Retention of the Soil Fumigant Dimethyl Disulfide by Virtually and Totally Impermeable Film Mulches

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Abstract. Alternative soil fumigants are needed to replace methyl bromide (MBr). One possible MBr alternative is dimethyl disulfide (DMDS). Highly impermeable plastic films such as virtually impermeable film (VIF) and totally impermeable film (TIF) can be used to increase fumigant retention. Possible advantages of increased fumigant retention are decreased fumigant use rates, decreased buffer zone requirements, reduced fumigant emissions, and improved pest control. Reduced fumigant emission may be especially important with DMDS because it has a sulfur odor, which is easily perceivable by the human nose. One potential drawback of decreasing film permeability may be longer plant back intervals, especially during periods with cool wet soils. The objective of these experiments was to evaluate the effect of TIF on DMDS retention at various rates compared with VIF. Experiments were conducted at the Virginia Tech Eastern Shore Agricultural Research and Extension Center (ESAREC) in Painter, VA, using high (561 L·ha⁻¹), standard (468 L·ha⁻¹), and reduced application rates (374, 281, and 187 L·ha⁻¹) of DMDS in combination with TIF and VIF during spring and fall seasons. Soil temperature and fumigant concentration within the soil were recorded. A stepwise decrease in fumigant retention was seen as fumigant rates were reduced under TIF. Retention periods were impacted by soil temperature. High temperatures decreased the retention period and low temperatures increased the retention period. Standard fumigant rates (468 L·ha⁻¹) under VIF resulted in similar fumigant concentrations in the soil as 281 L·ha⁻¹ under TIF. Similar fumigant concentrations and possibly similar planting interval can be achieved by reducing fumigant use rates ≈40% to 50% under TIF compared with VIF.

The use of MBr has been instrumental for the management of soilborne pests in many vegetable crops that use the plasticiculture production system. Vegetable producers rely on soil fumigants to maintain successful production. However, MBr was found to deplete stratospheric ozone and has been incrementally phased out under the Montreal Protocol on Substances that Deplete the Ozone Layer (United Nations Environment Programme, 2006). The use of MBr in field production still continues for several crops through critical use exemptions. Critical use of MBr has been approved by the U.S. Environmental Protection Agency (USEPA) for pre-plant use in cucurbits, eggplant, peppers, strawberry, and tomatoes (USEPA, 2012). Critical uses approved decrease annually and implementation of alternatives is necessary to maintain productivity of these industries.

DMDS fumigant has recently been registered by the USEPA and is marketed under the trade name Paladin. It is predicted to have a half-life of approximately several hours and is considered to have no ozone-depleting potential (Robinson et al., 2006). DMDS is produced by living organisms in wetlands and oceans as well as members of the plant families Aliiaceae and Brassicaceae (McKown, 2010). It is a natural compound that plays a role in the global sulfur cycle. DMDS is registered for pre-plant use in tomato, pepper, eggplant, cucurbit crops, and strawberries grown in plasticulture for the control of nematodes, weeds, and soilborne plant pathogens.

Many experiments have demonstrated the efficacy of DMDS to control a number of soilborne pests in various crops. DMDS has been proven to manage weeds (Garcia-Mendez et al., 2008) including yellow nutsedge (Cyperus esculentus L.) (Olson and Rich, 2007), purple nutsedge (Cyperus rotundus L.), and crabgrass (Digitaria sanguinalis L.) (Culpepper et al., 2008), and annual grasses and Amaranthus spp. (Othman et al., 2010). DMDS plus chloropicrin (DMDS:Pic) provided control of pathogens such as Phytophthora spp. (Othman et al., 2010) and nematodes (Lopez-Aranda et al., 2009). However, pure DMDS did not prove effective in controlling fungal populations (De Cal et al., 2004). Similar yields have been obtained using DMDS in cantaloupe, tomato, and strawberry (Garcia-Mendez et al., 2008; Olson and Rich, 2007; Othman et al., 2010) as MBr.

Plasticiculture is defined as “a system of growing vegetable crops where significant benefit is derived from using products derived from polyethylene (plastic) polymers” (Lamont, 2005). Typical plasticulture fresh market vegetable production uses raised beds covered with plastic mulch, drip irrigation, and pre-plant soil fumigation under the plastic mulch. Plastic mulch is typically made from either low- or high-density polyethylene (LDPE and HDPE, respectively), which are 0.01 to 0.03 mm thick and 122 to 152 cm wide.

Less permeable plastic mulches may retain fumigants for an extended period longer at a greater concentration. Beneficial of mulches with increased fumigant retention are a reduction in the amount of fumigant needed for effective pest control, lower emissions, and a decreased buffer zone requirement. Films manufactured by coextrusion containing multilayers with barrier polymers such as ethyl vinyl alcohol (EVOH) or polyamide (nylon) are significantly less permeable to fumigants (Gamliel et al., 1998; Ou et al., 2007; Santos et al., 2007; Wang et al., 1998; Yates et al., 2002) than LDPE and HDPE. These less permeable films were all classified as VIF in the literature regardless of the type of barrier material or permeability rate (Austerweil et al., 2006; Minuto et al., 1999; Ou et al., 2007; Wang et al., 1998; Yates et al., 2002). Films containing an EVOH barrier layer have subsequently been referred to as TIF (Chow, 2009; Qin et al., 2011). Qin et al. (2011) demonstrated that TIF mulch could retain 1,3-dichloropropene and Pic at higher concentrations and improve uniformity of fumigant distribution in the soil compared with polyethylene film. Fenimore and Ajwa (2011) also reported that 1,3-dichloropropene and Pic concentrations were 46% to 54% greater under TIF compared with HDPE film and that 33% less fumigant was needed to maintain strawberry yields and weed control. McAvoy and Freeman (2013) evaluated iodomethane combined with Pic in combination with TIF and reported that rates could be reduced by 60% while maintaining tomato yields and nutsedge control.

As a result of the lowered fumigant emissions provided by TIF, the USEPA has amended the re-registration eligibility decisions to approve a 60% buffer zone reduction credit for MBr:Pic when applied under certain types of TIF (USEPA, 2009).

A potential drawback of TIF is the planting interval, the period of time between fumigant application and planting, necessary for crop safety, which may need to be increased. Lengthy planting intervals may hinder adoption of TIF during certain seasons when environmental conditions are not ideal for soil fumigant dissipation such as early spring or late fall. The goal of these studies was to determine how TIF affected DMDS concentration in the soil and how various use rates may affect planting interval.

Materials and Methods

DMDS fumigant retention experiments were conducted at the Virginia Tech ESAREC in Painter, Accomack County, VA, during the fall of 2009, spring and fall of 2010, and spring and fall of 2011. Soil type at ESAREC is...
a Bojac sandy loam (Thermic Typic Hapludults) with 59% sand, 30% silt, and 11% clay with pH ranging from 6.2 to 6.5 and organic matter content of 0.50% to 0.75%. Soil was cultivated to a depth of 30 cm before fumigation. If necessary, overhead sprinkler irrigation was used to bring soil moisture capacity to between 50% and 75% field capacity. Soil moisture content of at least 75% field capacity is a mandatory good agricultural practice for DMDS application (Anonymous, 2012). A 79:21% w/w formulation of DMDS:Pic (United Phosphorus Inc., King of Prussia, PA) fumigant was shank-applied using a single-row combination bed press 76 cm wide and 20 cm high with three back-swept shanks spaced 19 cm apart. Shanks were 20 cm long and fumigant was released at the bottom of the shank, 20 cm below the raised bed surface. Experimental plots were 24 m long with a between-row spacing of 1.8 m. Fumigant was applied on 12 July 2009, 8 Apr. 2010, 14 June 2010, 2 May 2011, and 14 June 2011. Soil temperature at 20 cm before fumigant application was 24 °C in the fall of 2009, 13 °C in the spring of 2010, 23 °C in the fall of 2010, 21 °C in the spring of 2011, and 24 °C in the fall of 2011.

Two mulches were used to compare DMDS retention. During all experiments, either a black (spring) or white-on-black (fall) formulation of Blockade® VIF (Berry Plastics Corp., Evansville, IN) embossed polyethylene mulch with a thickness of 0.03 mm containing a nylon barrier was used. The TIF mulch used was a black (spring) or white-on-black (fall) Vaporsafe™ (Raven Industries Inc., Sioux Falls, SD) polyethylene mulch with 0.05-mm thickness containing an EVOH barrier. A white-on-black formulation was not available during the fall of 2009, so the mulch was painted white the day after application with white latex paint (Ace Hardware Corp., Oak Brook, IL). A 25% solution of paint was sprayed onto the beds at a rate of 40 gallons per acre. Comparative temperature readings were taken between the painted mulch and factory white VIF mulch and found to be statistically similar (data not presented).

The labeled rate for DMDS under VIF film in tomatoes to control nutsedge is 479 L·ha⁻¹ (Anonymous, 2012). DMDS:Pic is commonly used at 468 and 561 L·ha⁻¹ for many vegetable crops. The Fall 2009 experiment included a standard rate of DMDS:Pic [468 L·ha⁻¹ (535 kg·ha⁻¹) broadcast] under VIF and TIF, a high rate [561 L·ha⁻¹ (642 kg·ha⁻¹) broadcast] under VIF, and two reduced rates [281 L·ha⁻¹ (321 kg·ha⁻¹) and 374 L·ha⁻¹ (428 kg·ha⁻¹) broadcast] under TIF. The experiment was repeated in the spring and fall of 2010 and 2011 with the addition of a 187-L·ha⁻¹ (214 kg·ha⁻¹) broadcast rate under TIF. Experimental plots were arranged as a randomized complete block design with four replications.

Data Collection

Fumigant persistence data were measured using a MiniRAE 3000 volatile organic compound (VOC) meter with a 9.8-eV lamp (RAE Systems, San Jose, CA). This lamp can be used to detect DMDS but has no response to Pic. The maximum readable concentration for the MiniRAE 3000 is 15,000 µg·cm⁻³ isobutylene equivalent (3,000 µg·cm⁻³ DMDS). A particle filter was attached to the end of the VOC meter probe to prevent soil particles and moisture from entering the meter. Periodic samples were taken to determine when fumigant concentrations began decreasing below the maximum readable concentration and then sequential sampling was initiated. VOC readings were taken every other day after the fumigants started to dissipate until planting. VOC sampling was performed during the afternoon on sampling dates. Samples were taken equidistant from the bed center and the bed edge. A 1.3-cm diameter round wooden dowel was inserted vertically to a depth of 10 cm. The dowel was removed and the probe was immediately inserted into the headspace. A seal was formed between the mulch and particle filter and readings continued until values stabilized or decreased and maximum values were recorded. Three subsamples were taken from each plot and averaged. Sampling holes were covered with polyethylene tarpon tape (BAC Industries Inc., Minneapolis, MN) after measurement to prevent vapor escape. Subsequent samples were taken from separate sampling holes. Soil temperatures under the plastic were measured using two S-TMBM002 12-bit Temperature/RH Smart Sensors (Onset Computer Corp., Bourne, MA). These sensors were attached to a HOBO micro station data logger (Onset Computer Corp., Bourne, MA), which recorded and stored the data. Temperatures were measured within the fumigated zone at depths of 5 cm and 20 cm. The data logger took measurements every 30 s and averaged them every 2 min. Temperatures at both depths are reported for 0800 HR and 1500 HR. These represent the daily maximum and minimum temperatures.

Data Analysis

The retention data were transformed using a log transformation. Statistical differences between treatment means were determined by analysis of variance by day after fumigation (DAF). Significant differences between treatment means were separated using least significant difference at P = 0.05. Data are presented in original units.

Results

Fall 2009. Soil temperatures ranged between 21 and 40 °C during the period from fumigation until planting. Average maximum soil temperatures were 35 °C at 5 cm and 30 °C at 20 cm (Table 1). Minimum temperatures were 25 °C at 5 cm and 27 °C at 20 cm. During this experiment, the 468-L·ha⁻¹ rate under VIF was not sampled. In subsequent experiments, it was sampled in addition to the 561-L·ha⁻¹ rate and DMDS retention was found to be statistically similar (Tables 3 through 7). The labeled planting interval for Paladin™ at the recorded average low soil temperatures at 20 cm under specified VIF films was 21 DAF (Table 2).

Initially, the TIF mulch retained fumigants at a higher level than the VIF mulch regardless of rate (Table 3). From initiation of sampling until 29 d after fumigation, there were significant differences in fumigant concentration between treatments. In general, the 468-L·ha⁻¹ rate under TIF was retained at a higher level than the 374-L·ha⁻¹ rate under TIF followed by the 281-L·ha⁻¹ rate under TIF and the 561-L·ha⁻¹ rate under VIF. In this experiment, a reduced rate (281 L·ha⁻¹) under TIF maintained greater fumigant levels than a high rate (561 L·ha⁻¹) under VIF for 22 d. Four weeks after fumigation application, there were differences in fumigant retention level between treatments; however, they were negligible at such low concentrations. The VIF treatment (561 L·ha⁻¹) contained very low levels of fumigant (5 µg·cm⁻³ DMDS) at the labeled planting interval and could be safely planted. The treatments under TIF contained higher fumigant levels (39 to 3000 µg·cm⁻³ DMDS) at 21 DAF. Fumigant levels under TIF did not drop below 25 µg·cm⁻³ DMDS until 22 DAF for the 281-L·ha⁻¹ rate and 28 DAF for the 374- and 468-L·ha⁻¹ rates.

Spring 2010. Soil temperatures ranged between 9 and 39 °C during the period from fumigant application until planting. The average maximum soil temperature was 32 °C at 5 cm and 23 °C at 20 cm (Table 1). The average minimum temperatures were 16 °C at 5 cm and 19 °C at 20 cm. An error was made during application of the 374-L·ha⁻¹ rate under TIF; therefore, it was not included in the analysis. There were significant differences in retention levels between treatments (Table 4). The 468- and 281-L·ha⁻¹ rates under TIF resulted in the greatest fumigant vapor concentrations within the bed, which were significantly greater than all other treatments through nearly all sampling dates. The 187-L·ha⁻¹ rate under TIF resulted in the lowest fumigant concentrations; however, the concentration was often similar to the 468- and 561-L·ha⁻¹ rates under VIF. Fumigant rates can be reduced to 281 L·ha⁻¹ under TIF while maintaining greater fumigant levels in the bed.
Table 2. Dimethyl sulfoxide (DMDS) concentrations (µg·cm⁻³) under virtually impermeable film (VIF) and totally impermeable film (TIF) mulch at labeled planting intervals in shank-applied DMDS experiments performed in Painter, VA, during 2009–11.¹

| Season  | Treatment  | Labeled planting interval (DAF) | DMDS concn (µg·cm⁻³) at plant back | DAF required to reach DMDS concn below 25 µg·cm⁻³ |
|---------|------------|---------------------------------|------------------------------------|-----------------------------------------------|
| Fall 2009 | 281-L ha⁻¹ TIF | 21 | 39 | 22 |
| 374-L ha⁻¹ TIF | 21 | 1629 | 28 |
| 468-L ha⁻¹ TIF | 21 | 3000 | 28 |
| 561-L ha⁻¹ VIF | 21 | 5 | 16 |
| Spring 2010 | 187-L ha⁻¹ TIF | 28 | 11 | 24 |
| 281-L ha⁻¹ TIF | 28 | 128 | 30 |
| 468-L ha⁻¹ TIF | 28 | 111 | 34 |
| 468-L ha⁻¹ VIF | 28 | 25 | 28 |
| 561-L ha⁻¹ VIF | 28 | 18 | 28 |
| Fall 2010 | 187-L ha⁻¹ TIF | 21 | 2 | 14 |
| 281-L ha⁻¹ TIF | 21 | 126 | 24 |
| 374-L ha⁻¹ TIF | 21 | 152 | 26 |
| 468-L ha⁻¹ TIF | 21 | 708 | 28 |
| 468-L ha⁻¹ VIF | 21 | 25 | 21 |
| 561-L ha⁻¹ VIF | 21 | 33 | 24 |
| Spring 2011 | 187-L ha⁻¹ TIF | 21 | 1 | 21 |
| 281-L ha⁻¹ TIF | 21 | 126 | 25 |
| 374-L ha⁻¹ TIF | 21 | 516 | 28 |
| 468-L ha⁻¹ TIF | 21 | 1674 | 37 |
| 468-L ha⁻¹ VIF | 21 | 58 | 23 |
| 561-L ha⁻¹ VIF | 21 | 73 | 23 |
| Fall 2011 | 187-L ha⁻¹ TIF | 21 | 683 | 29 |
| 281-L ha⁻¹ TIF | 21 | 1501 | 34 |
| 374-L ha⁻¹ TIF | 21 | 1755 | 31 |
| 468-L ha⁻¹ TIF | 21 | 2675 | 36 |
| 468-L ha⁻¹ VIF | 21 | 30 | 24 |
| 561-L ha⁻¹ VIF | 21 | 87 | 24 |

¹Labeled planting intervals are expressed as days after fumigation (DAF). Planting intervals are based on average minimum soil temperatures at 20 cm when used with approved labeled VIF and metalized mulches. DMDS is not currently labeled for use with Vaporsafe™ TIF. DAF values for DMDS concentrations below 25 µg·cm⁻³ are indicated.

Table 3. Concentration (µg·cm⁻³) of shank-applied dimethyl sulfoxide under virtually impermeable film (VIF) and totally impermeable film (TIF) mulches.⁷

| Days after fumigation | 13 | 15 | 17 | 19 | 21 | 23 | 25 | 27 | 29 |
|-----------------------|----|----|----|----|----|----|----|----|----|
| 281-L ha⁻¹ TIF | 2495 a¹ | 2631 a | 3000 a | 1878 b | 409 b | 760 b | 4 b | 2 b | 0 b |
| 374 L ha⁻¹ TIF | 3000 a | 3000 a | 3000 a | 1603 ab | 2125 a | 1592 a | 761 a | 9 ab | 3 a |
| 468 L ha⁻¹ TIF | 3000 a | 3000 a | 3000 a | 2633 a | 2267 a | 855 a | 557 a | 8 a |
| 561 L ha⁻¹ VIF | 397 b | 35 b | 12 b | 6 c | 5 c | 3 c | 3 b | 3 b | 1 b |

²Experiments were performed during Fall 2009 at the Virginia Tech Eastern Shore Agricultural Research and Extension Center in Painter, VA.
³Means followed by the same letter are not significantly different at α ≤ 0.05 by least significant difference. Means are compared within the same day.

Table 4. Concentration (µg·cm⁻³) of shank-applied dimethyl sulfoxide under virtually impermeable film (VIF) and totally impermeable film (TIF) mulches.⁷

| Days after fumigation | 22 | 24 | 26 | 28 | 30 | 32 | 34 |
|-----------------------|----|----|----|----|----|----|----|
| 187 L ha⁻¹ TIF | 36 c⁷ | 18 c | 9 b | 11 b | 2 b | 0 c | 0 c |
| 281 L ha⁻¹ TIF | 846 a | 426 a | 299 a | 128 a | 25 a | 24 a | 5 ab |
| 468 L ha⁻¹ TIF | 1241 a | 285 a | 451 a | 111 a | 22 a | 32 a | 18 a |
| 468 L ha⁻¹ VIF | 130 bc | 73 b | 29 b | 24 b | 6 b | 5 b | 2 bc |
| 561 L ha⁻¹ VIF | 232 b | 72 b | 36 b | 18 b | 7 ab | 8 b | 2 bc |

⁷Experiments were performed during Spring 2010 at the Virginia Tech Eastern Shore Agricultural Research and Extension Center in Painter, VA.
⁸Means followed by the same letter are not significantly different at α ≤ 0.05 by least significant difference. Means are compared within the same day.

Fall 2010. Soil temperatures ranged from 19 to 41 °C during the period from fumigation until planting. The average minimum soil temperature was 25 °C at 5 cm and 27 °C at 20 cm (Table 1). Average maximum soil temperatures were 37 °C at 5 cm and 32 °C at 20 cm. DMDS retention under TIF showed a classical rate response (Table 5). The standard application rate (468 L ha⁻¹) under TIF resulted in statistically greater fumigant concentrations compared with other treatments for most of the sampling period. Retention under VIF was similar for 468- and 561-L ha⁻¹ rates. The retention of DMDS under VIF at both rates (468 and 561 L ha⁻¹) was generally similar to the lower fumigant rates (187 and 281 L ha⁻¹) under TIF while significantly lower than the 374 L ha⁻¹ rate under TIF. At the labeled planting interval for VIF films (21 DAF), the fumigant levels under VIF treatments were 25 to 33 µg·cm⁻³ DMDS; however, the DMDS concentration under TIF at the lowest application rate was very low (2 µg·cm⁻³ DMDS) (Table 2). Fumigant concentrations were below 25 µg·cm⁻³ DMDS at 24 DAF for the 281-L ha⁻¹ rate under TIF, 26 DAF for the 374-L ha⁻¹ rate under TIF, 28 DAF for the 468-L ha⁻¹ rate under TIF and 24 DAF for the 561-L ha⁻¹ rate under VIF.

Spring 2011. Soil temperatures ranged from 13 to 49 °C during the period after fumigation until fumigant planting. The average minimum temperatures under TIF mulch at a depth of 5 cm were 21 °C and at a depth of 20 cm, it was 22 °C (Table 1). Average maximum soil temperatures were 36 °C at 5 cm and 26 °C at 20 cm. The standard DMDS application rate of 468 L ha⁻¹ under VIF mulch was retained at similar levels as the higher rate of 561 L ha⁻¹ under VIF and 281 L ha⁻¹ under TIF (Table 6). The standard rate (468 L ha⁻¹) under VIF was retained at a higher level than the 187-L ha⁻¹ application rate under TIF until 25 DAF. The reduced rate of 374 L ha⁻¹ under TIF was retained at a higher level than the standard rate (468 L ha⁻¹) under VIF until 23 DAF. The standard rate (468 L ha⁻¹) under TIF was retained at the highest level and had similar retention levels as the 374-L ha⁻¹ rate under TIF. The labeled planting interval under VIF film at the observed mean low soil temperatures at 20 cm was 21 DAF (Table 2). The planting interval is 21 DAF for soil temperatures between 16 and 21.1 °C and 28 DAF for soil temperatures 21.7 °C and higher. The mean low temperature of 22 °C at 20 cm was very close to the threshold for the planting interval. Therefore, DMDS concentrations were higher than normal at the labeled planting interval. Measured DMDS was 1 µg·cm⁻³ under TIF at an application rate of 187 L ha⁻¹ and 58 to 73 µg·cm⁻³ under VIF film at 21 DAF. Fumigant levels were below 25 µg·cm⁻³ DMDS at 23 DAF for 468- and 561-L ha⁻¹ application rates under TIF, 25 DAF for 281-L ha⁻¹ application rate under TIF, 28 DAF for 374-L ha⁻¹ under TIF, and 37 DAF for 468 L ha⁻¹ under TIF.

Fall 2011. Soil temperatures under TIF mulch ranged from 21 to 39 °C during the
fumigant retention measurement period. Average minimum temperature was 25 °C at 5 cm and 26 °C at 20 cm (Table 1). Mean maximum soil temperatures were 33 °C at 5 cm and 28 °C at 20 cm. The standard rate (468 L·ha⁻¹) under VIF was retained at the lowest level until 13 DAF and was retained at a lower level than all the treatments under TIF until 17 d after treatment (Table 7). The treatments under VIF were retained at similar levels regardless of application rate after 15 DAF. The lowest rate (187 L·ha⁻¹) under TIF was retained at similar levels as the highest rate (468 L·ha⁻¹) under TIF until 22 DAF. The labeled planting interval for DMDS under VIF was 21 DAF at the recorded mean low soil temperatures at 20 cm (Table 2). It remains doubtful if tomato could have been planted safely at 21 DAF for any treatment because DMDS levels remained high (30 to 2675 μg·cm⁻³). Heavy rainfall may have accounted for such high retention levels and long planting intervals. According to the Paladin© label, the planting interval for DMDS is lengthened by heavy soils, low soil temperatures, and high soil moisture (Anonymous, 2012). DMDS levels were below 25 μg·cm⁻³ at 24 DAF for both VIF and totally impermeable film (TIF) mulches.

Table 5. Concentration (μg·cm⁻³) of shank-applied dimethyl disulfide under virtually impermeable film (VIF) and totally impermeable film (TIF) mulches.a

| Days after fumigation | 14 | 17 | 19 | 21 | 24 | 26 | 28 |
|-----------------------|----|----|----|----|----|----|----|
| 187 L·ha⁻¹ TIF | 22 c | 8 d | 3 c | 1 c | 0 c | 0 c | 0 c |
| 281 L·ha⁻¹ TIF | 861 b | 331 bc | 132 b | 126 b | 4 bc | 14 bc | 4 bc |
| 374 L·ha⁻¹ TIF | 2366 a | 485 b | 189 b | 151 ab | 56 ab | 7 b | 2 b |
| 468 L·ha⁻¹ TIF | 3000 a | 3000 a | 1074 a | 707 a | 91 a | 73 a | 24 a |
| 468 L·ha⁻¹ VIF | 489 b | 45 c | 30 b | 24 b | 2 bc | 1 bc | 0 c |
| 561 L·ha⁻¹ VIF | 205 b | 69 c | 46 b | 33 b | 4 bc | 2 bc | 0 bc |

aExperiments were performed during Fall 2010 at the Virginia Tech Eastern Shore Agricultural Research and Extension Center in Painter, VA.

Table 6. Concentration (μg·cm⁻³) of shank-applied dimethyl disulfide under virtually impermeable film (VIF) and totally impermeable film (TIF) mulches.a

| Days after fumigation | 14 | 16 | 18 | 21 | 23 | 25 | 28 | 30 | 32 | 35 | 37 |
|-----------------------|----|----|----|----|----|----|----|----|----|----|----|
| 187 L·ha⁻¹ TIF | 1337 b | 110 c | 37 c | 1 c | 0 c | 0 d | 0 c | 0 c | 0 c | 0 c |
| 281 L·ha⁻¹ TIF | 3000 a | 1433 b | 635 b | 125 b | 46 bc | 7 cd | 2 cd | 1 cd | 0 c | 0 c |
| 374 L·ha⁻¹ TIF | 3000 a | 3000 a | 2046 a | 515 a | 672 a | 248 ab | 17 ab | 10 ab | 14 b | 7 b | 5 b |
| 468 L·ha⁻¹ TIF | 3000 a | 3000 a | 1674 a | 1762 a | 1311 a | 798 a | 125 a | 115 a | 31 a | 19 a |
| 468 L·ha⁻¹ VIF | 3000 a | 1139 b | 344 b | 58 b | 18 b | 11 c | 3 bc | 5 bc | 8 b | 3 b | 2 b |
| 561 L·ha⁻¹ VIF | 3000 a | 1366 b | 342 b | 72 b | 25 b | 14 bc | 4 bc | 6 bc | 9 b | 6 b | 3 b |

aExperiments were performed during Spring 2011 at the Virginia Tech Eastern Shore Agricultural Research and Extension Center in Painter, VA.

Table 7. Concentration (μg·cm⁻³) of shank-applied dimethyl disulfide under virtually impermeable film (VIF) and totally impermeable film (TIF) mulches.a

| Days after fumigation | 10 | 13 | 15 | 17 | 20 | 22 | 24 | 27 | 29 | 31 | 34 | 36 |
|-----------------------|----|----|----|----|----|----|----|----|----|----|----|----|
| 187 L·ha⁻¹ TIF | 2620 a | 2561 a | 2089 a | 1587 ab | 1043 ab | 682 bc | 185 bc | 119 b | 2 cd | 2 b | 0 b | 0 b |
| 281 L·ha⁻¹ TIF | 3000 a | 2871 a | 2284 a | 1992 a | 1500 ab | 163 bc | 340 b | 86 b | 37 b | 0 b | 0 b |
| 374 L·ha⁻¹ TIF | 3000 a | 3000 a | 3000 a | 3000 a | 2594 a | 1755 ab | 620 ab | 605 b | 30 bc | 25 b | 1 b | 0 b |
| 468 L·ha⁻¹ TIF | 3000 a | 3000 a | 3000 a | 3000 a | 3000 a | 2675 a | 2186 a | 2327 a | 1944 a | 1615 a | 306 a | 10 a |
| 468 L·ha⁻¹ VIF | 855 b | 315 c | 56 b | 131 b | 61 b | 29 c | 3 c | 0 b | 0 b | 0 b | 0 b | 0 b |
| 561 L·ha⁻¹ VIF | 2551 a | 476 b | 261 b | 377 b | 163 b | 87 c | 16 c | 21 bc | 0 d | 0 b | 0 b | 0 b |

aExperiments were performed during Fall 2011 at the Virginia Tech Eastern Shore Agricultural Research and Extension Center in Painter, VA.

Discussion

These data suggest that it may be possible to decrease application rates by 40% to 50% under TIF compared with VIF while maintaining equal or greater fumigant vapor concentration within the bed for a similar or longer period of time. These results are similar to Fennimore and Ajwa (2011) in which fumigant concentration was increased by 46% to 54% when similar rates were applied under HDPE compared with TIF. Qin et al. (2011) also reported a significant increase in fumigant retention when TIF was used compared with standard film. Data from this study indicated a much greater increase in fumigant concentration between VIF and TIF films. However, Fennimore and Ajwa (2011) and Qin et al. (2011) evaluated different fumigant chemistries with generally less soil persistence. In nearly all cases, the 187-L·ha⁻¹ rate under TIF resulted in a lesser concentration than the standard rate under VIF. This rate may not result in a sufficient fumigant dose to control soilborne pests. The 281-L·ha⁻¹ rate under TIF was retained similarly or at a greater concentration than the 468- and 561-L·ha⁻¹ rates under VIF. The barrier layer in TIF mulch is more retentive to DMDS than the barrier layer in VIF. At an equivalent fumigant rate, TIF always retained DMDS at higher concentrations for a longer period of time. The USEPA has allowed for a 60% buffer zone reduction credit when using TIF films. For example, the buffer zone will be reduced from 41 m under VIF to 16 m under VIF when applied at a rate of 281 L·ha⁻¹ to an 8-ha field.

The retention period was longer when soil temperatures were lower during dry seasons and may not be economically viable. The planting interval post-fumigation has been mandated by the registrant and its duration is based on average low soil temperature at a depth of 20 cm (Anonymous, 2012). Based on the registrant issued label, planting interval would have been 21 d during all fall seasons and in the spring of 2011 and 28 d during the spring of 2010 for VIF film. The level of fumigant vapor in the soil that can be tolerated by vegetable transplants is unclear, but these data indicate that extensions in the planting interval may need to be implemented when applying DMDS under TIF mulch. Under normal rainfall conditions, the DMDS concentration was 25 μg·cm⁻³ or less at the labeled planting interval at the standard rate (468 L·ha⁻¹) under VIF. Although this concentration has not been tested for crop safety, it was used as a benchmark for other treatments because it was commonly found at the labeled planting interval for VIF mulch. This planting interval was determined by the registrant to avoid crop phytotoxicity so it is assumed that the DMDS concentration of 25 μg·cm⁻³ or less is not toxic to vegetable transplants. A possible planting interval for treatments under TIF mulch was suggested based on this concentration. The planting interval may need to be increased by 2 to 7 d for reduced rates (281 and 374 L·ha⁻¹) under TIF to reach similar fumigant concentrations as labeled planting intervals under VIF. DMDS applied at 468 L·ha⁻¹ under TIF may extend the planting interval too much to be a commercially viable option. This rate under TIF may not be needed to gain acceptable control of soilborne pests and may not be economically viable. The fumigant concentrations in this study were not always significantly greater under TIF mulch at the planting interval time but may be biologically significant and may cause phytotoxicity.
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