAS Institute Inc., Cary, NC, USA) and were subject to analysis of variance (ANOVA). Data were checked for normality of residuals and log transformation [log10 (x+50)] was used for weed biomass and average plant stand count for the season.

Results and Discussion.

Soil solarization treatments accumulated maximum temperature compared to black tarp at both depths of 5 cm and 15 cm during the treatment period (Table 4.1). At a 5 cm depth, maximum soil temperature under the zebra mulch was 3.5 ^{0} C higher than the black tarp and at 15 cm depth, the difference was 5.2^{0} C higher. Starting soil solarization earlier in the months of July and August may prove to be advantageous due to higher air temperature (as seen in Table 4.2) but land preparation immediately after the harvest season may be challenging for the grower. Table 4.2 shows high precipitation in the months of September 2016 (when the plugs were planted), October 2016, and in May 2017 (during harvest season, rendering ripe or near ripened fruits non- marketable when left on bed tops).

The two-way tarp by pelleted product interaction was not significant and only the tarp main effect was significant for weed biomass (P=0.0001). Weed biomass under the clear tarp was higher than under the black tarp (data not shown). Dominant weeds were nutsedge species (*Cyperus* species), wild mustard (*Sinapsis arvensis* L. ssp. *arvensis*) and Italian ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot]. For plant stand count, the two-way tarp by pelleted product interaction was not significant and only the tarp main effect was significant (P=0.02). A few strawberry plants died in the clear tarp treatments after the tarp was painted black, possibly due to toxic effect of paint and were not replaced with other plug plants. For the crop plant health rating, only the main effect of the pelleted product was significant. The lowest health rating was seen in plots with PPM w/o fertilizer as the plants were smaller in size. All other pelleted product treatments had a plant health rating of 8 or higher (Table 4.3). The fumigated plots, though not randomized as part of the study, had the highest numerical plant health rating as the plants had good size and looked healthy (Table 4.3). Neither the two-way interaction nor the treatment or tarp main effects were significant for marketable yield per plant. For the total yield per plant, only the treatment main effect was significant (Table 4.3). The lowest total yield was in PPM w/o fertilizer plots. Numerically, the fumigated plots had higher total yield compared to other treatments. Gilreath et al. (2008) showed that using 1,3-D (1,3-dichloropropene) and Pic (chloropicrin) improved plant vigor, early and total marketable yield and was similar to MB (methyl bromide) + Pic in strawberry production. Berry sweetness and fruit size were not influenced by either tarp or pelleted products (data not shown).

In this one-year trial at Flanagan Farm, all pelleted product treatments had significantly similar total yield and average crop health rating for the season except for the paper mulch without fertilizer. The paper mulch at the rate evaluated did not provide thorough coverage for the entire bed width and was only about one cm deep. The isothiocyanates have variable phytotoxicity, are volatile, have short lived efficacy (Brown and Morra, 2005). The PPM and mustard seed meal products thus did not prove to be effective for weed control. Beds covered with clear tarp allowed more light and had higher weed biomass than those covered with black tarp. More weed biomass does not necessarily indicate more weed density, fewer weeds may have higher biomass and thus be a greater competitor for the crop for nutrients and moisture. Weed count was not noted at this site, and only weed biomass was recorded. The clear tarp did not show any added benefit in respect to plant growth or yield compared to black tarp. One reason for the lack of effectiveness in the solarization treatment maybe that solarization was carried on for approximately four weeks. A solarization period of six weeks or longer was more effective in Virginia (Samtani et al., 2017). Another reason is that sandy soils are lighter in color (State loam, 0 to 2 per cent slope). The darker soils absorbed more radiation resulting in higher temperature (Elmore et al., 2007). Painting the clear area of the zebra mulch with a black paint after the plants were transplanted proved to be detrimental to the plants possibly due to toxicity from paint. The early season health rating was low for plots treated with paper pellet without fertilizer and the black plastic control plots. For the paper pellet plots without fertilizer, this trend continued and these plots had the lowest total yield. A possible reason for low early season health rating and low total yield could be that one of the component was ground corn stalks. Corn residues allowed to decompose at 22-23º C in soil for 30 days had a phytotoxic effect on lettuce seedlings and reduced growth (Chou and Patrick 1976). However, the black plastic control plots which had lower early health rating eventually had yield comparable to other plots. In the future, if the study were to be repeated, to prevent loss of plants under the clear tarp, it would be advisable to paint the clear tarp before the plants are transplanted in the bed.

Conclusion.

In this study at Flanagan Farms, the four-week period of soil solarization did not reduce weed biomass or improve yield over black tarp, and perhaps a longer duration of six weeks or more would have performed better. Though the paper pellet rates were chosen keeping the economic factor in mind, the depth was not adequate for weed control and in future, a higher rate should be investigated from locally available sources.

Table 4.1 Soil temperature in 2016-17 growing season collected at 5 cm and 15 cm depth during 4-week solarization treatment period in beds with clear (zebra) tarp and black tarp at Flanagan Farm, Virginia Beach, Virginia[a].

Depth	Tarp	Maximum	Mean	Temp ≥ 40º C
		--------ºC-----		-----hr----
5 cm	Clear	51.8	30.9	125
	Black	48.3	29.0	45
15 cm	Clear	45.8	30.4	68
	Black	40.6	28.7	7

[a]Data were collected from 24 August to 26 September, 2016. Soil temperature for no tarp was not noted at the site.

Table 4.2 Table showing monthly average air temperature and monthly precipitation at Virginia Beach, Virginia, in 2016-17 growing season.

Monthly average air temperature (º C) in 2016-17 growing season

Year	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June
2016-17	29.9	29.4	23.9	18.1	10.6	6.7	6.6	9.4	8.9	17.8	18.9	23.9

Monthly total precipitation (cm) in 2016-17 growing season

Year			Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June[a]
2016-17			12	8.6	2.0	2.3	3.4	0.6	4.5	2.5	7.3	1.2

[a]Precipitation data for the month of June is the total until the harvest date, i.e. 13 June in 2016-17 growing season

Source: United States Department of Agriculture, Natural Resources Conservation Service, National Water and Climate Center (2017), Oceana NAS weather station

Table 4.3 Average crop health rating, cumulative total (marketable + non-marketable) yield per plant in annual plasticulture strawberry production at Flanagan Farms, Virginia Beach, Virginia, in the 2016-17 growing season.

Treatment	Rate	Average health rating[b] for the 2016-17 growing season	Cumulative total yield
	------kg ha^{-1}----		------g/plant----
Mustard seed meal	2,242	8.0 a	756.4 a
Paper pellet mulch	6,103	8.1 a	715.2 a
Paper pellet mulch + Mustard seed meal	2,242 + 6,103	8.0 a	719.3 a
Paper pellet mulch w/o fertilizer	6,103	7.6 b	593.7 b
Control (black plastic)	-	8.0 a	747.8 a
Pr > F Treatment		0.02	-
1,3-D + chloropicrin	135	8.8	948.5

[a]The three fumigated subplots were not replicated as part of the main study but were adjacent to the study, so that a comparison can be made with the main treatments.

[b] Health rating was collected on a scale of 0-10 where 0 meant dead and 10 vigorous plants.

Table 4.4 Table showing marketable and non-marketable yield in annual plasticulture production at Flanagan Farms, Virginia Beach, Virginia in the 2016-17 growing season.

Treatment	Marketable	Nonmarketable
	------------------(g/plant)---------------	
Mustard seed meal	414.5	341.9
Paper mulch	380.7	334.5
Paper mulch w/o fertilizer	327.6	266.1
Paper mulch + Mustard seed meal	388.6	330.7
Black plastic control	410.6	337.2
1,3-D + chloropicrin	473.3	475.2

[a] The three fumigated subplots were not replicated as part of the main study but were adjacent to the study, so that a comparison can be made with the main treatments.

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Summary

Soil solarization is adopted primarily in warmer regions of the world as a preplant method to reduce soilborne pests by covering the moist soil with clear polyethylene to trap heat. But the effectiveness of solarization may be lowered due to cloudy days, or if the treatment period experiences cooler temperature. In coastal Virginia, six weeks of soil solarization effectively controlled weeds in a previous study. In the mid-Atlantic region, the harvest season of strawberries planted in annual hill production ends in June and for the next season berries are transplanted from mid-September to early October. Ideally for soil solarization to have its best efficacy, it needs to be initiated in July. But getting the fields ready immediately after harvest of last crop may not be practical for growers and thus implementing longer periods of solarization may be challenging for growers. To fit the fumigation window for treatment application, we initiated a three-week period of soil solarization and thought to combine soil solarization with bio-based pelleted products- paper pellet mulch, corn gluten meal, and mustard seed meal.

Pelleted products were evaluated individually and with soil solarization. Early season weed density was lowered with the use of paper pellet and soil solarization compared to black plastic control. Early season weed control is desirable for the crop plant as the strawberry plants are being established. As paper pellets degrade over time, their efficacy for weed control decreases. In many studies, a beneficial effect on crop yield have been observed when paper mulch is used, perhaps because as paper is degraded, it adds organic matter to the soil. In our study of soil solarization, paper pellet mulch increased yield compared to soil solarization or corn gluten meal in one season. To further evaluate paper pellets, different rates of paper pellets, and combination of paper pellet and mustard seed meal were evaluated in the 2015-16 and 2016-17 growing seasons. This study also included a fumigated plot for comparison and an black plastic control control. The lowest early season weed density was seen in the fumigated plots. Early season low weed density was also seen in the paper pellet and mustard seed meal combination treatment and one of the paper pellet treatment that was comparable to the fumigated plots. Early season weed biomass and time was also least in fumigated plots which was comparable to that of the paper pellet and mustard seed meal combination plots. In both seasons the marketable, total yield, and fruit size were significantly greater in mustard seed meal and paper pellet combined treatment compared to the black plastic control treatments. The fumigated plots were relatively weedy in 2016-17, especially populated with white clover. A study conducted (Appendix A) with different weed species in trays and different rates of paper pellets and their combinations with mustard seed meal showed similar results as the field experiments that the paper pellets did not control weeds. The container study with pansies showed no phytotoxic effect from paper pellet, mustard seed meal or their combinations on plant growth. At the grower farm where the best treatments observed at the AREC were tried in a one-season study, greater weed biomass under the clear tarp was seen compared to the black tarp. After the solarization period was over, we had painted the clear tarp black at the grower farm but that proved to be detrimental for plants and some plants perished. Any painting of the clear tarp should be done before planting of crops to avoid any phytotoxicity. We used a locally available paper pellet for the grower farm study, but the performance of this paper pellet was lower than all other treatments.

Paper pellets in combination with soil solarization was useful in lowering early season weed density, reduced early weed biomass, and increased yield when combined with mustard seed meal and needs further evaluation in strawberry annual plasticulture production. Apart from lowering early season weed density with paper pellets, a reduced period of soil solarization was not effective in consistently increasing yield in our study and perhaps in future, longer periods of soil solarization should be evaluated in coastal Virginia.

Appendix A

The objective of the study was to evaluate the effect of two paper pellet products and mustard seed meal on weed seed germination. A weed seed germination study was set up in the 2016-17 growing season in a completely randomized design with five treatments and four replications at the Hampton Road Agricultural Research and Extension Center, City of Virginia Beach. Treatments were mustard seed meal (MSM, Biofence 6 N:2 P_2O_5:0 K_2O, Southern States Corporation, Virginia Beach, Virginia) at 2242 kg ha^{-1}, paper pellet mulch (PPM, Pennmulch, Lebanon Seaboard Corporation, Lebanon, Pennsylvania, USA) at 6103 kg ha^{-1}, paper pellet mulch plus mustard seed meal at 6103 + 2242 kg ha^{-1}, Lesco (made of more than 83% cellulose fiber from newsprint, about 15% ground corn stalks, vegetable gum and biodegradable green dye) at 6103 kg ha^{-1} (Lesco Inc., Cleveland, Ohio) and control (black plastic). The depth of the paper mulches was about a cm and provided around 80% coverage of the surface. Pennmulch consisted of recycled newsprint with a starter fertilizer (0.07 N:1 P_2O_5: 0.04 K_2O), and the Lesco product was comprised of pelleted paper but without a fertilizer.

Preliminary weed seed germination study in containers

A germination test was initiated on 13 October 2016 for corn speedwell (*Veronica arvensis* L.), hairy bittercress (*Cardamine hirsuta* L.), white clover (*Trifolium repens* L.), henbit (*Lamium amplexicaule* L.), Persian speedwell (*Veronica persica* Poir.), common chickweed [*Stellaria media* (L.) Vill], and yellow woodsorrel (*Oxalis stricta*). Most of the weed were procured from Herbiseed (Twyford, England, RG10 0NJ) except common chickweed and yellow woodsorrel which were collected locally. These weed species were chosen as they were common in the conducted field studies. In the initial weed seed germination study (without mulches) where only the rate of germination of different species was observed, thirty weed seeds of each species were put in 1.9 l containers. with a proprietary potting mix which was a blend of vermiculite and peat moss (McDonalds Natural and Organic Potting Mix, McDonald Garden Center, Virginia Beach, Virginia) and watered regularly. On 31 October, 2016, the weed seeds that germinated were counted. Those which had a very low germination rate [yellow woodsorrel (10%), henbit (14%), corn speedwell (9%)] were excluded from the study and only four species - hairy bittercress (71%), white clover (81%), Persian speedwell (86%) and common chickweed (26%) were counted.

Since different weeds had different germination rates, in the final study which was carried out in flat trays with mulches to evaluate the effect of mulches on germination, seed numbers were chosen so that 30 plants of each species would germinate in each tray (the initial number of seeds put in each pot was 30). Accordingly, 115 seeds were for common chickweed, 42 for hairy bittercress, 37 for white clover seeds 35 for Persian speedwell seeds were planted (Table 2).

Weed seed germination in trays with different paper mulches and mustard seed meal

Plastic trays 53.3 cm in length, 25.4 cm in width and 6.4 cm in height were used. About 0.007 m^3 of potting mix (McDonalds Natural and Organic Potting Mix, Virginia Beach, Virginia) was placed in each tray. The potting mix had N: P_2O_5: K_2O ratio of 0.02 N:0.01 P_2O_5:0.02 K_2O. The K_2O level for each mulch was almost equal, so none was applied. No nitrogen or phosphate was added to MSM and MSM+PPM containers as nitrogen and phosphate were already high in these mulches. In MSM trays, N content in the mulch was 178 kg ha^{-1} and P_2O_5 was 67 kg ha^{-1} and in MSM+PPM trays, N was 178 kg ha^{-1} and P_2O_5 was 135 kg ha^{-1}. Phosphate was not added to the PPM only containers as P_2O_5 was 67 kg ha^{-1}. Nitrogen (34 N-0

P_2O_5-0 K_2O) was applied to all other trays at 67 kg ha^{-1}, and phosphate (0 N-44 P_2O_5-0 K_2O) at 34 kg ha^{-1}. The study on trays was set up on 11 November, 2016. The trays were kept outside the quonset initially but soon after due to cooler air temperatures, were moved to a quonset around 21 November. The seeds of the four species were planted at approximately at 1.3 cm depth in their respective rows, and mulch was put on top (approximately 1.0 cm depth). The trays were hand watered when required. Germinating weed seeds were counted and removed from the tray three times, 20 December, 2016, 12 January, 2017, and 25 January, 2017.

Data were analyzed using SAS v 9.4 (SAS Institute Inc, Cary, NC, USA) and were subject to analysis of variance (ANOVA). Dependent factors were percentage of all weed species and individual weed species that germinated, and the independent factor was the treatment. Prior to running the ANOVA, data were checked for normality of residuals for the dependent factor. Mean separation using LSD was done at alpha 0.1, using proc means.

There were statistical differences in treatments with a maximum number of seeds germinating in PPM (Table 1). This is contrary to the assumption that mulches are supposed to reduce weed emergence (Teasdale and Mohler, 2000). In our study, the mulches did not completely cover the surface (about 80% coverage was obtained with the paper mulches), which may have led to the emergence of weeds. The rates of mulches were chosen keeping the fact in mind the affordability of the product. The PPM with fertilizer and the ability to release water back to the media surface may have helped the weed seed by providing a favorable condition for germination. This was also seen in the field experiments (the SS study and the PPM and MSM study) where PPM alone did not provide sufficient weed control. Individual weed species such as common chickweed showed significant differences among treatments ($P=0.002$), with maximum seeds germinating in PPM+MSM and PPM trays. Common chickweed is favored by a wet environment (Wilen, 2006). Paper mulch also conserve moisture. The PPM with fertilizer may have favored common chickweed to germinate by providing a moist environment (Table 1). For white clover, there was a significant difference in treatments (P=0.03) and the least percentage of seeds germinated in PPM+MSM. The reduced percentage of germination of white clover in paper pellet and mustard seed meal trays could be partially due to the allelopathic property of the mustard seed meal. There were no significant differences among treatments in germination of either Persian speedwell (P=0.1) or hairy bittercress (P=0.3). The germination percentage of common chickweed was more (46.6%) than the initial germination test where only 26% had germinated. As it is a winter annual, perhaps the cooler temperature in December and January favored its germination. The germination percentage of white clover and hairy bittercress in the trays with mulches was similar to the initial germination study done in containers. However, Persian speedwell germination percentage in the final test was less than in the initial germination test. The germination test was carried out in mid-October when the temperature was warmer than in December and January when the counting was done for the actual test. The broadleaf winter annual weeds germinate in winter and though may grow during a warm period in winter, resume growth in spring (Peacock, 2017).

The treatments at the rate used did not control the weed species chosen for the study with maximum weed seed germination seen in the paper pellet trays Possibly due to the hygroscopic nature of paper, the paper pellets did not provide a dry environment and the gaps in between the paper pellets and disintegration with the progress of season may have favored weed seed germination. This is in agreement with our field work where paper pellet mulch alone was not sufficient to control weeds.

Table A.1 Germination test carried out prior to evaluating the effect of mulches on weed seed germination at Hampton Road AREC, Virginia Beach, in 2016.

Name of species	No. of seeds tested/rep	% Germinated	No of seeds used in the tray to get 30 plants
White Clover	30	81	37
Hairy bittercress	30	71	42
Common chickweed	30	26	115
Speedwell	30	86	35

Table A.2 Percent germination of individual weed species and total weeds germinated per tray in a two-month trial at Hampton Road AREC, Virginia Beach, Virginia in the 2016-17 season.

Treatment[ab]	Rate (kg ha^{-1})	Chickweed	Clover	Hairy bittercress	Speedwell	Average across the four species
MSM	2242	54.8 bc	86.5 a	54.8	43.6	58.2 b
Lesco	6103	45.5 c	93.3 a	64.3	62.9	59.3 b
PPM	6103	62.6 ab	93.3 a	72.0	67.2	70.0 a
PPM + MSM	6103+2242	71.3 a	68.9 b	46.4	46.4	62.6 b
Control (black plastic)		46.6 c	89.9 a	70.2	47.1	58.0 b
% emergence in germination study		26.0	81.0	71.0	86.0	
$P \leq 0.1$		0.002	0.03	0.3	0.1	0.06

[a]Mean separation was done using LSD at alpha = 0.1, Means within a column with the same letter are not significantly different from one another.

[b]MSM (Mustard seed meal, 6 N:2 P_2O_5:0 K_2O), Lesco (paper pellet mulch without fertilizer), PPM (paper pellet mulch with fertilizer (0.7 N:1 P_2O_5:0.4 K_2O), PPM + MSM (paper pellet mulch and mustard seed meal).

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Appendix B

Container Study

The objective of this study was to see if the different rates of paper pellet mulch and their combination with mustard seed meal had any phytotoxic effect on plant growth using garden pansy (*Viola tricolor*) as the model crop.

The study was initiated on 10 October, 2017in a completely randomized design (CRD), with eight treatments replicated five times. The treatments were mustard seed meal (MSM, MPT Mustard Products & Technologies Inc., Saskatoon, Canada) at 2242 kg ha^{-1}, three paper pellet mulch (PPM, Lebanon Seaboard Corporation, Pennsylvania, USA) rates applied at 4882 kg ha^{-1}, 6103 kg ha^{-1}, and 7324 kg ha^{-1} with and without MSM at 2282 kg ha^{-1}, and a black plastic control.

Identical nursery containers 19 cm diameter and 17.8 cm in height (Nursery Supplies Inc., Orange, California) were used for the study. The rates of N, P_2O_5, and K_2O were approximately the same in all containers after adjustments (4.5g N: 2.7g P_2O_5: 3.5g K_2O). The mustard seed meal treatment provided 5 N:1 P_2O_5:1 K_2O, and PPM treatment provided 0.7 N: 1 P_2O_5: 0.4 K_2O and thus fertilizer dosage was adjusted according to each treatment of the study. The fertilizer used for the study was Osmocote Plus 15 N:9 P_2O_5:12 K_2O (The Scotts's Company, Marysville, Ohio, USA). On 10 October, containers were filled with pine bark, the fertilizer and MSM were incorporated in the pots and the pots were hand watered. The pansies were planted two weeks later, a precautionary measure to prevent any phytotoxic effect on plants due to glucosinolates from the MSM pellets. Approximately two weeks after incorporating the fertilizer and MSM, on 27 October, 2017, the pansies (Majestic Giant II, Paramount Greenhouse and Nursery Inc, Norfolk, Virginia, USA) were planted in the containers and paper pellets were spread on the surface of the containers. The temperature dropped to 3.9º C on 10 November, 2017, and so the containers were relocated inside the high tunnel. Around 12 December, 2017 botrytis was detected on the flowers, so flowers were removed from the plants, the pots which were close to one another were spaced out (0.3 m between pots) for ventilation and sprayed with a fungicide. The same day all plants were treated with 1 3/8 pint Daconil Weatherstik (chlorothalanil) fungicide per 100 gallons of water. On 22 January, 2017, the plant canopy was noted, the shoots of plants were cut at the base, and weighed on a digital weighing scale (Model CS 2000, Ohaus Corporation, Pine Brook, New Jersey, USA). The roots were taken out of pots, shaken to remove the bark, dipped in water, kept on a towel to remove excess water and then weighed. The roots and shoots were kept in separate paper bags and kept for air drying. After air drying for 10 days, the shoots and roots were kept in a drying oven at 58° C for five days until no further loss in biomass occurred. The dry biomass was noted on weighing scale.

Data was analyzed using one-way analysis of variance (ANOVA). Proc Glm was used in SAS v 9.4 (SAS Institute Inc, Cary, North Carolina, USA) for the analysis of the canopy, fresh shoot weight, fresh root weight, dry shoot weight, dry root weight. No significant difference was found in any parameter among the treatments. Phytotoxic effect on the plant was not observed at the use of different rates of paper mulch and combination of paper mulch and mustard seed meal.

Table B.1 Average of 5 readings of canopy, fresh shoot weight, fresh root weight, dry shoot weight, dry root weight of pansies

Treatment	Rate	Canopy	Fresh shoot weight	Fresh root weight	Dry shoot weight	Dry root weight
	kg ha $^{-1}$	-cm--	-------------------------gm------------------------			
Paper pellet mulch	4882	24.4	2.5	0.8	1.1	0.6
Paper pellet mulch	6103	23.9	2.8	0.8	1.1	0.6
Paper pellet mulch	7324	22.9	2.2	0.6	1.1	0.5
Paper pellet mulch + Mustard seed meal	4882+2282	23.6	2.2	0.6	1.1	0.5
Paper pellet mulch + Mustard seed meal	6103+2282	23.4	2.5	0.7	1.1	0.5
Paper pellet mulch + Mustard seed meal	7324+2282	25.0	3.0	1.0	1.1	0.6
Mustard seed meal	2282	25.9	2.6	0.8	1.2	0.6
Untreated		22.6	2.3	0.8	1.1	0.5
Pr>F Treatment		0.6	0.3	0.5	0.8	0.3

Appendix C

Table C.1 Approximate amount of N, P_2O_5, K_2O added per plot from product, fertilizer 10 N: 0 P_2O_5: 20 K_2O and 0 N: 0 P_2O_5: 60 K_2O in the soil solarization study in 2014-15.

Treatment	N (kg ha^{-1})			P_2O_5 (kg ha^{-1})			K_2O (kg ha^{-1})		
	Product	Fertilizer	Total	Product	Fertilizer	Total	Product	Fertilizer	Total
CGM	171	0	171	0	0	0	0	123	123
MSM	56.1	5.5	61.6	11.2	0	11.2	11.2	112.1	123.3
MSM+CGM	227.2	0	227.2	11.2	0	11.2	11.2	112.1	123.3
MSM+SS	56.1	5.5	61.6	11.2	0	11.2	11.2	112.1	123.3
PPM	25.9	35.8	61.7	366.2	0	366.2	14.6	108.7	123.3
PPM+SS	25.9	35.8	61.7	366.2	0	366.2	14.6	108.7	123.3
SS	0	62	62	0	0	0	0	123	123
Control (black plastic)	0	62	62	0	0	0	0	123	123

Treatments were CGM: corn gluten meal, MSM: Mustard seed meal, MSM+CGM: Mustard seed meal and corn gluten meal, MSM+SS: Mustard seed meal and soil solarization, PPM: Paper pellet mulch, PPM+SS: Paper pellet mulch and soil solarization, SS: Soil solarization, Control (black plastic).