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Evaluation of Isothiocyanates and Herbicide Programs as Methyl Bromide Alternatives for Weed Control in Polyethylene-Mulched Tomato and Bell Pepper

Pratap Devkota
University of Arkansas, Fayetteville

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EVALUATION OF ISOTHIOCYANATES AND HERBICIDE PROGRAMS AS METHYL BROMIDE ALTERNATIVES FOR WEED CONTROL IN POLYETHYLENE-MULCHED TOMATO AND BELL PEPPER

EVALUATION OF ISOTHIOCYANATES AND HERBICIDE PROGRAMS AS METHYL BROMIDE ALTERNATIVES FOR WEED CONTROL IN POLYETHYLENE-MULCHED TOMATO AND BELL PEPPER

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Crop, Soil, and Environmental Sciences

By

Pratap Devkota
Tribhuvan University
Bachelor of Science in Agriculture, 2008

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University of Arkansas

ABSTRACT

Methyl bromide (MeBr), a Class I ozone-depleting substance, has been banned for ordinary agricultural uses. In the absence of an effective MeBr alternative, weed control is a major challenge for commercial tomato and bell pepper production. Field trials were conducted at Fayetteville, AR, to compare allyl isothiocyanate (ITC), metam sodium, and herbicide programs with the standard MeBr application (mixture of MeBr plus chloropicrin at 67% plus 33%, respectively, hereafter referred to as MeBr) for crop injury, weed control, viable yellow nutsedge tubers, and marketable yield in low-density polyethylene (LDPE) mulched tomato and bell pepper production. In addition, herbicide programs were evaluated for cost of production, gross return, net return, and net return relative to MeBr in LDPE-mulched tomato and bell pepper production. Allyl ITC and metam sodium did not injure tomato. Weed control and yield in tomato plots treated with allyl ITC at 750 kg ha^{-1} or metam sodium at 360 kg ha^{-1} were comparable to plots treated with MeBr at 390 kg ha^{-1}. Likewise, metam sodium at 360 kg ha^{-1} and MeBr-treated bell pepper plots were similar for weed control and yield. Tomato or bell pepper injury was ≥13% in PRE-applied imazosulfuron or *S*-metolachlor plots after POST-applied trifloxysulfuron plus halosulfuron at 0.008 and 0.027 kg ha^{-1}, respectively. Herbicide programs consisting of PRE-applied *S*-metolachlor followed by (fb) POST-applied trifloxysulfuron plus halosulfuron provided comparable weed control to MeBr in LDPE-mulched tomato and bell pepper. Tomato or bell pepper plots treated with the *S*-metolachlor-containing herbicide program yielded total marketable fruits equivalent to the plots treated with MeBr. The *S*-metolachlor herbicide program also provided a net return of 3,758.50 and 9,912.05 dollars ha^{-1} in tomato and bell pepper production, respectively. Moreover, the *S*-metolachlor herbicide program added a net return of $173.34 ha^{-1} relative to net return with MeBr treatment in bell

pepper. In conclusion, metam sodium at 360 kg ha^{-1} or PRE-applied *S*-metolachlor at 1.6 kg ha^{-1} fb POST-applied trifloxysulfuron plus halosulfuron at 0.008 and 0.027 kg ha^{-1} are viable MeBr alternatives for weed control in LDPE-mulched tomato and bell pepper.

This thesis is approved for
recommendation to the
Graduate Council

Thesis Director:

Jason K. Norsworthy, Ph.D.

Thesis Committee:

Nilda R. Burgos, Ph.D.

Richard J. Norman, Ph.D.

Ronald L. Rainey, Ph.D.

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DEDICATION

Dedicated to my family

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INTRODUCTION

Commercial vegetable production covers significant acreage and production value in the United States (U.S.) agriculture system. According to the U.S. Department of Agriculture (USDA), vegetable was harvested from 1.71 million acres with the total production value of $11.2 billion in year 2010. Among 24 vegetable crops, cultivated for fresh-market purpose in the U.S., tomato and bell pepper have considerable importance in commercial vegetable production. Tomato and bell pepper growere have to deal with many constraints for successful and profitable harvest. Among various pests affecting tomato and bell pepper production, weed problem is one of the most serious concerns in commercial production.

Without effective control of problematic weeds, such as Palmer amaranth, large crabgrass, and yellow nutsedge, tomato and bell pepper production results into huge economic loss because of poor quality and less quantity fruit harvest. In advanced vegetable production system using polyethylene-mulch, and drip irrigation and fertigation, weeds emerge from the openings made for transplanting crops and interfere with crop reducing yield. Moreover, weed from sedge family penetrates through the polyethylene mulch and compete with the crop lowering fruit harvest. Furthermore, nutsedge species degrades polyethylene mulch and lowers the durability by penetrating through the mulch, preventing its use for multiple seasons.

For successful vegetable production, timely and effective weed management is a key consideration. In past decades, commercial producers relied on MeBr for weed control; however, MeBr is banned for ordinary agricultural uses (except for critical use exemption) since 2005. With the elimination of MeBr, growers need viable alternatives for weed management in commercial tomato and bell pepper production. At present, allyl and methyl isothiocyanates (ITCs) are being evaluated as possible alternatives to MeBr for weed control in polyethylene mulched tomato and bell pepper production. However, the most effective ITC rate equivalent to MeBr for weed control and yield has not been reported until now. Herbicides are also an important component for weed management in commercial production. Therefore, PRE and POST herbicides were also evaluated in various experiments. Previous experiments with PRE- or POST herbicides applied alone were concluded ineffective as MeBr for weed control and yield in tomato and bell pepper.

Therefore, this research project was set forward in order to address the two primary objectives. First objective was to compare allyl ITC and metam sodium with MeBr for weed control and yield in polyethylene-mulched tomato and bell pepper production. Likewise, second objective was to evaluate the efficacy and profitability of herbicide programs, containing PRE fb POST herbicides, compared to MeBr for weed management in polyethylene-muched tomato and bell pepper production.

CHAPTER 1

COMPARISON OF ALLYL ISOTHIOCYANATE AND METAM SODIUM WITH METHYL BROMIDE FOR WEED CONTROL IN POLYETHYLENE-MULCHED TOMATO AND BELL PEPPER

Abstract

Methyl bromide (MeBr), classified as a Class I ozone-depleting substance, has been banned for ordinary agricultural uses. Because of the ban on MeBr and unavailability of effective soil fumigant alternatives, weed control is a major challenge in commercial tomato and bell pepper production. A field experiment was conducted to evaluate the effectiveness of allyl isothiocyanate (ITC) and metam sodium (methyl ITC generator) as MeBr alternatives for weed control, viable yellow nutsedge tuber density, and marketable yield in low-density polyethylene (LDPE) mulched tomato and bell pepper. Allyl ITC was applied at 450, 600, and 750 kg ha^{-1}; metam sodium was applied at 180, 270, and 360 kg ha^{-1}; and MeBr plus chloropicrin (67% and 33%, respectively) was applied at 390 kg ha^{-1}. Allyl ITC and metam sodium did not injure tomato and bell pepper. Allyl ITC at 750 kg ha^{-1} or metam sodium at 360 kg ha^{-1} controlled Palmer amaranth ≥79%, large crabgrass ≥76%, and yellow nutsedge ≥80% in tomato and bell pepper, with control similar to that of MeBr. The viable yellow nutsedge tuber density was ≤76 tubers m^{-2} in tomato plots treated with the highest rates of allyl ITC and metam sodium. Yellow nutsedge tuber density was ≤84 tubers m^{-2} in the bell pepper plots treated with the highest rate of allyl ITC and metam sodium. Moreover, density of viable yellow nutsedge tubers with allyl ITC at 750 kg ha^{-1} or metam sodium at 360 kg ha^{-1} was comparable to the tuber density with MeBr in tomato or bell pepper. Total marketable tomato yields (≥31.6 ton ha^{-1}) in plots treated with allyl ITC at 750 kg ha^{-1} or metam sodium at 360 kg ha^{-1} were comparable to tomato yield in plots treated with MeBr. Only the yield of bell pepper treated with the highest rate of metam sodium (53.5 ton ha^{-1}) was equivalent to the yield from bell pepper (62.5 ton ha^{-1}) treated with MeBr. In conclusion, metam sodium at 360 kg ha^{-1} is an effective MeBr alternative for LDPE mulched tomato and bell pepper. Although allyl ITC at 750 kg ha^{-1} is an effective alternative to MeBr in

LDPE-mulched tomato, total marketable yield with allyl ITC was lower than the yield from MeBr in LDPE-mulched bell pepper.

Nomenclature: Allyl isothiocyanate; metam sodium; methyl bromide (MeBr); large crabgrass, *Digitaria sanguinalis* (L.) Scop. DIGSA; Palmer amaranth, *Amaranthus palmeri* S. Wats. AMAPA; yellow nutsedge, *Cyperus esculentus* L. CYPES; bell pepper, *Capsicum annuum* L. ‘Heritage’; tomato, *Solanum lycopersicum* L. ‘Amelia’.

Key words: Isothiocyanate, low-density polyethylene mulch, methyl bromide alternatives, soil fumigation.

Introduction and Literature Review

Tomato Cultivation. Tomato is considered the most important vegetable crop in the U.S. and ranks first in terms of economic value as a fresh-market vegetable as well as for processed product production (e.g. juice, ketchup, canned tomato, and tomato paste) (USDA 2011). In 2010, tomato was planted on over 42,290 ha in the U.S. for fresh-market production and on over 116,910 ha for processed products. Similarly, total production was 1.3 and 11.6 million metric tons, with a market value of $1.39 and 0.92 billion for fresh and processing tomato, respectively (USDA 2011). In the U.S., the top producers of fresh-market tomato are Florida, California, Tennessee, and Virginia, with total values of 630, 396, 52, and 51 million dollars, respectively (USDA 2011). However, in the processed product market, California, Indiana, Ohio, and Michigan are the top-producing states, with a total production value of 878, 21, 15, and 11 million dollars, respectively (USDA 2011). In Arkansas, tomato was cultivated on 445 ha as fresh-market tomato, with a total production of 8.5 thousand metric tons and a total economic value of 10.5 million dollars in 2010 (USDA 2011).

Tomato plants are best grown in the late spring to early summer. The best temperature range for optimal production is 21 to 27 C, with an optimal germination of 20 C (Strange et al. 2000). Tomato does not tolerate frost at any stage of development. Generally, seeds are sown into trays in a nursery or greenhouse, and 4- to 6-wk-old seedlings are transplanted into the field (Santos 2007). The seedlings are often hardened (subjected to field conditions) for a week before transplanting to enhance the survival of transplanted seedlings. Seedlings can be transplanted into bare beds or plastic-mulched beds; however, with the advancement in crop production technology, polyethylene mulching has become popular for commercial tomato production. The plastic-mulched technique has been in wide-scale use since the early 1980s.

Moreover, plasticulture helps growers to achieve early harvest, high yield, and superior quality (Sanders et al. 1996). To ensure vigorous plant growth and development, tomato seedlings are usually planted in a single row on the plastic-mulched beds. In addition to bedding, staking is also common among the growers to obtain good quality fruits for fresh-market purposes, whereas staking is not widely practiced for processed production. Tomato fruits are ready for harvest after they reach physiological maturity, which generally takes about 4 weeks after flowering. For fresh-market tomato, fruits are harvested by hand-picking when they are firm and start turning pink and harvesting is done several times in a single growing season. In contrast, tomato for processing is harvested mechanically and usually just once after the fruits are fully ripened (Swaider et al. 1992). After harvest, the fruits are separated into different grades before being sent to commercial markets. The USDA grading scale for fresh-market tomato is: jumbo, extra large, large, medium, and small (USDA 1997).

Bell Pepper Cultivation. Bell pepper is also a popular vegetable commodity for consumption as a fresh or processed product. Bell pepper ranks seventh in terms of value of production among all commercially grown vegetable crops for fresh and processed markets in the U.S. In 2010, bell pepper was grown on about 21,336 ha, with a total production of 713,910 metric tons and a total value of 637 million dollars (USDA 2011). Florida and California were the top bell pepper producers in the U.S. for 2010, with a production value of 295.5 and 227.5 million dollars, respectively (USDA 2011).

Bell pepper has a climatic requirement very similar to tomato. It is a warm-season crop and cannot tolerate freezing temperature at any stage of development. Ideal growth occurs at a temperature range of 23 to 30 C (Hartz et al. 2008). The plasticulture system is also ideal for commercial bell pepper production. Seedlings are grown in the greenhouse using trays or flat beds, and 4- to 6-wk-old seedlings are transplanted into the field (Santos 2007). For better plant survival in the field, seedlings are 'hardened' for 1 wk before transplanting. In intensive bell pepper production systems, transplants are planted in double rows on a raised bed covered with polyethylene mulch. In addition to providing good growing conditions, polyethylene mulch also reduces volatilization loss of soil-applied fumigants and enhances their activity for weed control (Bangarwa et al. 2010). Bell pepper fruits are harvested about 4 to 5 wk after flowering and when fruit develops immature green color or at a mature stage after full color is developed (Hartz et al. 2008; Swaider et al. 1992). For fresh-market production, bell peppers are harvested manually to avoid bruising and cracking due to the brittleness and sensitivity of the fruit, and multiple harvesting is carried out in 10- to 15-d intervals (Hartz et al. 2008). The standard marketable size and grades for fresh marketing are: U.S. Fancy, U.S. No. 1, and U.S. No. 2 (USDA 2005).

Weeds are a major constraint for optimum vegetable yield. Annual, biennial, and perennial weeds are problematic in tomato and bell pepper production. Weeds cause allelopathic effects, environmental and physiological stress, and competition for sunlight, moisture, and nutrients with the crops (Ferguson and Rathinasabapathi 2003). Weeds also interfere with cultural practices (spraying pesticides and harvesting), reduce fruit quality and yield, and cause loss of millions of dollars annually in commercial vegetable production (Swaider et al. 1992). Even in plasticulture vegetable production, weed growth is often enhanced because of drip line irrigation and fertigation, which make weeds more competitive with the crop. If left uncontrolled, severe weed infestations can occur in plasticulture, and yield reduction of at least 50% is commonly observed in vegetable production (Culpepper 2009). Among various weed species occurring in polyethylene-mulched vegetable production Palmer amaranth, large crabgrass, and yellow nutsedge are considered serious weed in the southern U.S.

Palmer amaranth is widely distributed throughout the southern U.S. Palmer amaranth is a summer annual, erect-growing plant, and is among the most troublesome weeds in vegetable production systems. It is a weed from the Amaranthaceae family. Amaranth weeds are highly competitive to vegetable crops and reduce yield significantly. A*maranthus* spp. emerging early in the season reduce 99% of the bell pepper yield at 32 plants m^{-1} (Fu and Ashley 2006). Palmer amaranth grows rapidly, so the slow-growing vegetable crop is not capable of preventing Palmer amaranth growth. Within a few weeks, Palmer amaranth starts shading the crop by rapid vertical and horizontal expansion (Norsworthy et al. 2008). With warm, moist soil and intense sunlight, Palmer amaranth attains a 2-m height within 10 wk after emergence (Norsworthy et al. 2008) and produces 2 and 0.95 kg of biomass $plant^{-1}$ in monoculture and mixed stands, respectively (Garvey 1999). At a base temperature of 10 C, Palmer amaranth grows 0.18 to 0.21 cm per growing degree day (GDD) with suitable moisture, nutrient, and light conditions (Horak and Loughin 2000). Meyers et al. (2010) reported 36 to 81% loss of marketable sweet potato (*Ipomoea batatas* L.) from Palmer amaranth at 0.5 to 6.5 plants m^{-1}. Palmer amaranth residue is also allellopathic and phytotoxic to vegetable crops. Soil-incorporated Palmer amaranth residue suppressed the growth of carrot (*Daucus carota* subsp. *sativus*) and cabbage (*Brassica oleracea* var. *capitata*) by 49 and 68%, respectively, and the phytotoxity of the residue can persist up to 11 weeks after cabbage and carrot planting (Menges 1987).

Large crabgrass is a grassy weed common in most of the bell pepper production areas in the U.S. Among the weeds of vegetable crops, large crabgrass is one of the most important weeds in the U.S. (Bridges and Baumann 1992). It is a summer annual with a prostrate growth habit and grows about 0.3 to 1.2 m tall. After seedling emergence, plant size increases tremendously by tillering. A full-sized plant with enough space for growth can produce an average of 150,000 seeds (Anonymous 2001). In the early stages of growth, large crabgrass can be controlled effectively by cultivation or by application of suitable herbicides (Hartzler and Foy 1983), but it is more difficult to manage after it starts forming tillers and adventitious roots. After large crabgrass is establishment, it interferes season-long and yield loss is prominent. In seeded tomato, season-long presence of large crabgrass at 55 plants m^{-2} reduced tomato yield by 76% compared to large crabgrass free tomato plots (Bhowmik and Reddy 1988). Similarly, Aguyoh and Masuinas (2003) reported 46 to 50% yield reduction in snap bean (*Phaseolus vulgaris* L.) production from season-long interference of large crabgrass and suggested that large crabgrass even at <2 plant m^{-1} can reduce yield significantly. In plastic-mulched bell pepper, large crabgrass attained the same height of 34 cm as bell pepper at 580 GDD (Norsworthy et al. 2008), and season-long interference of large crabgrass caused complete loss of marketable yield (Fu and Ashley 1999).

Yellow nutsedge is a perennial weed with an upright growth habit. Stems are triangular, solid, with gradually pointed three-ranked leaves enclosed in sheaths, and without ligules. Although it produces viable seeds, seedlings emerged from seeds do not usually survive. Therefore, yellow nutsedge plants usually reproduce and distribute by tubers and basal bulbs. Tubers are highly tolerant to drought and freezing conditions (Benedixen and Nandihalli 1987), so it is also a major weed in the north central and north eastern regions of the U.S. Morales-Payan et al. (2003b) reported 34% reduction in aboveground tomato dry weight production with season-long interference of yellow nutsedge. The presence of yellow nutsedge throughout the growing season reduced yield by 50% in tomato production (Stall and Morales-Payan 2003).

Likewise, yellow nutsedge present throughout the growing season reduces yield up to 74% in bell pepper production (Motis et al. 2001). Season-long interference of yellow nutsedge at five or fewer shoots m^{-2} reduces bell pepper yield 10% (Motis et al. 2003). Moreover, when left uncontrolled yellow nutsedge infestation can be more severe later in the growing season because of its rapid spread from viable tubers. Anderson (1999) reported that a single tuber can produce up to 36 plants and about 332 tubers in 16 weeks, and within a year it can form a patch of 6-m diam with 1900 plants and 7000 tubers.

In tomato and bell pepper production, methyl bromide was the most extensively used soil fumigant and was used for weed control from the 1950s until it was banned for use in vegetables in 2005. Of the total MeBr used in the U.S., about 85% was used as a preplant soil fumigant for high-value crop production (Julian et al. 1998). However, in 1993, MeBr was listed as a Class I ozone-depleting substance by the U.S. Environmental Protection Agency (EPA). In January 2005, the Montreal Protocol and the US Clean Air Act mandated a ban on production and use of MeBr, with an exception for some critical uses. With the elimination of MeBr, growers need viable alternatives to manage a wide range of weed species. Therefore, research for MeBr alternatives is a primary focus for weed management in tomato and bell pepper.

Isothiocyanates (ITCs) are soil fumigants, reported to have potential broad-spectrum activities, including herbicidal properties. ITC compounds are effective in controlling different soil organisms such as nematodes (Lear 1956), insects (Borek et al. 1998), and soil pathogens (Smolinska et al. 1997). Peterson et al. (2001) reported that ITCs are very effective in suppressing weed seed germination. Furthermore, control of various annual and perennial weeds, including nutsedge species, by application of ITC compounds has been reported (Bangarwa 2010; Norsworthy and Meehan 2005a; Norsworthy and Meehan 2005b). Norsworthy et al. (2006) reported a significant reduction in shoot density and biomass production of yellow nutsedge and purple nutsedge from ITCs. ITCs are highly volatile compounds, so they are used in combination with LDPE mulch for preventing volatilization losses and for higher use efficiency (Austerwil et al. 2006). There are various types of ITCs, such as: allyl, methyl, propyl, butyl, benzyl, and 2-phenylethyl ITC, being evaluated for insect, pathogen, and weed control.

Allyl ITC has been evaluated for weed control and is reported to have greater potential than propyl, butyl, benzyl, and 2-phenylethyl ITCs for suppressing the germination and growth of barnyardgrass (*Echinocloa crus-galli* L. Beauv.), redroot pigweed (*Amaranthus retroflexus* L.), and garden pea (*Pisum sativum* L.) (Al-Khatib et al. 1997). Allyl ITC is volatile and when properly incorporated into the soil, it spreads uniformly in the soil (Peterson et al. 2001). Inhibition of seed germination of dandelion (*Taraxacum officinale* Weber) from allyl ITC is also reported by Vaughn and Boydston (1997). Norsworthy and Meehan (2005b) estimated the lethal concentration 50% (LC_{50}) of allyl ITC to be 269, 807, and 4260 nmol g^{-1} of soil for reducing the emergence of Palmer amaranth, pitted morningglory (*Ipomoea lacunosa* L.), and yellow nutsedge, respectively. In the same study, allyl ITC at 10,000 nmol g^{-1} of soil reduced yellow nutsedge emergence by 76%. When allyl ITC was compared to MeBr, allyl ITC provided similar weed control (Bangarwa 2010; Bangarwa et al. 2011a) to MeBr in controlling various weeds. Bangarwa (2010) reported effective control of yellow nutsedge, Palmer amaranth, and large crabgrass from allyl ITC. Moreover, marketable tomato and bell pepper yield from plots treated with allyl ITC was comparable to yield in MeBr-treated plots.

Metam sodium degrades rapidly and forms methyl ITC as a primary active agent after soil fumigation (Ajwa et al. 2003). When incorporated properly into the soil, methyl ITC has activity against plant pathogens, weeds, insects, and nematodes (Duniway 2002). Metam sodium is effective when applied alone or mixed with other available fumigants. Ajwa et al. (2002) reported higher strawberry (*Fragaria ananassa* L.) yield in plots with drip-irrigation applied 1,3-dichloropropene (1,3-D) plus 32% chloropicrin (C-32) and metam sodium compared to the non-treated strawberry plots because of effective control of weeds and disease pathogens. Furthermore, metam-sodium applied alone or in combination with 1,3-D plus 17% chloropicrin (C-17) or 1,3-D plus 35% chloropicrin (C-35) controlled weeds, fungi, arthropods, and nematodes, ensuring good plant stand and vigor in tomato transplants (Csinos et al. 2000). Gilreath et al. (2008) also reported metam sodium + C-35 to be similar to MeBr for plant vigor, nematode control, and total marketable yield in strawberry production. Bewik (1989) observed that tomato yield was similar between metam sodium and MeBr. In a MeBr-alternative study involving bell pepper and cucumber (*Cucumis sativus* L.) rotation, marketable bell pepper fruit increased by 38% with the metam sodium application compared with the non-treated check (Gilreath et al. 2004).

Because of the ban on MeBr, growers are left with only a few options in managing troublesome weeds in tomato and bell pepper production. The ban on MeBr accounts for millions of dollar of annual economic losses in commercial tomato and bell pepper production, with weeds causing a significant portion of these losses. At present, there are only a few alternatives to MeBr for weed management in tomato and bell pepper production. Therefore, research on effective weed control alternatives to MeBr is imperative. In previously conducted MeBr-alternative research, allyl ITC and metam sodium (Vapam), in separate trials, provided effective weed control (Bangarwa et al. 2011a; Gilreath et al. 2004). Moreover, these fumigants were reported as potential alternatives to MeBr for weed control in tomato and bell pepper.

However, allyl ITC and metam sodium rates for weed control comparable to MeBr need to be speficied with the follow up research. Therefore, an experiment was conducted with the primary objective of narrowing down and specifying the allyl ITC rate and comparing the effectiveness of allyl ITC with metam sodium and MeBr for weed control in LDPE-mulched tomato and bell pepper.

Material and Methods

An experiment was conducted at the Arkansas Agricultural Research and Extension Center at the University of Arkansas, Fayetteville, AR, during summer 2010 and 2011. In the 2010 experimental field, the soil type was a Razort silt loam (fine-loamy, mixed, active, mesic Mollic Hapludalfs) with pH of 6.3 and organic matter content of 1.8% (USDA Web Soil Survey). In the 2011 experimental site, the soil type was a Captina silt loam (fine-silty, siliceous, active, mesic Typic Fragiudults) with pH of 6.1 and organic matter of 1.8%. For both years, the experimental fields were tilled once in late March and twice in early April to remove any plant residue present on the soil surface. Plant residue reduces the efficiency of soil-applied fumigants by preventing uniform spreading into the soil. At field preparation, Palmer amaranth and large crabgrass seed and yellow nutsedge tubers (Azlin Seed Company, 112 Lilac Drive, Leland, MS, 38756) were broadcasted over the whole field to achieve uniform weed populations throughout the plots.

The experiment was set up as a randomized complete block design with four replications. Treatments consisted of three rates of allyl ITC (95% purity, Sigma-Aldrich Inc., 6000 N. Teutonia, Milwaukee, WI, 53209) and metam sodium (Vapam®HL, 42% purity, AMVAC Chemical Corporation, 4100 E. Washington Blvd, Los Angeles, CA, 90023) applied under

LDPE mulch (black, embossed, 1.0 mil thick, Polygro LLC, Tampa, FL, 33655). Allyl ITC was applied at 450, 600, and 750 kg ha^{-1}, and metam sodium was applied at 180, 270, and 360 kg ha^{-1}. Rates for allyl ITC were chosen to clearly define the effective rate based on a previous study conducted by Bangarwa (2010). For metam sodium, the highest rate was chosen based on previous MeBr-alternative studies, and lower rates were added to evaluate metam sodium effectiveness at lower rates (Gilreath et al. 2005; Johnson and Mullinix 2007). Within 1 d after application greater than 90% of the applied ITC can escape from the soil because of volatilization (Brown and Morra 1995). Therefore, for retention of the applied ITCs in the soil and for the maximum weed control efficiency, use of polyethylene mulch is critical. There are various types of polyethylene mulch commercially available; however, LDPE mulch costs less and it is as effective as virtually impermeable film (VIF) for soil fumigant retention (Bangarwa et al. 2010). Additionally, a non-treated check and a standard treatment of MeBr plus chloropicrin at 261 and 129 kg ha^{-1} (mixture of 67 and 33%, respectively at 390 kg ha^{-1}) were used for comparison.

Allyl ITC and metam sodium were applied as a broadcast spray using a CO_2-pressurized backpack sprayer, and spray was delivered at 280 L ha^{-1}. In order to achieve the higher rates of allyl ITC and metam sodium, treatments were sprayed on a plot by multiple passes (1 pass was equivalent to 150 and 90 kg ha^{-1} for allyl ITC and metam sodium, respectively). Immediately after application, treatments were incorporated into the top 10 cm of soil using a roto-tiller. Immediately after incorporation of treatments into the soil, raised beds were formed and beds were covered with LDPE mulch successively in a single pass. MeBr was injected into the raised bed with two-knives attached to a tractor-mounted MeBr applicator, and beds were covered with LDPE mulch. A single row of drip tape was simultaneously placed underneath the LDPE mulch, at the center of the bed to facilitate irrigation and fertigation. In a raised bed, each plot was separated by cutting the LDPE mulch at the end of the plot and covering the cut ends of the mulch with soil. This prevented mixing of treatments across the plots. The final size of each plot was 4.5 m long and 0.75 m wide at the top of raise-bed for tomato, and 3.6 m long and 0.75 m wide at the top of the raise-bed for bell pepper. After setting the mulch and drip lines, plots were irrigated to activate the applied fumigants.

At 3 wk after fumigant application, seven openings (in a single row, at 0.6 m apart) were punched through the LDPE mulch in each plot for transplanting tomato. Similarly, 20 openings (in a double row with, 10 openings/-row, spaced 0.3 by 0.3 m) were punched in each bell pepper plot. Plots were left for aeration for 3 d before transplanting the seedlings. The aeration of plots allowed the escape of fumigant molecules trapped between the soil surface and LDPE mulch, minimizing crop injury (Bangarwa et al. 2011a). After aeration, four- to six-leaf ‘Amelia’ tomato and ‘Heritage’ bell pepper (Seedway LLC, 1734 Railroad Place, Hall, NY, 11463) seedlings were transplanted. Plots were regularly fertigated, sprayed with insecticides and fungicides to prevent insect and disease damage, and managed with standard practices recommended for plasticulture tomato and bell pepper production (Holmes and Kemble 2010). Weeds between plastic-mulched beds were managed by hooded application of *S*-metolachlor at 2 wk after transplanting (WATP) and paraquat at 4, 6, and 8 WATP.

Visual ratings were recorded for weed control and crop injury at 2, 4, 6, and 8 WATP. Weed control and crop injury ratings were based on a 0 to 100% scale, where 0 = no weed control or no crop injury, and 100 = complete weed control or death of crop. Palmer amaranth and large crabgrass could not penetrate through the LDPE mulch. Therefore, Palmer amaranth and large crabgrass control ratings were based on the plant emergence from the LDPE mulch openings. However, yellow nutsedge penetrated through LDPE mulch. So, the yellow nutsedge control rating was based on the plants that emerged from the LDPE mulch openings as well as plants that penetrated through the LDPE mulch.

Mature marketable tomato and bell pepper fruits were harvested multiple times throughout the season and graded according to market standards for tomato and bell pepper (USDA 1997; USDA 2005). Tomato fruits were graded for jumbo, extra large, large, medium, and small categories and bell pepper fruits were graded for U.S. Fancy, U.S. No. 1, and U.S. No. 2 categories. Fruit weights were recorded according to the grades. First and second harvests from each season were added to determine the early-season yield for tomato and bell pepper. Likewise, the total marketable yield of tomato and bell pepper was calculated by summing fruit weights of different grades from all harvests. At the end-of-season (at 4 months after transplanting), five soil core samples (a sample sized 10 cm in diam and 15 cm in depth) were collected from each tomato and bell pepper plot. Core samples were sieved and washed to determine the number of viable yellow nutsedge tubers. Tubers that were firm and creamy white were classified as viable tubers.

Data were analyzed with PROC GLM using the Statistical Analysis Software (version 9.2, SAS Institute Inc, Campus Drive, Cary, NC, 27513). If the year by treatment interaction was not-significant, data from the 2 yr were averaged. If the year by treatment interaction was significant, data were analyzed separately by year. In addition, the non-normal data were transformed with arcsine and log transformations for weed control and yield data, respectively. Data were subjected to one-way ANOVA, and means were separated by Fisher’s protected LSD ($\alpha = 0.05$).

Results and Discussion

Weed Control. The year by treatment interaction was non-significant for Palmer amaranth, large crabgrass, and yellow nutsedge control in tomato and bell pepper, so weed control was averaged over 2010 and 2011. Weed control was rate-responsive for allyl ITC and metam sodium. Lower rates of both fumigants were effective early in the growing season (for 2 to 3 WATP, data not shown) and provided weed control comparable to MeBr. However, weed control with the lower rates of allyl ITC and metam sodium was effective for early wks, and weed control was inferior to MeBr at 4 WATP, except for Palmer amaranth and large crabgrass control with metam sodium at 270 kg ha^{-1} (Table 1). Good weed control from lower rates of allyl ITC and metam sodium at early wks is attributed to the delayed weed seed germination because of short period dormancy induced by lower rates of ITCs. Peterson et al. (2001) reported that at low concentrations ITCs induce secondary seed dormancy and delay the germination of seed, but the dormant seed are viable and germinate in the later weeks.

On the other hand, the highest rate of allyl ITC and metam sodium were more effective than their respective lower rates. Allyl ITC at 750 kg ha^{-1} and metam sodium at 360 kg ha^{-1} controlled weeds comparably to MeBr, and control lasted all season. Peterson et al. (2001) reported that the activity of ITCs increases rapidly after the ITC rate exceeds the effective dose for 50% control (ED_{50}). In addition, the higher rates of ITC have greater activity on seed enzymes, which results in the loss of seed viability, and those seed do not germinate (Brown and Morra 1995; Peterson et al. 2001). Therefore, the highest rate of ITC (750 kg ha^{-1}) was effective season-long for weed control and controlled weeds at a level comparable to MeBr, whereas lower rates failed to provide control comparable to MeBr.

Palmer amaranth control. There were significant differences (α=0.05) among allyl ITC and metam sodium rates for Palmer amaranth control in tomato (Table 1). The highest rates of allyl ITC and metam sodium were more effective than the lower rates for Palmer amaranth control in tomato. Allyl ITC at 750 kg ha^{-1} and metam sodium at 360 kg ha^{-1} controlled Palmer amaranth ≥79% season-long in LDPE-mulched tomato. Moreover, Palmer amaranth control from these treatments was equivalent to the control with MeBr. Allyl ITC at 913 (±191) kg ha^{-1} controlled Palmer amaranth equivalent to MeBr in polyethylene-mulched tomato in the previous study conducted by Bangarwa (2010). In addition to the highest rate of allyl ITC and metam sodium, metam sodium at 270 kg ha^{-1} controlled Palmer amaranth comparable to the control with MeBr. Effective control of Palmer amaranth with the lower rate of metam sodium (270 kg ha^{-1}) is because of the seed size of the Palmer amaranth. The smaller the seed size, the less tolerant is the seed to physical and chemical stresses (Westoby et al. 1996). Furthermore, increase in seed size is directly related to tolerance to methyl ITC (Peterson et al. 2001).

Allyl ITC at 750 kg ha^{-1} or metam sodium at 360 kg ha^{-1} was comparable to MeBr for Palmer amaranth control in bell pepper at 8 WATP (Table 2). By the end-of-season, Palmer amaranth control was 83 and 87% from allyl ITC at 750 kg ha^{-1} and metam sodium at 360 kg ha^{-1}, respectively, and the control was similar to control from MeBr. Palmer amaranth control from allyl ITC at 750 kg ha^{-1} in this study corresponds with the result of Bangarwa et al. (2011a) who concluded that allyl ITC at 888 (±225) kg ha^{-1} was similar to the standard MeBr treatment for Palmer amaranth control in plasticulture bell pepper. In bell peppr, lower rates of allyl ITC and metam sodium were ineffective compared to MeBr for Palmer amaranth control after 6 WATP.

Large crabgrass control. In tomato, large crabgrass control was effective season-long from allyl ITC at 750 kg ha^{-1} and metam sodium at 360 kg ha^{-1}. Large crabgrass control from the highest rates of allyl ITC and metam sodium was similar to control with MeBr (Table 1). At 8 WATP, large crabgrass control was 76 and 85% from allyl ITC at 750 kg ha^{-1} and metam sodium at 360 kg ha^{-1}, respectively, and the control was similar to the MeBr. Bangarwa (2010) also reported equivalent large crabgrass control from allyl ITC at 805 (±158) kg ha^{-1} and the standard MeBr treatment in plasticulture tomato. The lower rates of allyl ITC and metam sodium were not as effective as MeBr for large crabgrass control. Although, metam sodium at 270 kg ha^{-1} controlled large crabgrass similar to MeBr at 4 WATP, control did not compared with MeBr at 6 and 8 WATP.

In bell pepper, large crabgrass control from the highest rate of allyl ITC and metam sodium was comparable to MeBr treatment (Table 2). The effectiveness of allyl ITC and metam sodium for large crabgrass control in bell pepper was similar to the control pattern observed in tomato. At 8 WATP, allyl ITC at 750 kg ha^{-1} and metam sodium at 360 kg ha^{-1} controlled large crabgrass ≥78% in LDPE-mulched bell pepper production, and the control was equivalent to the control with MeBr treatment. In previous experiment, Bangarwa et al. (2011a) reported that allyl ITC at 651 (±118) kg ha^{-1} controlled large crabgrass comparable to the control with MeBr in plasticulture bell pepper.

Yellow nutsedge control. Soil fumigation with allyl ITC and metam sodium affected yellow nutsedge population in tomato. The highest rates of allyl ITC and metam sodium were more effective than the respective lower rates for yellow nutsedge control in tomato (Table 1). At 8 WATP, yellow nutsedge control with allyl ITC at 750 kg ha^{-1} or metam sodium at 360 kg ha^{-1}

was similar to MeBr (80 to 92%). Likewise, comparable yellow nutsedge control with allyl ITC at 827 (±118) kg ha^{-1} and MeBr has been reported in polyethylene-mulched tomato (Bangarwa 2010). In another study, Locascio et al. (1997) evaluated metam sodium at 155 kg ha^{-1} and concluded that it is not comparable to MeBr for reducing yellow nutsedge density; however, yellow nutsedge density in plots treated with metam sodium at 155 kg ha^{-1} plus pebulate at 4.5 kg ha^{-1} was comparable to MeBr treated plots. In the present experiment also metam sodium at 180 kg ha^{-1} did not control yellow nutsedge equivalent to the control with MeBr; however, yellow nutsedge control with metam sodium at 360 kg ha^{-1} was comparable to the control with MeBr. Johnson and Mullinix (2007) reported 85% yellow nutsedge control with the soil fumigation of metam sodium at 380 kg ha^{-1} under black polyethylene mulch in cantaloupe (*Cucumis melo* var. *cantalupensis)* production. Similarly, metam sodium applied at 485 kg ha^{-1} was comparable to the MeBr for maintaining purple nutsedge density throughout the growing season (Gilreath and Santos 2004).

At 4 WATP, yellow nutsedge control with allyl ITC at 750 kg ha^{-1} was lower than the control with MeBr (Table 2). However, yellow nutsedge control was as effective with the highest rates of allyl ITC and metam sodium as with MeBr at 6 and 8 WATP in LDPE-mulched bell pepper. At 8 WATP, yellow nutsedge control was 80 and 83% from the allyl ITC at 750 kg ha^{-1} and metam sodium at 360 kg ha^{-1}, respectively. Likewise, Bangarwa et al. (2011a) reported equivalent yellow nutsedge control from allyl ITC at 924 (±74) kg ha^{-1} and MeBr in plasticulture bell pepper. In the study conducted by Gilreath et al. (2005), drip-applied metam sodium at 710 L ha^{-1} (equivalent to 360 kg ha^{-1}) was comparable to MeBr plus chloropicrin at 400 kg ha^{-1} for *Cyperus* control in two of three bell pepper growing seasons. However, metam sodium was broadcast-applied in our experiment and yellow nutsedge control did not vary between years. In a similar study, purple nutsedge density in bell pepper plots at 10 WAT was 2.7 plants m^{-2} with broadcast-applied metam sodium at 485 kg ha^{-1} and was comparable to purple nutsedge density (7.3 plants m^{-2}) in MeBr-treated plots (Gilreath and Santos 2004).

Viable Yellow Nutsedge Tubers. The lower rates of allyl ITC and metam sodium failed to reduce viable nutsedge tuber density compared to MeBr-treated plots in LDPE-mulched tomato and bell pepper production. However, viable tubers in plots treated with allyl ITC at 750 kg ha^{-1} or metam sodium at 360 kg ha^{-1} were similar to the MeBr treatment (Table 3). At the end-of-season, viable yellow nutsedge tubers were ≤76 in tomato plots and ≤84 in bell pepper plots treated with allyl ITC at 750 kg ha^{-1} or metam sodium at 360 kg ha^{-1}.

Although allyl ITC at 750 kg ha^{-1} or metam sodium at 360 kg ha^{-1} was comparable to MeBr for viable yellow nutsedge tubers density, these fumigants did not control viable tubers to a level to prevent yellow nutsedge interference in the next growing season. Viable yellow nutsedge tuber density was ≥30 tubers m^{-2} in tomato plots treated with allyl ITC at 750 kg ha^{-1} or metam sodium at 360 kg ha^{-1} (Table 3). Moreover, the presence of viable yellow nutsedge tubers at a density more than 25 tubers m^{-2} reduced 25% of total marketable tomato yield (Morales-Payen et al. 2003a). Furthermore, Bangarwa (2010) reported >25% reduction of tomato dry weight and >24% reduction in marketable yield from initial yellow nutsedge tuber density at 50 tubers m^{-2} in LDPE-mulched tomato. Likewise, viable yellow nutsedge tuber density in our experiment was ≥57 tubers m^{-2} in bell pepper plots treated with allyl ITC at 750 kg ha^{-1} or metam sodium at 360 kg ha^{-1}. Previous research has shown that bell pepper dry weight and marketable yield reduction were ≥42 and ≥47%, respectively, with an initial yellow nutsedge tubers density at 50 tubers m^{-2} (Bangarwa et al. 2011b).

Tomato and Bell Pepper Injury. Allyl ITC and metam sodium did not injure tomato and bell pepper. This study shows that tomato and bell pepper seedlings at the 4- to 6-leaf stage can be transplanted into LDPE-mulched raised beds at 3 wk after applying these fumigants. However, direct exposure of the seedling to the fumigant vapor trapped between the soil surface and LDPE mulch should be prevented by aerating the raised beds for 3 d prior to transplanting seedlings. In a similar study, Bangarwa (2010) observed 8 and 11% injury at 2 WATP in tomato and bell pepper, respectively, from allyl ITC at 1500 kg ha^{-1} applied under virtually impermeable film (VIF). However, injury was ≤ 3% from allyl ITC applied at 1500 kg ha^{-1} under LDPE mulch. In another study, chloropicrin at 170 kg ha^{-1} followed by metam sodium at 360 kg ha^{-1} was safe to tomato, and tomato vigor was comparable to tomato plants in plots treated with MeBr (Santos et al. 2006).

Tomato Yield. Tomato yield was dependent on treatment efficacy. Plots with low weed density or greater percentage weed control resulted in higher tomato yield than plots with higher weed density or lower weed control. Weed pressure was lower in plots treated with allyl ITC at 750 kg ha^{-1} or metam sodium at 360 kg ha^{-1} compared to plots treated with lower rates. Early-season tomato yield from plots treated with the highest rate of allyl ITC and metam sodium were similar to early-season yield from plots treated with MeBr (Table 4). Tomato plots treated with allyl ITC at 750 kg ha^{-1} and metam sodium at 360 kg ha^{-1} yielded jumbo, extra large, medium, and small category tomato fruit similar to those categories in MeBr-treated plots. Among different tomato grades, the jumbo category accounted for the highest percentage (≥41%) of the early-season yield. Likewise, the early-season tomato yield contributed about 15% of the total marketable tomato yield.

Marketable tomato yield, the total yield of all grades, was higher from tomato treated with the high rates of allyl ITC and metam sodium than with lower rates and did not differ from the yield of MeBr-treated tomato (Table 5). Marketable tomato yield in this study corresponds with the yield reported in previous studies. For example, Bangarwa (2010) reported similar marketable tomato yield in plots treated with allyl ITC at 887 (±84) kg ha^{-1} and MeBr. Similarly, marketable tomato yield in plots treated with metam sodium at 360 kg ha^{-1} was equivalent to yield from plots treated with MeBr (Gilreath et al. 2003). Among the different USDA grades, the jumbo category contributed the highest percentage toward total marketable yield. The jumbo category yield was 13.1 ton ha^{-1} (41% of the total yield) for allyl ITC at 750 kg ha^{-1}, 14.8 ton ha^{-1} (43% of the total yield) for metam sodium at 360 kg ha^{-1}, and 22.5 ton ha^{-1} (44% of the total yield) for MeBr. Likewise, extra large category tomato yield contributed >19% for the total yield for these treatments. The total marketable tomato yields from plots treated with allyl ITC at 750 kg ha^{-1} and metam sodium at 360 kg ha^{-1} were 1.39 and 1.63 times, respectively, greater than the total marketable tomato yield from non-treated check plots.

Bell Pepper Yield. Early-season bell pepper yield from plots treated with allyl ITC at 750 kg ha^{-1} and metam sodium at 270 and 360 kg ha^{-1} was >12.3 ton ha^{-1}, and these yields were equivalent to the early-season bell pepper yield from plots treated with MeBr (Table 6). Similarly, USDA-grade bell pepper yield from plots treated with allyl ITC at 750 kg ha^{-1} and metam sodium at 270 and 360 kg ha^{-1} was similar to yields from MeBr-treated plots. Furthermore, early-season yield contributed ≥23% of total marketable bell pepper yield. In a similar study, Bangarwa et al. (2011a) reported similar early-season yield from plots treated with allyl ITC and MeBr.

Bell pepper treated with metam sodium at 270 and 360 kg ha^{-1} yielded 12.4 and 13.2 ton ha^{-1} of U.S. Fancy category fruit, and yields were similar to the U.S. Fancy category yield in plots treated with MeBr (Table 7). However, yields of U.S. No. 1 and No. 2 fruit from bell pepper treated with metam sodium at 270 kg ha^{-1} were lower than the yield in those categories from bell pepper plots treated with MeBr. Bell pepper treated with metam sodium at 360 kg ha^{-1} yielded 53.5 ton ha^{-1} total marketable bell pepper, which was 92% greater than the yield (27.8 ton ha^{-1}) from non-treated plants. The weed control effectiveness of metam sodium at 360 kg ha^{-1} reflected into higher total marketable bell pepper yield, whereas, at lower rates metam sodium provided less percentage weed control, and the yield was lower compared to MeBr. Gilreath et al. (2004) observed higher bell pepper yield in the first year and equivalent bell pepper yield in the second year in plots treated with metam sodium at 483 kg ha^{-1} compared to yields in plots treated with MeBr at 400 kg ha^{-1}.

Total marketable bell pepper yield in plots treated with allyl ITC at 750 kg ha^{-1} was lower than in MeBr-treated plots because of a lower yield of U.S. Fancy category fruit (Table 7). Allyl ITC at 750 kg ha^{-1} provided numerically 12, 13, and 12 percentage points less control of Palmer amaranth, large crabgrass, and yellow nutsedge, respectively, than from MeBr. Bell pepper has a short stature, an open canopy, and a slow growth habit, so yield loss because of weed interference is more pronounced in bell pepper than in other robust vegetable crops (Norsworthy et al. 2008). Morales-Payen et al. (1997, 1998) observed more yield loss (73%) in bell pepper than yield loss (42%) in tomato because of purple nutsedge interference. In the present experiment, U.S. Fancy grade yield and total marketable yield in the plots treated with the highest rate of allyl ITC was lower than in MeBr-treated plots. This result illustrates that weed interference reduces U.S. Fancy grade fruit; the highest quality of bell pepper fruit, and eventually lowers the total marketable yield. In a previous study, Bangarwa et al. (2011a) predicted equivalent bell pepper yield with allyl ITC applied at 932 (±127) kg ha^{-1} and MeBr in polyethylene-mulched bell pepper. However, in this study we applied allyl ITC at 750 kg ha^{-1}, a lower rate than the predicted rate by Bangarwa et al. (2011a), and at this rate, total marketable bell pepper yield from allyl ITC-treated plots was not comparable to MeBr-treated plots.

In conclusion, preplant soil fumigation with allyl ITC at 750 kg ha^{-1} or metam sodium at 360 kg ha^{-1} was safe for LDPE-mulched tomato and bell pepper. At these rates, allyl ITC and metam sodium controlled Palmer amaranth, large crabgrass, yellow nutsedge, and viable yellow nutsedge tuber density comparable to MeBr in LDPE-mulched tomato. Furthermore, total marketable tomato yield from allyl ITC at 750 kg ha^{-1} and metam sodium at 360 kg ha^{-1} was comparable to the tomato yield from MeBr. In bell pepper, weed control and viable yellow nutsedge tuber density from allyl ITC at 750 kg ha^{-1} was comparable to MeBr; however, the total marketable yield was lower from allyl ITC at 750 kg ha^{-1} than from MeBr. U.S. Fancy grade yield was lower from allyl ITC at 750 kg ha^{-1} which resulted into lower total marketable bell pepper yield from this treatment. This experiment was a follow up research to the study conducted by Bangarwa (2010) in order to specify the allyl ITC rate comparable to MeBr in LDPE-mulched tomato and bell pepper. Bangarwa (2010) reported allyl ITC rate range of 913 (±191) and 932 (±191) kg ha^{-1} for tomato and bell pepper, respectively, as potential alternative to MeBr. With the current study, we have concluded allyl ITC at 750 kg ha^{-1} as effective alternative to MeBr in tomato. However, allyl ITC at 750 kg ha^{-1} was not an effective alternative to MeBr in bell pepper. Therefore, effective allyl ITC rate for bell pepper has to be concluded by future research. On the other hand, LDPE-mulched bell pepper plots treated with metam sodium at 360 kg ha^{-1} provided equivalent weed control, yellow nutsedge tuber density, and total marketable yield compared to plots treated with MeBr.

This study illustrates that metam sodium at 360 kg ha^{-1} is a viable stand-alone alternative to MeBr for weed control and yield maintenance in LDPE-mulched tomato and bell pepper production. However, factors such as soil type, fumigation incorporation depth, and bed width and height may influence the effectiveness of the soil-applied fumigant (Ajwa et al. 2002). For optimal effectiveness of soil-applied fumigants, uniform irrigation and complete wetting of the raised bed immediately after fumigant application is very critical (Csinos et al. 2002). If the beds are partially wet, dissipation of methyl ITC from wet regions to dry regions is slow because of the higher affinity of methyl ITC to the moisture (Noling and Becker 1994). As the irrigation period and amount of water needed to irrigate the field vary according to soil type and soil gradient, the irrigation system should be managed accordingly.

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Table 1. Effect of allyl isothiocyanate (ITC), metam sodium, and methyl bromide plus chloropicrin on Palmer amaranth, large crabgrass, and yellow nutsedge control in LDPE-mulched tomato at 4, 6, and 8 weeks after transplanting (WATP), averaged over 2010 and 2011.

		Weed control[a]								
		Palmer amaranth			Large crabgrass			Yellow nutsedge		
Soil fumigants	Rate	4 WATP[b]	6 WATP	8 WATP	4 WATP[c]	6 WATP	8WATP[d]	4 WATP[e]	6 WATP	8 WATP
	$kg\ ai\ ha^{-1}$	%								
Allyl ITC	450	76 e	41 c	23 c	87 cd	49 d	31c	54 c	45 d	38 c
	600	88 cd	67 b	41 bc	93 bcd	59 c	38 c	57 c	48 cd	41 c
	750	90 bcd	88 a	79 a	95 abc	86 a	76 ab	89 ab	84 ab	80 ab
Metam sodium	180	84 de	66 b	49 b	86 d	61 c	36 c	68 c	59 c	49 c
	270	93 abc	87 a	83 a	96 ab	78 b	63 b	88 b	79 b	71 b
	360	98 ab	94 a	85 a	98 a	89 a	85 a	93 ab	89 ab	86 a
Methyl bromide + chloropicrin	261 129	100 a	98 a	94 a	99 a	93 a	91 a	97 a	94 a	90 a

[a] Treatment means within a column followed by the same letter are not different based on Fisher's protected LSD at $\alpha = 0.05$.

[b] Palmer amaranth did not emerge until 4 WATP in 2010; therefore, only data for 2011 are shown at 4 WATP.

[cde] Mean separation based on arcsine transformed data.

Table 2. Effect of allyl isothiocyanate (ITC), metam sodium, and methyl bromide plus chloropicrin on Palmer amaranth, large crabgrass, and yellow nutsedge control in LDPE-mulched bell pepper at 4, 6, and 8 weeks after transplanting (WATP), averaged over 2010 and 2011.

		Weed control[a]								
		Palmer amaranth			Large crabgrass			Yellow nutsedge		
Soil fumigants	Rate	4 WATP[b]	6 WATP	8 WATP	4 WATP	6 WATP	8WATP	4 WATP	6 WATP	8 WATP
	kg ai ha^{-1}	%								
Allyl ITC	450	88 d	64 c	49 cd	93 b	61 c	43 c	44 d	37 e	33 d
	600	90 cd	82 bc	69 bc	96 ab	69 bc	52 c	64 c	56 de	48 cd
	750	93 cd	91 ab	83 ab	98 ab	89 a	78 ab	88 b	84 ab	80 ab
Metam sodium	180	94 bcd	65 c	46 d	95 ab	66 d	51 c	71 c	64 cd	49 c
	270	95 bc	89 ab	78 b	96 ab	76 b	59 bc	89 ab	78 bc	73 b
	360	98 ab	96 ab	87 ab	98 ab	90 a	84 a	92 ab	88 ab	83 ab
Methyl bromide + chloropicrin	261 129	100 a	98 a	97 a	100 a	93 a	89 a	96 a	94 a	92 a

[a] Treatment means within a column followed by the same letter are not different based on Fisher's protected LSD at α = 0.05. Mean separation based on arcsine transformed data.

[b] Palmer amaranth did not emerge until 4 WATP in 2010; therefore, only data for 2011 are shown at 4 WATP.

Table 3. Effect of allyl isothiocyanate (ITC), metam sodium, and methyl bromide plus chloropicrin on viable yellow nutsedge tubers in tomato and bell pepper, averaged over 2010 and 2011.[a]

		Tuber density[b]	
Soil fumigants	Rate	Tomato	Bell pepper
	kg ai ha^{-1}	-----------------tubers m^{-2}	------------------
Allyl ITC	450	116 b	187 bc
	600	140 ab	149 c
	750	76 bcd	84 d
Metam sodium	180	123 b	220 ab
	270	97 bc	149 c
	360	30 cd	57 d
Methyl bromide + chloropicrin	261 129	22 d	51 d
Non-treated check	-	193 a	273 a

[a] Treatment means within a column followed by the same letter are not different based on Fisher's protected LSD at $\alpha = 0.05$.

[b] Tuber density (tubers m^{-2}) determined from five soil cores (0.1-m diam by 0.15-m depth) pulled for each tomato and bell pepper plot.

Table 4. Effect of allyl isothiocyanate (ITC), metam sodium, and methyl bromide plus chloropicrin on early-season tomato yield, averaged over 2010 and 2011.[a]

Soil fumigants	Rate	Tomato yield[b]					
		Jumbo	Extra large	Large	Medium	Small	Total yield[c]
	kg ai ha^{-1}	----------ton ha^{-1}----------					
Allyl ITC	450	1.8 bcd	0.8 bcd	0.6 bc	0.3 b	0.2 ab	3.7 bcd
	600	1.6 bcd	0.6 cd	0.2 c	0.1 b	0.1 b	2.6 cd
	750	1.9 abc	0.9 abc	0.9 b	0.6 ab	0.3 a	4.7 ab
Metam sodium	180	1.1 cd	0.5 cd	0.5 bc	0.2 b	0.1 b	2.4 d
	270	2.5 ab	1.0 abc	0.6 bc	0.4 ab	0.1 b	4.6 abc
	360	3.6 ab	1.4 ab	0.8 b	0.4 ab	0.2 ab	6.4 ab
Methyl bromide + Chloropicrin	261 129	4.7 a	2.2 a	1.8 a	0.7 a	0.1 b	9.5 a
Non-treated control	-	1.0 d	0.5 d	0.4 bc	0.4 ab	0.1 b	2.5 cd

[a] Treatment means within a column followed by the same letter are not different based on Fisher's protected LSD at $\alpha = 0.05$. Mean separation based on arcsine transformed data.

[b] Early-season tomato yield according to the USDA grade and the early total yield.

[c] Total yield determined by summing first and second harvest from 2010 and 2011, respectively.

Table 5. Effect of allyl isothiocyanate (ITC), metam sodium, and methyl bromide plus chloropicrin on marketable tomato yield, averaged over 2010 and 2011.[a]

Soil fumigants	Rate	Tomato yield[b]					
		Jumbo	Extra large	Large	Medium	Small	Total yield [c]
	kg ai ha^{-1}	---------------ton ha^{-1}---------------					
Allyl ITC	450	7.2 de	3.6 de	3.4 cd	2.9 bc	1.8 bc	18.9 d
	600	8.6 cd	3.9 cd	3.2 d	2.5 c	1.4 c	19.6 cd
	750	13.1 abc	6.1 abc	5.3 ab	3.9 ab	3.2 a	31.6 ab
Metam sodium	180	5.2 ef	2.8 ef	3.0 d	3.2 bc	2.8 a	17.0 de
	270	11.9 bc	5.4 bcd	4.4 bc	3.4 ab	2.3 abc	27.4 bc
	360	14.8 ab	6.9 ab	6.0 a	4.4 a	2.6 ab	34.8 ab
Methyl bromide + Chloropicrin	261 129	16.9 a	7.6 a	5.9 a	4.9 a	2.9 a	38.2 a
Non-treated control	-	3.9 f	2.2 f	2.8 d	2.7 bc	1.7 bc	13.3 e

[a] Treatment means within a column followed by the same letter are not different based on Fisher's protected LSD at α = 0.05. Mean separation based on arcsine transformed data.

[b] Marketable tomato yield according to the USDA grade and the total yield.

[c] Total yield determined by summing seven and five harvest from 2010 and 2011, respectively.

Table 6. Effect of allyl isothiocyanate (ITC), metam sodium, and methyl bromide plus chloropicrin on early-season bell pepper yield, averaged over 2010 and 2011.[a]

Soil fumigants	Rate	Bell pepper yield [b]			
		U.S. Fancy	U.S. No. 1	U.S. No. 2	Total yield [c]
	kg ai ha^{-1}	------------------------------- ton ha^{-1}---------------------------			
Allyl ITC	450	3.5 ab	3.4 abc	2.7 b	9.6 bcd
	600	2.6 bc	3.0 bc	3.4 ab	9.0 cd
	750	4.2 ab	4.7 a	4.4 a	13.3 ab
Metam sodium	180	1.5 c	2.3 c	2.9 b	6.8 d
	270	4.5 ab	3.6 abc	4.2 a	12.3 abc
	360	4.7 ab	3.8 ab	4.4 a	12.9 ab
Methyl bromide +	261	5.4 a	4.7 a	4.3 a	14.4 a
chloropicrin	129				
Non-treated check	-	2.9 bc	3.1bc	2.8 b	8.9 cd

[a] Treatment means within a column followed by the same letter are not different based on Fisher's protected LSD at α = 0.05.

[b] Early season bell pepper yield according to the USDA grade and the early total yield.

[c] Early season yield determined by summing first and second harvest from 2010 and 2011.

Table 7. Effect of allyl isothiocyanate (ITC), metam sodium, and methyl bromide plus chloropicrin on marketable bell pepper yield, averaged over 2010 and 2011.[a]

		Bell pepper yield [b]			
Soil fumigants	Rate	U.S. Fancy	U.S. No. 1	U.S. No. 2	Total yield [c]
	kg ai ha^{-1}	---------------------------------- ton ha^{-1}			--------------------------------
Allyl ITC	450	9.5 bc	9.9 cd	12.0 e	31.4 d
	600	9.6 bc	11.4 bcd	17.1 dc	38.0 cd
	750	11.6 b	14.9 ab	24.2 ab	50.6 b
Metam sodium	180	6.0 c	7.9 d	13.8 de	27.8 d
	270	13.2 ab	13.3 bc	20.9 bc	47.3 bc
	360	12.4 ab	14.7 ab	26.4 a	53.5 ab
Methyl bromide + chloropicrin	261 129	17.1 a	18.4 a	27.0 a	62.5 a
Non-treated check	-	6.1 c	8.1 d	13.8 de	27.8 d

[a] Treatment means within a column followed by the same letter are not different based on Fisher’s protected LSD at $\alpha = 0.05$.

[b] Marketable bell pepper yield according to the USDA grade and the total yield.

[c] Total yield determined by summing four and five harvest from 2010 and 2011, respectively.

CHAPTER 2

EFFICACY AND ECONOMICS OF HERBICIDE PROGRAMS COMPARED TO METHYL BROMIDE FOR WEED CONTROL IN POLYETHYLENE-MULCHED TOMATO AND BELL PEPPER

Abstract

The ban on methyl bromide (MeBr) incurs a huge economic loss in commercial tomato and bell pepper production. In the absence of effective MeBr alternatives, weeds are a serious concern for optimum yield. A field study was conducted in summer 2010 and 2011, at Fayetteville, AR, to compare the efficacy and economics of herbicide programs consisting of PRE-applied followed by (fb) POST-applied herbicides in low density polyethylene (LDPE) mulched tomato and bell pepper. PRE-applied imazosulfuron at 0.112, 0.224, and 0.336 kg ai ha^{-1} and *S*-metolachlor at 1.6 kg ai ha^{-1} were fb a POST-applied mixture of trifloxysulfuron plus halosulfuron at 0.008 and 0.027 kg ai ha^{-1} at 4 wk after transplant (WATP). The standard MeBr treatment (2:1 mixture of MeBr plus chloropicrin at 390 kg ai ha^{-1}) and weed-free and non-treated check plots were used for comparison. PRE-applied *S*-metolachlor fb POST-applied herbicides controlled Palmer amaranth ≥89%, large crabgrass ≥78%, and yellow nutsedge ≥90%, which was comparable to the control with MeBr in tomato and bell pepper. After POST herbicide application, tomato and bell pepper injury was ≥17 and ≥13%, respectively, at 6 WATP; however, the crops recovered in later weeks. Plots treated with *S*-metolachlor-containing herbicide program yielded marketable tomato and bell pepper fruit comparable to the yield in plots treated with MeBr. Economic evaluation of the herbicide programs for LDPE-mulched tomato and bell pepper demonstrated the loss of ≥\$3,277.76 ha^{-1} and ≥ \$7,010.00 ha^{-1}, respectively, from imazosulfuron herbicide programs. However, the *S*-metolachlor- containing herbicide program was profitable and provided a net return of \$3,758.50 and \$9,912.05 ha^{-1} in LDPE-mulched tomato and bell pepper, respectively. In addition, the *S*-metolachlor herbicide program was \$173.34 ha^{-1} more profitable than the MeBr treatment in LDPE-mulched bell pepper. In conclusion, a herbicide program consisting of PRE-applied *S*-metolachlor fb POST-applied trifloxysulfuron plus halosulfuron is a viable alternative to MeBr for weed control and marketable yield in LDPE-mulched tomato and bell pepper production.

Nomenclature: Halosulfuron; imazosulfuron; methyl bromide (MeBr); *S*-metolachlor; trifloxysulfuron; large crabgrass, *Digitaria sanguinalis* (L.) Scop. DIGSA; Palmer amaranth, *Amaranthus palmeri* S. Wats. AMAPA; yellow nutsedge, *Cyperus esculentus* L. CYPES; bell pepper, *Capsicum annum* L. ‘Heritage’; tomato, *Solanum lycopersicum* L. ‘Amelia’.

Key words: Herbicide program, low-density polyethylene (LDPE) mulch, methyl bromide alternative, PRE fb POST-applied herbicide.

Introduction and Literature Review

Tomato and bell pepper have considerable importance for commercial vegetable production in the United States (U.S.). At present, tomato and bell pepper rank 1st and 7th for economic value among the 24 commercially produced vegetable crops in the U.S. (USDA 2011). In 2010, tomato and bell pepper were cultivated on 64,500 and 22,000 ha in the U.S. with the total production value of 2.31 billion and 637 million dollars, respectively (USDA 2011). With the advancement in vegetable production technology, plasticulture production is popular among commercial vegetable producers. Plasticulture helps growers to achieve quick maturity, high yield, and superior fruit quality (Sanders et al. 1996). However, in plasticulture tomato and bell pepper production, weeds cause economic losses annually and are the major constraint for optimal production. Palmer amaranth, large crabgrass, and yellow nutsedge are among the 10 most troublesome weeds in vegetable production in the Southeast U.S. (Webster 2006).

Palmer amaranth is among the most troublesome weeds in vegetable production systems. Palmer amaranth grows vigorously horizontally and vertically with rapid height increase and canopy formation, and accumulates greater biomass within a few weeks after emergence as compared to other *Amaranthus* species (Norsworthy et al. 2008; Sellers et al. 2003). Palmer amaranth grows 0.18 to 0.21 cm per growing degree day (GDD) (at base 10C) under suitable moisture, nutrient, and light conditions (Horak and Loughin 2000). In plasticulture system, Palmer amaranth grows to a height more than 2 m and shades tomato plants, reducing fruit number and size (Garvey 1999). Palmer amaranth reaches the same height as bell pepper in 287 GDD (at base 10C) and reduces fruit set within 6 WATP (Norsworthy et al. 2008). Meyers et al. (2010b) reported reduction of 36 to 81% marketable sweet potato [*Ipomoea batatas* (L.) Lam.] from Palmer amaranth interference at 0.5 to 6.5 plants m^{-1} row.

In the U.S., large crabgrass is prevalent in most of the vegetable producing states. Season-long large crabgrass interference, at densities as low as 1 plant m^{-2}, reduces bell pepper yield more than 30% (Fu and Ashley 2006). After large crabgrass reaches a height of 8 to 10 cm and starts forming tillers and adventitious roots, management is more difficult than on smaller plants (Monks and Schultheis 1998). Based on GDD, large crabgrass growing and interfering with plasticulture grown bell pepper can obtain the same height (34 cm) as bell pepper at 580 GDD (Norsworthy et al. 2008), and season-long interference causes total crop failure in bell pepper production (Fu and Ashley 1999). Large crabgrass interferes with watermelon (*Citrullus lanatus* L.) for 1 to 6 WATP, reducing marketable yield significantly (Monks and Schultheis 1998).

Yellow nutsedge ranks the sixteenth most troublesome weed throughout the world and is one of the most problematic weeds of vegetable crops in the U.S. (Holm et al. 1997). It is designated as a noxious weed in 10 states; meanwhile, it is considered a serious weed throughout the U.S (Anderson 1999). Yield losses ranged from 30 to 89% in vegetable crops due to nutsedge infestation (Dusky et al. 1997; Morales-Payan et al. 1997). Season-long interference of yellow nutsedge reduced bell pepper yield more than 70% (Morales-Payan et al. 2003; Motis et al. 2004). According to Motis et al. (2001), yellow nutsedge tubers present in a 30.5-cm-radius patch and spaced at 5 or 10 cm apart reduced >65% yield in plasticulture bell pepper. Season-long interference of yellow nutsedge, established from 30 viable yellow nutsedge tubers m^{-2}, reduced yield by 20% in polyethylene-mulched bell pepper (Motis et al. 2003). In a polyethylene-mulched system, nutsedges are capable of penetrating and emerging through the mulch. With a pointed leaf tip, nutsedges spp. can penetrate polyethylene mulches four times thicker than those used for commercial vegetable production (Henson and Little 1969; Webster

2005), and can successfully compete with crops for available inputs (Morales-Payen et al. 1997; Santos et al. 1997). Therefore, yellow nutsedge is a serious concern for growers who want to use a single polyethylene mulch application for two to three growing seasons.

For successful vegetable production, timely and effective weed management is a key consideration (Strange et al. 2000). In tomato and bell pepper production, weed control is a primary practice, often accounting a significant portion of the total operating cost. In the past years, MeBr was used primarily as a preplant soil fumigant for weed control in tomato and bell pepper production. MeBr was effective on *Cyperus* species as well as other weeds common in vegetable production (Locascio et al. 1997). In 1993, MeBr was classified as Class-I ozone-depleting substance. Furthermore, the Montreal Protocol and U.S. Clean Air Act mandated a ban on production and ordinary agricultural uses (except for use under critical use exemption) of MeBr since January 2005. The ban on MeBr and unavailability of suitable alternatives for weed control incurs an annual economic loss of $116 and 16 million in commercial tomato and bell pepper production, respectively (Carpenter et al. 2000).

An effective management strategy at the critical period of weed growth and interference is important for successful weed management. After the ban on use of MeBr in plasticulture vegetable production, which was a widely adopted practice for commercial production, the methods available for controlling weeds are more limited than in conventional production. Because of the polyethylene mulch on top of the bed and drip tape underneath the polyethylene mulch, mechanical weeding (such as tillage, hoeing, flaming) is impossible. Although in a small-scale production, weeds can be controlled manually by hand weeding, it is not a feasible option for large-scale commercial production and when weed populations are high (Strange et al. 2000). Weed control methods using cover crops, such as glucosinolate-producing crops, were also ineffective in controlling large crabgrass and Palmer amaranth in plasticulture tomato and bell pepper production (Bangarwa 2010; Norsworthy et al. 2007). Therefore, herbicides are a suitable alternative to MeBr compared to manual, mechanical, or cultural weed control.

S-metolachlor belongs to the chloroacetamide class of herbicides and developed by Syngenta Crop Protection Inc. (Anonymous 2010b). It is a non-specific biosynthesis inhibitor with a selective mode of action. It has good activity on annual grasses, broadleaf weeds, and yellow nutsedge and is used for weed control in various vegetable crops. It provided excellent control of large crabgrass, pitted morningglory (*Ipomoea lacunosa* L.), eclipta (*Eclipta prostrata* L.), and redroot pigweed (*Amaranthus retroflexus* L.) in plasticulture tomato (Adcock et al. 2008). *S*-metolachlor applied PRE at 1.3 kg ha^{-1} controlled Palmer amaranth >80% in sweet potato (Meyers et al. 2010a). Bollman and Sprague (2007) reported 94% control of pigweed species with *S*-metolachlor applied at 1.4 kg ha^{-1}. In direct-seeded chili (*Capsicum frutescent* L.) and jalapeno pepper (*Capsicum annum* L.), crops were tolerant to *S*-metolachlor applied PPI without yield reduction (Schroeder 1992). In a study with drip-applied *S*-metolachlor in tomato, Santos et al. (2008) reported that extra large grade and total yields were increased by 75 and 57%, respectively, with an optimum control of broadleaf weeds. Bangarwa et al. (2009) reported yellow nutsedge and Palmer amaranth control of 67 and 77%, respectively, from PRE-applied *S*-metolachlor at 1.6 kg ha^{-1}.

Imazosulfuron belongs to the sulfonylurea class of herbicides, and it is widely evaluated for possible registration and use in Solanaceous crops. It has activity against annual and perennial broadleaf weeds and sedges (Dittmar et al. 2011; Riar and Norsworthy 2011). Imazosulfuron has shown potential for suppressing yellow nutsedge, purple nutsedge (*Cyperus rotundus* L.), and hairy galinsoga (*Galinsoga ciliata* Raf.) in plasticulture tomato (Boydston and

Felix 2008; Pekarek 2009). Santos et al. (2008) reported several fresh-market tomato varieties tolerant to post-directed imazosulfuron, making it a possible herbicide option for controlling nutsedge and broadleaf weeds in plasticulture tomato production. Imazosulfuron applied PRE had excellent activity on yellow nutsedge and did not injure bell pepper (Pekarek 2009). In bermudagrass (*Cynodon dactylon* L.) sod, imazosulfuron controlled yellow and purple nutsedge >90% (Henry and Sladek 2008). Similarly, PRE- and POST-applied imazosulfuron controlled 70 to 98% yellow nutsedge in potato (Boydston and Felix 2008). Dittmar et al. (2011), reported that drip-applied imazosulfuron controlled yellow nutsedge >69% in the greenhouse and reduced yellow nutsedge density in the field by 10 times compared to the density in non-treated plots.

Trifloxysulfuron is a sulfonylurea herbicide developed by Syngenta Crop Protection Inc. (Anonymous 2010b). It is labeled in cotton (*Gossypium hirsutum* L.), sugarcane (*Saccharum officinarum* L.), and for tomato transplants. Trifloxysulfuron has activity against pitted morningglory and ivyleaf morningglory (*Ipomoea hederacea* Jacq.), purple and yellow nutsedge, redroot pigweed, common lambsquarters, coffee senna (*Senna occidentalis* L.), sicklepod [*Senna obtusifolia* (L.) H. S. Irwin & Barneby], hemp sesbania (*Sesbania herbacea* L.), and seedling johnsongrass [*Sorghum halepense* (L.) Pers.] (Branson et al. 2005). Bangarwa et al. (2009) also reported the control of yellow nutsedge, large crabgrass, and Palmer amaranth from POST-applied trifloxysulfuron. In the greenhouse, trifloxysulfuron lowered photosynthetic rate and stomatal conductance of yellow nutsedge and provided control >69%, and in a field experiment, yellow nutsedge density was reduced 13-fold compared to non-treated plots (Dittmar et al. 2011).

Halosulfuron belongs to the sulfonylurea class of herbicides and is produced by Gowan (Anonymous 2010a). It is registered for many horticultural crops including tomato and cucurbits. It can be applied PRE or POST for many vegetable crops (McElroy et al. 2004). Based on halosulfuron concentration required to reduce yellow nutsedge dry weight by 90% (GR_{90}), Adock et al. (2008) reported greater activity from POST-applied than from PRE-applied halosulfuron. According to Bangarwa et al. (2009), POST-applied halosulfuron controlled yellow nutsedge 78% at 8 to 9 WATP in plasticulture tomato. Likewise, POST-applied halosulfuron at a rate of 0.035 kg ha^{-1} resulted in an 80% reduction in tuber density and fresh weight biomass of both purple and yellow nutsedge (Nelson and Renner 2002). According to Dittmar et al. (2011), halosulfuron controlled yellow nutsedge >69% and also reduced photosynthetic rate of yellow nutsedge compared to non-treated plants.

In absence of MeBr and unavailability of effective herbicide programs, weeds are a major constraint for optimum vegetable yield. Currently, there are only a few PRE- or POST-applied herbicides registered for vegetable crops. *S*-metolachlor or imazosulfuron applied PRE and trifloxysulfuron or halosulfuron applied POST evaluated in the previous experiments showed weed control potential in vegetable crops. However, when applied alone, these PRE- or POST-applied herbicides were not comparable to MeBr for weed control. For yellow nutsedge, PRE-applied fb POST-applied herbicides are important for an effective management program (Dittmar et al. 2011). Other research has also shown the benefit of applying PRE-applied fb POST-applied herbicides as a potential MeBr alternative for weed control in plasticulture tomato and bell pepper (Bangarwa 2010). Therefore, the primary objective of this research was to evaluate herbicide programs for Palmer amaranth, large crabgrass, and yellow nutsedge control and yield in LDPE-mulched tomato and bell pepper production.

Success of weed management programs relates not only to weed control effectiveness, but also economic soundness. Therefore, while evaluating MeBr alternative programs, it is important to evaluate the economic feasibility of proposed programs. Partial budget analysis helps producers to compare the economic viability of available alternatives and to incorporate the best program in the production system (Rainey 2010). Previously, studies were conducted to evaluate the economics of weed control programs as MeBr alternatives in a plasticulture production system. Sydorovych et al. (2008) evaluated the economics of soil fumigants as MeBr alternative for tomato and strawberry (*Fragaria ananassa* L.) production in a plasticulture system. Bangarwa et al. (2010) studied the economic returns of crucifer cover crops compared with MeBr in plasticulture tomato production. However, there is no published record on the effectiveness and economics of PRE- fb POST-applied herbicides as an alternative for MeBr in LDPE-mulched tomato and bell pepper production. Therefore, evaluation of economics (total cost of production, gross return, and net return) of the herbicide programs consisting of PRE- fb POST-applied herbicides compared with standard MeBr application for LDPE-mulched tomato and bell pepper production was also the research focus of this experiment.

Material and Methods

A field experiment was conducted to evaluate PRE-applied fb POST-applied herbicides for weed control in LDPE-mulched (black, embossed, 1.0 mil thick, Polygro LLC, Tampa, FL, 33655) tomato and bell pepper production. The experiment was conducted at the Agricultural Research and Extension Center at the University of Arkansas, Fayetteville, AR, in summer 2010 and 2011. In 2010, soil type at the experimental site was Razort silt loam (fine-loamy, mixed, active, mesic Mollic Hapludalfs) with pH of 6.3 and organic matter content of 1.8%. In 2011, the experiment was conducted on a Captina silt loam (fine-silty, siliceous, active, mesic Typic Fragiudults) with pH of 6.1 and organic matter of 1.8% (USDA Web Soil Survey). The experimental field was tilled in early April and in early May, to clean, loosen, and aerate the soil. In order to evaluate uniform plant populations, Palmer amaranth and large crabgrass seed and yellow nutsedge tubers (Azlin Seed Company, 112 Lilac Drive, Leland, MS 38756) were broadcast and incorporated into the experimental field to maintain uniform weed population throughout the plots. After incorporation of weed propagules into the soil, raise beds were formed, and plots were laid out.

The experiment was designed as a randomized complete block and each treatment was replicated four times. Treatments consisted of PRE-applied imazosulfuron (75DG; Valent USA Co., Walnut Creek, CA) at 0.112, 0.224, and 0.336 kg ha^{-1} and *S*-metolachlor (Dual Magnum 7.62 EC; Syngenta Crop Protection, Greensboro, NC) at 1.60 kg ha^{-1}. PRE treatments were broadcast on top of the raised beds using a CO_2-pressurized backpack sprayer calibrated to deliver 187 L ha^{-1}. Thereafter, beds were covered with LDPE mulch. LDPE mulch was used for the experiment because it is easy to handle (stretchable and less tearing), and its performance is similar to other polyethylene mulches for weed control (Bangarwa 2010). Moreover, the cost for LDPE mulch is lower than cost of virtually impermeable film (VIF) mulch. MeBr treatment was injected into the raised bed with double knives attached to a tractor-mounted MeBr applicator. Beds were then covered with LDPE mulch. A non-treated check with only LDPE-mulch and a hand-weeded control (weed-free control) with LDPE mulch were included for comparison. Plots were separated by cutting LDPE mulch at the end of each plot and covering the cut ends with soil. The final size of each plot was 4.5 m long and 0.75 m wide at the top of the bed for tomato and 3.6 m long and 0.75 m wide at top of the bed for bell pepper. After the treatment application, drip tape was attached to the irrigation system, and the field was irrigated to incorporate and activate the PRE-applied herbicides.

At 3 d after PRE herbicide application, holes were punched in the LDPE mulch for transplant establishment. Tomato 'Amelia' was transplanted in a single row with plants spaced at 0.6 m, and bell pepper 'Heritage' was transplanted in two rows with a 0.3- by 0.3-m spacing between plants. Transplants were grown in the greenhouse from seed obtained from Seedway LLC, Hall, NY, and tomato and bell pepper seedlings were at the four- to six-leaf stage when transplanted in the field. Plots were regularly fertigated, and managed with standard practices recommended for plasticulture tomato and bell pepper production (Holmes and Keemble 2010). Weeds emerging in the alleys between plastic-mulched beds were controlled all season by a hooded-sprayer application of *S*-metolachlor and paraquat at 1.065 and 0.56 kg ai ha^{-1}, respectively. *S*-metolachlor was applied at 2 WATP; while paraquat was applied at 4, 6, and 8 WATP. At 4 WATP, each PRE treatment was fb a POST-applied mixture of trifloxysulfuron (Envoke 75 DG, Syngenta Crop Protection, Greensboro, NC) at 0.008 kg ai ha^{-1} plus halosulfuron at 0.027 kg ai ha^{-1} (Sandea 75 DG; Gowan Co., Yuma, AZ). POST herbicides were applied over-the-top of tomato; whereas, the application was post-directed for bell pepper. POST herbicide mixtures also included 0.25% (v/v) nonionic surfactant (Induce; Helena Chemical Company, Memphis, TN). These herbicides were chosen because of their promising effect against yellow nutsedge and purple nutsedge when applied separately in tomato and bell pepper (Bangarwa et al. 2010; Pekarek 2009).

Parameters evaluated were crop injury and weed control ratings, hand weeding time, and marketable fruit yield. Plots were rated visually for crop injury and weed control (Palmer amaranth, large crabgrass, and yellow nutsedge) at 2, 4, 6, and 8 WATP. Crop injury and weed control ratings were made on a 0 to 100% scale, where 0 = no crop injury or no weed control and 100 = complete death of crop or complete weed control. Weed-free plots were hand weeded every week, and hand-weeding times were recorded. Hand-weeding time from all the weeks were added and converted to hours per hectare to determine the total hand-weeding time for the season. Marketable tomato and bell pepper fruits were harvested throughout the growing season and graded according to the USDA grades (USDA 1997; USDA 2005). Tomato grades recorded were jumbo, extra large, large, medium, and small, and bell pepper grades were U.S. Fancy, U.S. No. 1, and U.S. No. 2. There were six and five harvests for tomato in 2010 and 2011, respectively, and four harvests of bell pepper for both the years. For each harvest, fruit number and weights were recorded according to USDA grades for tomato and bell pepper. After the complete harvest, total marketable tomato and bell pepper yield was determined by summing fruit weight of different grades from all the harvests. At the end of the season, five soil core samples, each sample 10-cm-diam and 15-cm deep, was pulled from each tomato and bell pepper plot. Core samples were washed, and viable yellow nutsedge tubers were recorded. Tubers that were firm and creamy white were considered to be viable.

Data on weed control, crop injury, early yield (i.e. sum of yield from the first and second harvests), total marketable fruit yield (i.e. sum of the yield from all the harvests), and viable yellow nutsedge tubers were subjected to statistical analysis. Data were analyzed using PROC GLM in Statistical Analysis Software (SAS version 9.2). Weed control and injury data were transformed with arcsine transformation, and yield data were transformed with log transformation. Data were subjected to one-way ANOVA, and means were compared using Fisher’s protected LSD ($\alpha = 0.05$). Analysis was conducted on transformed data; however, non-transformed means are presented.

In addition to weed control efficacy, economic feasibility of the above-mentioned herbicide programs relative to the standard methyl bromide treatment and weed-free control were evaluated for fresh-market tomato and bell pepper production in the LDPE mulch system. Differential costs of inputs versus returns were calculated for each herbicide program. The method used for economic analysis was based on previous economic studies conducted by Bangarwa et al. (2010) and Sydorovych et al. (2008). Preharvest cost, weed management costs, and harvesting and marketing costs were calculated and the sum of these costs accounted for the total cost of a particular treatment. Preharvest costs included all the inputs (except weed management inputs) required for tomato and bell pepper production. Preharvest cost was calculated based on the vegetable planning budgets developed by the Department of Agricultural Economics, Mississippi State University (Hood et al. 2011), and appropriate adjustments were made in the budget according to the input used in the current experiments. Fertilizer cost was estimated based on the drip-applied fertilizer and added to the cost of lime. Machinery cost was based on implements and tractor used for raise-bed formation, mulch laying, and spraying pesticide. Labor cost was estimated by summation of hand and operator labor.

Input prices were based on the price for vegetable production in 2011. Labor cost was calculated based on \$8.97 and 11.59 hour^{-1} for hand labor and machine operator labor. The fuel cost for machinery was calculated based on \$0.9 L^{-1}. The interest on operating capital was calculated based on annual interest rate of 6%, and calculated for 6 months for tomato or bell pepper production. Weed management cost accounted the cost of LDPE mulch and herbicides for herbicide programs; cost of LDPE mulch and MeBr for the MeBr treatment; cost of LDPE mulch and hand weeding labor for the weed-free control; and cost of LDPE mulch for the non-treated check. Harvesting and marketing cost consisted of harvesting labor, material (buckets and packing boxes), grading and packing labor, hauling, and transportation to the terminal market. For calculation of harvesting and marketing cost a fixed charge of $5.36 per 11.36-kg box of tomato and $4.82 per 13.63-kg carton of bell pepper were estimated.

Gross return for tomato and bell pepper was calculated by adding returns from each grade yield. Returns for each grade of tomato were calculated based on $15.6, 14.1, 13.1, 12.7, and 12.0 per box of jumbo, extra large, large, medium, and small grades of tomato, respectively. Likewise, returns for each grade of bell pepper were based on $18.0, 16.0, and 14.5 per carton of U.S. Fancy, U.S. No. 1, and U.S. No. 2 grades of bell pepper, respectively. Market prices for jumbo, extra large, large, and medium grades of mature green tomato and U.S. Fancy and U.S. No. 1 grades of green bell pepper were obtained from the Dallas Terminal Market report for August 2011 (USDA-AMS 2011). As prices per box for small grade of tomato and U.S. No. 2 grade of bell pepper were not listed in the Dallas Terminal Market report, prices for these grades were assumed to be $12.0 and 14.5 per box for small and U.S. No. 2, respectively, for calculating the returns. Net returns were calculated for each treatment by subtracting total cost from gross return. In addition, net return relative to the MeBr treatment was calculated for each treatment by subtracting net return of MeBr from the respective treatment.

Results and Discussion

There were no treatment-by-year interactions for Palmer amaranth, large crabgrass, and yellow nutsedge control. Similarly, the treatment-by-year interaction was non-significant for viable yellow nutsedge tuber density, crop injury, and marketable yield in tomato and bell pepper. Therefore, data are averaged over years and presented accordingly. Weed control data are presented based on arcsine transformation, and yield data are presented based on Log10 transformation.

Palmer amaranth control. PRE-applied treatments differed ($\alpha = 0.05$) for Palmer amaranth control in LDPE-mulched tomato. Palmer amaranth control from imazosulfuron was marginal from the early weeks, and imazosulfuron applied PRE at 0.112, 0.224, and 0.336 kg ha^{-1} were not comparable to MeBr for Palmer amaranth control at 4 WATP (Table 1). The highest rate of imazosulfuron controlled about half of the Palmer amaranth population compared to the non-treated check at 4 WATP. In previous studies, there are mixed results on the activity of PRE-applied imazosulfuron for broadleaf weed control in bare soil conditions. Riar and Norsworthy (2011) reported 29 to 79% control of hemp sesbania (*Sesbania exaltata* Raf.) with PRE-applied imazosulfuron at 0.224 to 0.336 kg ha^{-1}; whereas, Godara et al. (2012) reported 86 to 89% hemp sesbania control with PRE-applied imazosulfuron at $\geq$0.168 kg ha^{-1} in drill-seeded rice (*Oryza sativa* L.). Felix and Boydston (2010) observed effective control of common lambsquarters, redroot pigweed, and common mallow (*Malva neglecta* L.) with PRE-applied imazosulfuron. In another study, soil temperature and pH were reported as the key factors responsible for imazosulfuron activity in soil (Moricca et al. 2001).

After the POST herbicide applications, Palmer amaranth growth ceased temporarily (for about 1 to 2 wk), but Palmer amaranth control did not increase significantly (Table 1). Moreover, by the time POST herbicides were applied, Palmer amaranth plants were about 15 to 30 cm tall, so POST-applied herbicide mixtures at 4 WATP were not effective against Palmer amaranth. Singh and Singh (2004) reported higher redroot pigweed control from POST-applied trifloxysulfuron applied at the four-leaf than at the six-leaf stage. Norsworthy and Meister (2007) found that POST-applied halosulfuron was ineffective against Palmer amaranth regardless of the plant size, and halosulfuron applied POST on 7.5- and 15-cm-tall Palmer amaranth provided only 28 and 10% control, respectively. At 8 WATP, imazosulfuron herbicide programs controlled ≤20% of Palmer amaranth, and control with MeBr and *S*-metolachlor fb trifloxysulfuron + halosulfuron was 94 and 89%, respectively. In a previous study, POST-applied trifloxysulfuron at 0.008 kg ha^{-1} or halosulfuron at 0.027 kg ha^{-1} applied at 4 WATP controlled Palmer amaranth ≤55 and ≤37%, respectively, at 8 WATP in LDPE-mulched tomato (Bangarwa et al. 2010). In the present experiment, trifloxysulfuron and halosulfuron were tank-mixed; however, there was no increased effect of the POST-applied herbicide mixture for Palmer amaranth control.

Conversely, *S*-metolachlor applied PRE at 1.6 kg ha^{-1} was more effective than imazosulfuron and controlled Palmer amaranth 95%, comparable to MeBr at 4 WATP (Table 1). Bangarwa et al. (2010) reported higher control of Palmer amaranth from PRE-applied *S*-metolachlor than from PRE-applied halosulfuron. Likewise, PRE-applied *S*-metolachlor at 1.14 kg ha^{-1} was most effective in maintaining low broadleaf weed density (2 plants m^{-2}) compared to weed density (>7 plants m^{-2}) with napromide, pebulate, and trifluralin herbicides in direct-seeded tomato (Santos et al. 2008). Application of POST herbicides after *S*-metolachlor maintained Palmer amaranth control through 8 WATP. The effective Palmer amaranth control is because of the PRE efficacy of *S*-metolachlor early in the season fb the POST control of newly emerged Palmer amaranth by trifloxysulfuron plus halosulfuron.

In bell pepper, Palmer amaranth control from the herbicide programs was similar to that in tomato. At 4 WATP, PRE-applied imazosulfuron controlled Palmer amaranth ≤65%, which was lower than the control from MeBr (Table 2). Likewise, after POST herbicide application, Palmer amaranth control in imazosulfuron-treated plots was not as effective as control in MeBr-treated plots. At 8 WATP, Palmer amaranth control was negligible (≤8%) from herbicide programs consisting of PRE-applied imazosulfuron fb POST-applied trifloxysulfuron plus halosulfuron. In a previous study, POST-applied trifloxysulfuron at 0.007 kg ha^{-1} and halosulfuron at 0.024 kg ha^{-1} controlled Palmer amaranth 4 and 33%, respectively, at 8 WATP in polyethylene-mulched bell pepper (Bangarwa 2010). In contrast to the imazosulfuron treatment, PRE-applied *S*-metolachlor provided excellent control of Palmer amaranth (≥96%) at 4 WATP. Furthermore, PRE-applied *S*-metolachlor fb POST-applied trifloxysulfuron plus halosulfuron provided effective season-long Palmer amaranth control. At 8 WATP, Palmer amaranth control (≥90%) from this herbicide combination was comparable to the control (95%) with MeBr in LDPE-mulched bell pepper.

Large crabgrass control. Large crabgrass control differed with the increased rate of PRE-applied imazosulfuron in LDPE-mulched tomato at 4 WATP (Table 3). However, imazosulfuron applied PRE at 0.112, 0.224, and 0.336 kg ha^{-1} did not control large crabgrass effectively in LDPE-mulched tomato production. At 4 WATP, large crabgrass control from the highest rate of imazosulfuron was 72%, which was lower than the 95% control with MeBr. In a previous experiment, imazosulfuron applied PRE fb clomazone preflood showed variable control (51 to 100%) of barnyardgrass at 2 wk after preflood in drill-seeded rice (Riar and Norsworthy 2011).

After the POST application of trifloxysulfuron plus halosulfuron, large crabgrass control percentages increased numerically at 6 WATP than the control at 4 WATP; however, large crabgrass control in PRE-applied imazosulfuron plots was not comparable to the control with MeBr (Table 3). At the last rating, imazosulfuron-containing herbicide programs did not control large crabgrass effectively, and control (<71%) was not comparable with MeBr (91%). Lower control of large crabgrass with POST herbicides is because large crabgrass plants were maybe well-established because large crabgrass plants had tillers and adventitious roots before the

POST herbicides were applied. Chernicky et al. (1984) reported better control of large crabgrass at early growth than at later growth stages. Hartzler and Foy (1983) observed poor large crabgrass control with POST herbicides applied to 8- to 10-cm-tall large crabgrass with adventitious roots in the nodes. In another experiment, halosulfuron applied POST at 0.035 kg ha^{-1} to two- to three-leaf (2.5 to 5 cm) large crabgrass provided little or no reduction in large crabgrass dry weight (Kammler et al. 2010). Moreover, halosulfuron when mixed with sethoxydim, antagonized the efficacy of sethoxydim, and large crabgrass control from the mixture was 76% in pumpkin (*Cucurbita maxima* L.) production (Kammler et al. 2008).

S-metolachlor applied PRE controlled large crabgrass comparable to the control with MeBr in LDPE-mulched tomato (Table 3). At 4 WATP, large crabgrass control was 90% from PRE-applied *S*-metolachlor, a level similar to that with MeBr. This result is in agreement with findings of Bangarwa et al. (2009), who reported 85% large crabgrass control with PRE-applied *S*-metolachlor at 1.6 kg ha^{-1} in plasticulture tomato. Similarly, POST-applied trifloxysulfuron plus halosulfuron maintained large crabgrass control in PRE-applied *S*-metolachlor plots equivalent to the control in MeBr plots at 6 and 8 WATP. At 8 WATP, the *S*-metolachlor-containing herbicide program controlled large crabgrass 88%, similarly, large crabgrass control from MeBr was 91%.

Imazosulfuron applied PRE did not control large crabgrass effectively early in the season in LDPE-mulched bell pepper. At 4 WATP, large crabgrass control from PRE-applied imazosulfuron treatments was ≤72%, and control was lower than with MeBr (Table 4). After the POST herbicides application, large crabgrass control percentage did not increase in bell pepper plots treated with PRE-applied imazosulfuron. Therefore, large crabgrass control with imazosulfuron-containing herbicide programs differed from the MeBr treatment at 6 and 8

WATP. In a previous experiment, POST-applied trifloxysulfuron at 0.004 to 0.015 kg ha^{-1} did not control large crabgrass in cotton (*Gossypium hirsutum* L.) (Richardson et al. 2007). Likewise, POST-applied halosulfuron at 0.026 kg ha^{-1}, evaluated for weed control in potato, provided partial control (66%) of large crabgrass (Boydston 2007).

PRE-applied *S*-metolachlor controlled large crabgrass effectively early in the season, providing 89% control at 4 WATP, which was comparable to MeBr (Table 4). Similarly, Pekarek (2009) observed >88% large crabgrass control with PRE-applied *S*-metolachlor at 1.6 kg ha^{-1} in plasticulture bell pepper, and Bangarwa (2010), observed 74% large crabgrass control with PRE-applied *S*-metolachlor at 1.4 kg ha^{-1} in plasticulture bell pepper. After POST herbicides were applied, the *S*-metolachlor-containing herbicide program maintained large crabgrass control equivalent with MeBr at 6 and 8 WATP. Large crabgrass control with the *S*-metolachlor herbicide program was ≥78% at 8 WATP. In plasticulture bell pepper, POST-applied trifloxysulfuron at 0.007 kg ha^{-1} and halosulfuron at 0.024 kg ha^{-1} provided large crabgrass control of 33 and 4%, respectively, at 8 WATP (Bangarwa 2010). Even the lower activity of trifloxysulfuron and halosulfuron was helpful in maintaining large crabgrass control due to greater activity of *S*-metolachlor on large crabgrass early in the season.

Yellow nutsedge control. PRE-applied imazosulfuron did not control yellow nutsedge effectively in LDPE-mulched tomato. One-way ANOVA illustrated the difference in yellow nutsedge control with the various rates of PRE-applied imazosulfuron; however, imazosulfuron treatments did not control yellow nutsedge comparable to MeBr (Table 5). PRE-applied imazosulfuron even at the highest rate (0.336 kg ha^{-1}) controlled yellow nutsedge 65% at 4 WATP, and control was lower than with MeBr. In another study, PRE-applied imazosulfuron at

0.224 and 0.336 kg ha^{-1} provided variable yellow nutsedge control (22 to 99%) in drill-seeded rice (Riar and Norsworthy 2011). After the POST application of trifloxysulfuron plus halosulfuron, yellow nutsedge control increased in the tomato plots treated with PRE herbicides. Although yellow nutsedge control percentage increased numerically after the POST herbicide application, control was not effective with PRE-applied imazosulfuron. At 8 WATP, yellow nutsedge control from the imazosulfuron-containing herbicide program was ≤77%, which was less than control with MeBr (91%).

Yellow nutsedge control with PRE-applied *S*-metolachlor was lower than with MeBr at 2 and 4 WATP (Table 5). In a similar study, yellow nutsedge control was 67% with the PRE-applied *S*-metolachlor in plasticulture tomato (Bangarwa et al. 2009). After POST application of trifloxysuflruron plus halosulfuron, yellow nutsedge control in plots treated with *S*-metolachlor PRE increased, and control was comparable with MeBr. Yellow nutsedge control with the *S*-metolachlor-containing herbicide program was 92 and 90% at 6 and 8 WATP, respectively. Adock et al. (2008) also reported that PRE-applied *S*-metolachlor fb POST-applied halosulfuron was an effective treatment for yellow nutsedge control in polyethylene-mulched tomato. PRE-applied *S*-metolachlor fb POST-applied halosulfuron reduced 44 and 29% of yellow nutsedge biomass and plastic punctures, respectively, in polyethylene-mulched tomato (Adock et al. 2008).

PRE-applied herbicides were not effective for early-season yellow nutsedge control in LDPE-mulched bell pepper (Table 6). At 4 WATP, yellow nutsedge control from all the PRE-applied treatments was ≤77%, which was lower than with MeBr. Among the PRE-applied treatments, *S*-metolachlor provided higher yellow nutsedge control than PRE-applied imazosulfuron. In a previous study, Bangarwa (2010) observed higher yellow nutsedge control with PRE-applied *S*-metolachlor (69%) than control with PRE-applied halosulfuron (30%) in polyethylene-mulched bell pepper at 4 WATP. Similarly, Adock (2007) reported 78% control of yellow nutsedge in plastic-mulched bell pepper with PRE-applied *S*-metolachlor at 1.4 kg ha^{-1}.

After the application of POST herbicides, yellow nutsedge control increased at 6 and 8 WATP. However, in PRE-applied imazosulfuron plots, yellow nutsedge control after POST herbicide application was lower than control from MeBr. At 8 WATP, imazosulfuron-containing herbicide programs controlled yellow nutsedge ≤73%, providing lower yellow nutsedge control than MeBr (91%). In contrast, after the POST herbicides were applied, yellow nutsedge control in PRE-applied *S*-metolachlor-treated plots increased to an effective level. At 8 WATP, yellow nutsedge control with the *S*-metolachlor-containing herbicide program was 90%, and equivalent to MeBr.

Viable yellow nutsedge tubers. Viable yellow nutsedge tuber density did not differ among herbicide programs and MeBr treatment in LDPE-mulched tomato (Table 7). Later in the season, imazosulfuron-treated plots were covered densely with Palmer amaranth plants that were greater than 2 m tall with widespread branches and dense foliage. Because of the height and wider canopy, Palmer amaranth completely overtook yellow nutsedge plants reducing plant stand and growth. Greater interference of Palmer amaranth with yellow nutsedge might be the reason for lower tuber production in plots treated with imazosulfuron herbicide programs. Shading response of yellow nutsedge was studied by Patterson (1982), who concluded that yellow nutsedge leaf dry weight, total dry weight, number of shoots, and number of tubers decreased from 35 to 6 g, 69 to 9 g, 33 to 10 shoots, and 75 to 9 tubers, respectively, when yellow nutsedge was transferred from full light condition (at 30 d after planting) to 85% shade in the later season.

Similarly, Santos et al. (1997) reported a linear relationship between shading and reduction in shoot and tuber dry weight of yellow nutsedge.

In plots treated with the *S*-metolachlor-containing herbicide program, yellow nutsedge tubers were fewer because of the effective control of yellow nutsedge (Table 6). At the end of the season, PRE-applied *S*-metolachlor fb POST-applied trifloxysulfuron plus halosulfuron reduced viable yellow nutsedge tuber density by 77% compared to the tuber density in the non-treated check (Table 7). Kelly and Renner (2002) have reported >80% reduction in yellow nutsedge tuber density with POST-applied halosulfuron at 0.035 kg ha^{-1} (Kelly and Renner 2002).

Yellow nutsedge tuber density was significantly lower in bell pepper plots treated with herbicide programs compared to tuber density in non-treated control plots (Table 7). However, none of the herbicide programs reduced yellow nutsedge tubers equivalent to MeBr in LDPE-mulched bell pepper. Among herbicide programs, the *S*-metolachlor-containing herbicide program provided numerically fewer viable yellow nutsedge tubers (100 tubers m^{-2}) than in plots treated with imazosulfuron herbicide programs (≥119 tubers m^{-2}). Moreover, yellow nutsedge tuber density was reduced by 1/3 with *S*-metolachlor herbicide program compared to the tuber number in non-treated plots.

Tomato and bell pepper injury. Among PRE-applied treatments, only imazosulfuron at 0.336 kg ha^{-1} injured tomato and bell pepper (Table 8). At 2 WATP, imazosulfuron at the highest rate caused 11 and 10% injury to tomato and bell pepper, respectively, but injury was transient and the crops recovered from injury. At 4 WATP, there was no injury in tomato and bell pepper from PRE-applied imazosulfuron. Pekarek (2009) reported an increase in height reduction and injury in bell pepper with increasing rate of POST-applied imazosulfuron in a greenhouse experiment, and injury ranged from 12 to 27% at 4 WAT. In the same study, imazosulfuron applied POST in a field experiment showed <10% and <5% bell pepper injury in early and late ratings. PRE-applied *S*-metolachlor at 1.6 kg ha^{-1} was safe for LDPE-mulched tomato and bell pepper. In another study, *S*-metolachlor applied PRE at 1.8 kg ha^{-1} in combination with a Brassicaceae cover crop injured bell pepper grown in a plasticulture system about 15% (Pekarek 2009). This injury was attributed mainly to the volatile compounds released from the Brassicaceae crop rather than injury from *S*-metolachlor.

After POST application of trifloxysulfuron plus halosulfuron, injury was prominent in tomato and bell pepper and was ≥17% and ≥13%, respectively, at 6 WATP (Table 8). In a previous study, tomato injury was about 6% with POST-applied trifloxysulfuron or halosulfuron in the plasticulture system (Bangarwa et al. 2009). Likewise, the POST-directed application of trifloxysulfuron or halosulfuron caused 9% injury in plasticulture bell pepper (Bangarwa 2010). In our experiment, higher injury in tomato and bell pepper was observed because trifloxysulfuron and halosulfuron were applied in mixture. At 8 WATP, imazosulfuron- or *S*-metolachlor-containing herbicide programs caused injury ≤8 and ≤9% for tomato and bell pepper, respectively.

Tomato yield. The imazosulfuron-containing herbicide programs differed from MeBr for early-season tomato yield. Early-season tomato yield from plots treated with imazosulfuron herbicide program was less than 50% of the early-season yield in plots treated with MeBr (Table 9). In contrast, early-season yield with the *S*-metolachlor herbicide program was equivalent to MeBr treatment. Although there was tomato injury after the POST application of trifloxysulfuron plus halosulfuron (Table 8), injury did not affect early-season tomato yield in PRE-applied *S*-metolachlor plots (Table 9). Early-season yield contributed 23% of the total marketable yield in plots treated with the *S*-metolachlor herbicide program.

Herbicide programs consisting of PRE-applied imazosulfuron fb POST-applied herbicides differed from MeBr treatment for total marketable tomato yield. Marketable tomato yield in the imazosulfuron herbicide program treated plots was lower than in plots treated with MeBr (Table 10). Likewise, marketable tomato yield did not increase with increased rate of imazosulfuron because of similar weed control with different rates. In a previous study, Dittmar et al. (2010) reported significant yield loss (in a linear fashion) in relation to increased rate of imazosulfuron when applied POST in watermelon (*Citrullus lanatus* Thunb.). Imazosulfuron-treated tomato plots also differed with MeBr treated plots for USDA grade tomato fruit yield. The imazosulfuron herbicide program was ineffective for season-long control of Palmer amaranth (Table 1), large crabgrass (Table 3), and yellow nutsedge (Table 5). Moreover, Palmer amaranth control was negligible and there was greater yield loss in the imazosulfuron-treated tomato plots compared to *S*-metolachlor, MeBr, and weed-free control plots (Table 10).

Herbicide programs consisting of PRE-applied *S*-metolachlor and POST-applied trifloxysulfuron plus halosulfuron yielded total marketable tomato fruit comparable to that treated with MeBr. Among the different grade tomato fruit, jumbo grade fruit yield contributed the highest percentage (38%) of the total marketable yield in the *S*-metolachlor-treated plots (Table 10). Likewise, extra large, large, medium, and small grade tomato yields contributed 19, 17, 13, and 13% of the total marketable tomato yield. The total marketable tomato yield (23.1 ton ha^{-1}) in *S*-metolachlor-treated plots was 2.34 times greater than yield (9.8 ton ha^{-1}) in non-treated plots. Bangarwa et al. (2009) reported a similar result for tomato yield with PRE-applied

S-metolachlor in plasticulture tomato, where he observed 2.79 times greater yield in tomato plots treated with *S*-metolachlor at 1.6 kg ha^{-1} compared to the yield in non-treated check plots. Likewise, tomato treated with POST-applied trifloxysulfuron at 0.007 kg ha^{-1} or halosulfuron at 0.04 kg ha^{-1} yielded total marketable fruit 98% higher than non-treated plots (Jennings 2010).

Bell pepper yield. All the herbicide programs differed (at α=0.05) from MeBr for early-season bell pepper yield. Bell pepper plots treated with PRE-applied imazosulfuron or *S*-metolachlor fb POST-applied trifloxysulfuron plus halosulfuron had lower early-season yield than plots treated with MeBr (Table 11). In imazosulfuron, *S*-metolachlor, and MeBr treated bell pepper plots early-season yield contributed ≥30, 12, and 21%, respectively, of total marketable yield.

Imazosulfuron-treated bell pepper plots yielded lower marketable yield compared to *S*-metolachlor-treated plots (Table 12). Moreover, total marketable yield from bell pepper plots treated with the *S*-metolachlor herbicide program was equivalent to the total marketable yield in plots treated with MeBr (Table 12). At end-of- season, total marketable yield in bell pepper plots treated with the *S*-metolachlor herbicide program was 29.9 ton ha^{-1}, which was 7.8 times greater than yield in the non-treated check plots. For the total marketable yield, U.S. Fancy, U.S. No.1, and U.S. No. 2 bell paper grades contributed 29, 27, and 44%, respectively.

Economic evaluation for tomato and bell pepper production.

Preharvest cost. Costs of all the variable inputs required for tomato production were included in the preharvest cost (Table 13). Although weed management cost is a part of preharvest cost, weed management cost are presented separately in the later discussion. Preharvest cost (\$11,349.65 ha^{-1}) was the summation of preharvest variable costs and preharvest fixed costs.

Preharvest variable cost included the inputs that were used for a single growing season (from crop planting to harvesting) and consisted of the cost for mulch cleanup and field preparation, lime and fertilizer, seed and transplant, drip tape, labor, irrigation, pesticides, stakes and string, repair and maintenance, and interest on operating capital. For tomato production, total preharvest variable cost was estimated as \$9,895.77 ha^{-1} and this amount is equal for all treatments. Preharvest fixed cost includes cost of those inputs that can be used for multiple seasons. Preharvest fixed cost is the summation of costs required for possessing implements, tractors, and an irrigation setup necessary for the production. In tomato production, the estimated preharvest fixed cost was \$1,453.88 ha^{-1}, and this cost is similar for all treatments.

Similarly, preharvest cost (\$11,294.88 ha^{-1}) accounted for all the variable and fixed inputs necessary for bell pepper production (Table 16). Total preharvest variable cost was based on mulch cleanup and field preparation, lime and fertilizer, transplant, drip tape, labor, irrigation, pesticides, repair and maintenance, and interest on operating capital. In bell pepper production, staking and tying is not a common production practice; therefore, cost of these inputs is not included in variable cost. The total preharvest variable cost was \$10,131.81 ha^{-1} for a treatment, and this cost was equal for all treatments. Likewise, preharvest fixed costs were amount for ownership of implements, tractor, and irrigation system and accounted for a total cost of \$1163.07 ha^{-1}.

Weed management cost. Weed management cost is the summation of various inputs that are directly related to weed control and are presented accordingly for tomato production (Table 14). For herbicide programs, weed management cost is the sum of LDPE-mulch and herbicides applied for weed control. The cost of LDPE mulch, \$720.25 ha^{-1} is a common cost for all treatments irrespective of the weed control method. The total weed management cost for the herbicide program containing PRE-applied imazosulfuron fb POST-applied trifloxysulfuron + halosulfuron ranged from \$831.65 to 877.91 ha^{-1}. Likewise, weed management cost for the *S*-metolachlor-containing herbicide program was \$858.94 ha^{-1}. MeBr treatment cost was highest among treatments, with total weed management cost of \$5,782.45 ha^{-1}. The cost for the MeBr treatement was \$5,062.20 ha^{-1} (MeBr cost \$12.98 kg^{-1}). In the weed-free control, hand-weeding time was recorded as 225 hrs ha^{-1} and labor cost was calculated (labor charge \$8.97 hr^{-1}) to be \$2,018.87 ha^{-1}. Labor cost was added to the cost of LDPE mulch to estimate the total weed management cost of \$2,739.12 ha^{-1} in the weed-free control. In the non-treated control, weed management cost was the cost of LDPE mulch alone.

Cost of LDPE mulch, herbicides, and MeBr in bell pepper production (Table 17) was similar to the cost incurred in tomato (Table 14). Therefore, weed management costs for herbicide programs, MeBr treatment, and non-treated control in bell pepper were similar to the respective costs in tomato production. In bell pepper, hand-weeding time in the weed-free control plots was 292.02 hrs ha^{-1}, and the hand-weeding cost was \$2,619.41 ha^{-1} (labor charge of \$8.97 hr^{-1}) (Table 17). Therefore, weed management cost for the weed-free control was estimated to be \$3,339.66 ha^{-1}.

Harvesting and marketing cost. Harvesting and marketing cost for tomato production is calculated based on the total yield irrespective of the grades (Table 15). As a fixed charge of \$5.36 per box (weighed 11.36 kg per box) of tomato was estimated for calculating harvesting and marketing cost, harvesting and marketing cost is higher for the treatments that produced higher yield. In tomato production, the weed-free control, MeBr treatment, and the *S*-

metolachlor-containing herbicide program yielded higher, with harvesting and marketing costs of \$13,624.17, 13,396.18, and 9,945.71 ha^{-1}, respectively, whereas imazosulfuron-treated plots and non-treated plots yielded lower, with harvesting and marketing cost of ≤\$5,593.81 ha^{-1}.

In bell pepper, harvesting and marketing costs were estimated based on a fixed charge of 4.82 per carton (weighed 13.63 kg per carton). The weed-free control, MeBr treatment, and *S*-metolachlor-containing herbicide program yielded higher and had harvesting and marketing costs of \$14,297.93, 11,723.96, and 9,630.80 ha^{-1}, respectively. On the other hand, bell pepper yield was lower in the plots treated with the imazosulfuron-containing herbicide program and non-treated check. Therefore, total harvesting and marketing cost for imazosulfuron herbicide program and non-treated check was ≤\$2,238.12 ha^{-1} (Table 18).

Gross returns and net returns. Gross returns in tomato production were estimated by adding returns from jumbo, extra large, large, medium, and small grades. Among the different grades of tomato, returns were highest from jumbo grade (data not shown) because this category yield contributed the highest percentage of total yield. Tomato plots treated with the imazosulfuron-containing herbicide programs provided gross returns ranging from \$8,746 to 14,543.60 ha^{-1} (Table 15). With these gross returns, there was loss of \$3277.76 to 6916.96 ha^{-1} on net return with the imazosulfuron-containing programs. Furthermore, losses in net return relative to MeBr treatment ranged from \$7,707.88 to 11,347.08 ha^{-1} for imazosulfuron herbicide programs. Gross returns were estimated to be \$35,668.80, 34,958.40, and 25,912.80 for the weed-free control, MeBr treatment, and *S*-metolachlor-containing herbicide program, respectively. Moreover, there was a gain in net returns from these treatments, and they were profitable treatments. Hand-weeded plots had the highest net return with \$7,955.86 ha^{-1}. Likewise, net returns were

$4,430.11, and 3,758.50 ha^{-1} for MeBr and *S*-metolachlor containing herbicide program treated plots, respectively. However, only the weed-free control plot showed a gain in net return ($3,525.75 ha^{-1}) relative to the MeBr treatment. With the *S*-metolachlor herbicide program, there was a loss of $671.61 ha^{-1} on net return relative to the MeBr treatment.

Returns from U.S. Fancy, U.S. No. 1, and U.S. No. 2 grades were totaled to estimate gross from each treatment in bell pepper production. Among the different grades of bell pepper, U.S. No. 2 grade contributed the highest amount for gross return (data not shown). Gross return from the imazosulfuron herbicide program ranged from $4,266.67 to $7,100 ha^{-1} (Table 18). Because of ineffective weed control from imazosulfuron herbicide program there was a loss of $7,300.25 to $9,184.09 ha^{-1} in bell pepper production. Similarly, loss in net returns relative to MeBr was estimated to be $17,038.96 to $18,922.80 with the imazosulfuron herbicide program. The *S*-metolachlor herbicide program provided higher gross return ($31,696.67 ha^{-1}) compared to the imazosulfuron herbicide program. In addition, there was a gain of $9,912.05 ha^{-1} in net return from the *S*-metolachlor herbicide program. Net return from the *S*-metolachlor herbicide program was higher relative to the net return from the MeBr treatment by $173.34 ha^{-1}. However, the highest gross return of $46,913.33, net return of 17,980.86, and net return relative to MeBr of $8,242.15, respectively, was obtained from the weed-free control.

In conclusion, PRE-applied imazosulfuron did not provide good weed control in the early weeks. Weeds emerged in the early weeks and established rapidly in the imazosulfuron-treated plots because of favorable growing conditions in the polyethylene mulch production system. Because weeds grew so rapidly, they were too large for POST-applied trifloxysulfuron plus halosulfuron to control in the imazosulfuron-treated plots. This experiment demonstrates that a PRE-applied imazosulfuron herbicide program is not an effective alternative to MeBr for weed management in LDPE-mulched tomato and bell pepper. However, PRE-applied *S*-metolachlor fb POST-applied trifloxysulfuron plus halosulfuron is an effective alternative for Palmer amaranth, large crabgrass, and yellow nutsedge control in LDPE-mulched tomato and bell pepper production. Moreover, the *S*-metolachlor program provided total marketable tomato and bell pepper yield equivalent to the MeBr treatment.

Economic evaluation demonstrated that hand-weeding is the best alternative to MeBr for weed management in LDPE-mulched tomato and bell pepper production. However, the hand-weeding method is not a practical option for large acreage tomato and bell pepper production because of labor unavailability. In this regard, herbicide application could be a feasible option for weed control in commercial production. Among herbicide programs, the imazosulfuron herbicide program was not a profitable weed management option in LDPE-mulched tomato and bell pepper production. However, the *S*-metolchlor program added a significant amount of net return in tomato production. Similarly, it added a net return and net return relative to MeBr in LDPE-mulched bell pepper production. Therefore, from this experiment, PRE-applied *S*-metolachlor fb POST-applied trifloxysulfuron plus halosulfuron is suggested as a MeBr alternative for weed management in LDPE-mulched tomato and bell pepper production.

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Table 1. Effect of methyl bromide plus chloropicrin and PRE-applied imazosulfuron and *S*-metolachlor fb POST-applied trifloxysulfuron plus halosulfuron on Palmer amaranth control in tomato, averaged over 2010 and 2011.

			Palmer amaranth control[a]			
Treatment	Rate	Timing[b]	2 WATP[c]	4 WATP	6 WATP	8 WATP
	kg ai ha^{-1}		----------%			%----------
Imazosulfuron fb	0.112	PRE	82 b	40 c	43 b	14 bc
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
Imazosulfuron fb	0.224	PRE	82 b	46 c	47 b	8 c
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
Imazosulfuron fb	0.336	PRE	88 b	56 b	55 b	19 b
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
S-metolachlor fb	1.6	PRE	96 a	95 a	91 a	89 a
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
Methyl bromide +	261	PRE	99 a	97 a	96 a	94 a
chloropicrin	129					

[a] Treatment means within a column followed by the same letter are not different based on Fisher's protected LSD at α = 0.05. Data are presented as non-transformed means but LSD letters are based on acrsine transformation.

[b] PRE herbicides applied 3 d before transplanting, and POST treatment applied at 4 wk after transplanting tomato.

[c] Palmer amaranth did not emerge until 2 WATP in 2010; therefore, Palmer amaranth control at 2 WATP is only for 2011.

Table 2. Effect of PRE-applied imazosulfuron and *S*-metolachlor fb POST-applied trifloxysulfuron plus halosulfuron, and methyl bromide plus chloropicrin on Palmer amaranth control in bell pepper, averaged over 2010 and 2011.

			Palmer amaranth control[a]			
Treatment	Rate	Timing[b]	2 WATP[c]	4 WATP	6 WATP	8 WATP
	kg ai ha^{-1}		%			
Imazosulfuron fb	0.112	PRE	82 b	56 c	22 b	3 c
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
Imazosulfuron fb	0.224	PRE	81 b	52 c	25 b	5 bc
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
Imazosulfuron fb	0.336	PRE	88 b	65 b	29 b	8 b
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
S-metolachlor fb	1.6	PRE	100 a	96 a	90 a	90 a
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
Methyl bromide +	261	PRE	99 a	98 a	95 a	95 a
chloropicrin	129					

[a] Treatment means within a column followed by the same letter are not different based on Fisher's protected LSD at α = 0.05. Mean separation based on arcsine transformed data.

[b] PRE herbicides applied at 3 d before transplanting, and POST treatment applied at 4 wk after transplanting bell pepper.

[c] Palmer amaranth did not emerge until 2 WATP in 2010; therefore, Palmer amaranth control at 2 WATP is only for 2011.

Table 3. Effect of PRE-applied imazosulfuron and *S*-metolachlor fb POST-applied trifloxysulfuron plus halosulfuron, and methyl bromide plus chloropicrin on large crabgrass control in tomato, averaged over 2010 and 2011.

			Large crabgrass control[a]			
Treatment	Rate	Timing [b]	2 WATP[c]	4 WATP	6 WATP	8 WATP
	kg ai ha^{-1}		%			
Imazosulfuron fb	0.112	PRE	85 b	59 c	67 c	53 c
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
Imazosulfuron fb	0.224	PRE	85 b	63 bc	73 bc	64 bc
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
Imazosulfuron fb	0.336	PRE	91 b	72 b	82 b	71 b
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
S-metolachlor fb	1.6	PRE	97 a	90 a	94 a	88 a
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
Methyl bromide +	261	PRE	98 a	95 a	95 a	91 a
chloropicrin	129					

[a] Treatment means within a column followed by the same letter are not different based on Fisher's protected LSD at α = 0.05. Mean separation based on arcsine transformed data.

[b] PRE herbicides applied at 3 d before transplanting, and POST treatment applied at 4 wk after transplanting tomato.

[c] Large crabgrass did not emerge until 2 WATP in 2010; therefore, large crabgrass control at 2 WATP is only for 2011.

Table 4. Effect of PRE-applied imazosulfuron and *S*-metolachlor fb POST-applied trifloxysulfuron plus halosulfuron, and methyl bromide plus chloropicrin on large crabgrass control in bell pepper, averaged over 2010 and 2011.

			Large crabgrass control[a]			
Treatment	Rate	Timing[b]	2 WATP[c]	4 WATP	6 WATP	8 WATP
	kg ai ha^{-1}		---%			
Imazosulfuron fb	0.112	PRE	85 b	46 c	36 c	22 c
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
Imazosulfuron fb	0.224	PRE	86 b	62 bc	45 bc	24 c
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
Imazosulfuron fb	0.336	PRE	90 b	72 b	56 b	49 b
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
S-metolachlor fb	1.6	PRE	99 a	89 a	85 a	78 a
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
Methyl bromide +	261	PRE	100 a	95 a	92 a	89 a
chloropicrin	129					

[a] Treatment means within a column followed by the same letter are not different based on Fisher's protected LSD at α = 0.05. Mean separation based on arcsine transformed data.

[b] PRE herbicides applied at 3 d before transplanting, and POST treatment applied at 4 wk after transplanting bell pepper.

[c] Large crabgrass did not emerge until 2 WATP in 2010; therefore, Palmer amaranth control at 2 WATP is only for 2011.

Table 5. Effect of PRE-applied imazosulfuron and *S*-metolachlor fb POST-applied trifloxysulfuron plus halosulfuron, and methyl bromide plus chloropicrin on yellow nutsedge control in tomato, averaged over 2010 and 2011.

Treatment	Rate	Timing[b]	Yellow nutsedge control[a]			
			2 WATP	4 WATP	6 WATP	8 WATP
	kg ai ha^{-1}		%			
Imazosulfuron fb	0.112	PRE	60 d	45 e	61 d	66 c
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
Imazosulfuron fb	0.224	PRE	64 d	52 d	67 c	71 c
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
Imazosulfuron fb	0.336	PRE	78 c	65 c	75 b	77 b
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
S-metolachlor fb	1.6	PRE	91 b	84 b	92 a	90 a
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
Methyl bromide +	261	PRE	96 a	93 a	92 a	91 a
chloropicrin	129					

[a] Treatment means within a column followed by the same letter are not different based on Fisher's protected LSD at α = 0.05. Mean separation based on arcsine transformed data.

[b] PRE herbicides applied at 3 d before transplanting, and POST treatments applied at 4 wk after transplanting tomato.

Table 6. Effect of PRE-applied imazosulfuron and *S*-metolachlor fb POST-applied trifloxysulfuron plus halosulfuron, and methyl bromide plus chloropicrin on yellow nutsedge control in bell pepper, averaged over 2010 and 2011.

			Yellow nutsedge control[a]			
Treatment	Rate	Timing[b]	2 WATP	4 WATP	6 WATP	8 WATP
	kg ai ha^{-1}		----------------	----------------	% ----------------	----------------
Imazosulfuron fb	0.112	PRE	61 d	43 e	56 c	62 c
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
Imazosulfuron fb	0.224	PRE	63 d	52 d	61 c	68 b
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
Imazosulfuron fb	0.336	PRE	73 c	58 c	69 b	73 b
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
S-metolachlor fb	1.6	PRE	92 b	77 b	90 a	90 a
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
Methyl bromide +	261	PRE	95 a	93 a	92 a	91 a
chloropicrin	129					

[a] Treatment means within a column followed by the same letter are not different based on Fisher's protected LSD at α = 0.05. Mean separation based on arcsine transformed data.

[b] PRE herbicides applied at 3 d before transplanting, and POST treatments applied at 4 wk after transplanting bell pepper.

Table 7. Effect of PRE-applied imazosulfuron and *S*-metolachlor fb POST-applied trifloxysulfuron plus halosulfuron, and methyl bromide plus chloropicrin on viable yellow nutsedge tuber density in tomato and bell pepper, averaged over 2010 and 2011.

			Tuber density[ab]	
Soil fumigants	Rate	Timings[c]	Tomato	Bell pepper
	kg ai ha^{-1}		----------------------tubers m^{-2}	--------------------------
Imazosulfuron fb	0.112	PRE	60 b	228 b
trifloxysulfuron +	0.008	POST		
halosulfuron	0.027			
Imazosulfuron fb	0.224	PRE	49 bc	140 c
trifloxysulfuron +	0.008	POST		
halosulfuron	0.027			
Imazosulfuron fb	0.336	PRE	43 bc	119 c
trifloxysulfuron +	0.008	POST		
halosulfuron	0.027			
S-metolachlor fb	1.6	PRE	41 bc	100 c
trifloxysulfuron +	0.008	POST		
halosulfuron	0.027			
Methyl bromide +	261	PRE	29 c	55 d
chloropicrin	129			
Non-treated check	-	-	177 a	302 a

[a] Treatment means within a column followed by the same letter are not different based on Fisher's protected LSD at α = 0.05. Mean separation based square root transformation.

[b] Tuber density (tubers m^{-2}) determined from 5 soil cores (0.1-m diam. by 0.15-m depth) pulled from each tomato and bell pepper plot.

[c] PRE herbicides applied at 3 d before transplanting, and POST treatments applied at 4 wk after transplanting bell pepper.

Table 8. Effect of PRE-applied imazosulfuron and *S*-metolachlor fb POST-applied trifloxysulfuron plus halosulfuron, and methyl bromide plus chloropicrin on tomato and bell pepper injury, averaged over 2010 and 2011.

			Injury[a]					
			Tomato			Bell Pepper		
Treatment	Rate	Timing[b]	2 WATP	6 WATP	8WATP	2 WATP	6 WATP	8WATP
	kg ai ha^{-1}		-----%					-----
Imazosulfuron fb	0.112	PRE	0 b	18 a	8 a	0 b	14 ab	6 a
trifloxysulfuron +	0.008	POST						
halosulfuron	0.027							
Imazosulfuron fb	0.224	PRE	0 b	17 a	7 a	0 b	13 b	5 a
trifloxysulfuron +	0.008	POST						
halosulfuron	0.027							
Imazosulfuron fb	0.336	PRE	11 a	19 a	8 a	10 a	19 a	9 a
trifloxysulfuron +	0.008	POST						
halosulfuron	0.027							
S-metolachlor fb	1.6	PRE	0 b	19 a	8 a	0 b	17 ab	8 a
trifloxysulfuron +	0.008	POST						
halosulfuron	0.027							

[a] Treatment means within a column followed by the same letter are not different based on Fisher's protected LSD at α = 0.05. Mean separation based on arcsine transformed data.

[b] PRE herbicides applied at 3 d before transplanting, and POST herbicides applied at 4 wk after transplanting tomato.

Table 9. Effect of PRE-applied imazosulfuron and *S*-metolachlor fb POST-applied trifloxysulfuron plus halosulfuron, and methyl bromide plus chloropicrin on early-season tomato yield, averaged over 2010 and 2011.

			Tomato yield[ab]					
Treatment	Rate	Timing[c]	Jumbo	Extra large	Large	Medium	Small	Total yield [d]
	kg ai ha^{-1}		------------------------------------- ton ha^{-1}	-------------------------------------				
Imazosulfuron fb	0.112	PRE	0.6 b	0.4 c	0.5 bcd	0.4 a	0.3 a	2.2 d
trifloxysulfuron +	0.008	POST						
halosulfuron	0.027							
Imazosulfuron fb	0.224	PRE	0.7 ab	0.4 c	0.3 cd	0.5 a	0.6 a	2.6 bcd
trifloxysulfuron +	0.008	POST						
halosulfuron	0.027							
Imazosulfuron fb	0.336	PRE	0.6 b	0.4 bc	0.4 bcd	0.5 a	0.3 a	2.2 d
trifloxysulfuron +	0.008	POST						
halosulfuron	0.027							
S-metolachlor fb	1.6	PRE	1.6 a	0.9 ab	0.9 abc	1.1 a	0.7 a	5.2 ab
trifloxysulfuron +	0.008	POST						
halosulfuron	0.027							
Methyl bromide +	261	PRE	1.4 ab	0.9 ab	1.0 ab	1.0 a	0.8 a	5.1 abc
chloropicrin	129							
Weed-free control	-	-	1.5 ab	0.9 a	1.2 a	1.0 a	0.7 a	5.3 a
Non-treated control	-	-	0.7 ab	0.3 c	0.2 d	0.5 a	0.7 a	2.4 cd

[a] Treatment means within a column followed by the same letter are not different based on Fisher's protected LSD at $\alpha = 0.05$. Mean separation based on Log10 transformation.

[b] Early-season tomato yield according to the USDA grade and the total early yield.

[c] PRE herbicides applied at 3 d before transplanting, and POST herbicides applied at 4 wk after transplanting tomato.

[d] Total yield determined by summation of first and second harvests for 2010 and 2011, respectively.

Table 10. Effect of PRE-applied imazosulfuron and *S*-metolachlor fb POST-applied trifloxysulfuron plus halosulfuron, and methyl bromide plus chloropicrin on marketable tomato yield, averaged over 2010 and 2011.

			Tomato yield[ab]					
Treatment	Rate	Timing[c]	Jumbo	Extra large	Large	Medium	Small	Total yield [d]
	kg ai ha^{-1}		ton ha^{-1}					
Imazosulfuron fb	0.112	PRE	4.4 b	2.3 b	2.0 c	1.6 b	1.6 b	11.9 b
trifloxysulfuron +	0.008	POST						
halosulfuron	0.027							
Imazosulfuron fb	0.224	PRE	2.3 b	1.2 b	1.2 c	1.6 b	1.7 b	8.1 b
trifloxysulfuron +	0.008	POST						
halosulfuron	0.027							
Imazosulfuron fb	0.336	PRE	4.6 b	2.5 b	2.4 bc	1.8 b	1.7 b	13.0 b
trifloxysulfuron +	0.008	POST						
halosulfuron	0.027							
S-metolachlor fb	1.6	PRE	8.6 a	4.4 a	3.8 ab	3.1 a	3.2 a	23.1 a
trifloxysulfuron +	0.008	POST						
halosulfuron	0.027							
Methyl bromide +	261	PRE	11.8 a	5.9 a	5.0 a	4.6 a	3.8 a	31.1 a
chloropicrin	129							
Weed free control	-	-	12.5 a	6.2 a	5.2 a	3.9 a	3.8 a	31.6 a
Non-treated control	-	-	2.9 b	1.6 b	1.7 c	1.5 b	2.0 b	9.8 b

[a] Treatment means within a column followed by the same letter are not different based on Fisher's protected LSD at $\alpha = 0.05$. Mean separation based on Log10 transformation.

[b] Marketable tomato yield according to the USDA grade and the total early yield.

[c] PRE herbicides applied at 3 d before transplanting, and POST herbicides applied at 4 wk after transplanting tomato.

[d] Total yield determined by summation of six and five harvests for 2010 and 2011, respectively.

Table 11. Effect of PRE-applied imazosulfuron and *S*-metolachlor fb POST-applied trifloxysulfuron plus halosulfuron, and methyl bromide plus chloropicrin on early-season bell pepper yield, averaged over 2010 and 2011.

			Bell pepper yield[ab]			
Treatment	Rate	Timing[c]	U.S. Fancy	U.S. No. 1	U.S. No. 2	Total yield [d]
	kg ai ha^{-1}		ton ha^{-1}			
Imazosulfuron fb	0.112	PRE	0.5 c	1.0 cd	1.5 bc	3.1 b
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
Imazosulfuron fb	0.224	PRE	0.3 c	0.4 cd	0.6 d	1.3 c
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
Imazosulfuron fb	0.336	PRE	0.3 c	0.8 cd	1.0 cd	2.1 bc
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
S-metolachlor fb	1.6	PRE	0.8 c	1.4 bc	1.3 cd	3.5 b
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
Methyl bromide +	261	PRE	2.6 b	2.4 ab	2.8 ab	7.7 a
chloropicrin	129					
Weed-free control	-	-	3.8 a	3.0 a	3.4 a	10.2 a
Non-treated control	-	-	0.3 c	0.3 d	0.8 cd	1.4 bc

[a] Treatment means within a column followed by the same letter are not different based on Fisher's protected LSD at α = 0.05. Mean separation based on Log10 transformation.

[b] Early-season bell pepper yield according to the USDA grade and the total early yield.

[c] PRE herbicides applied at 3 d before transplanting, and POST herbicides applied at 4 wk after transplanting bell pepper.

[d] Total yield determined by summation of first and second harvests for 2010 and 2011, respectively.

Table 12. Effect of PRE-applied imazosulfuron and *S*-metolachlor fb POST-applied trifloxysulfuron plus halosulfuron, and methyl bromide plus chloropicrin on marketable bell pepper yield, averaged over 2010 and 2011.

			Bell pepper yield[ab]			
Treatment	Rate	Timing[c]	U.S. Fancy	U.S. No. 1	U.S. No. 2	Total yield [d]
	kg ai ha^{-1}		---------------------------------------	ton ha^{-1}	------------------------------	
Imazosulfuron fb	0.112	PRE	1.1 c	1.8 b	3.9 b	6.8 bc
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
Imazosulfuron fb	0.224	PRE	1.0 c	0.7 b	2.4 b	4.0 c
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
Imazosulfuron fb	0.336	PRE	1.2 c	1.5 b	4.2 b	7.0 b
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
S-metolachlor fb	1.6	PRE	8.5 ab	8.1 a	13.3 a	29.9 a
trifloxysulfuron +	0.008	POST				
halosulfuron	0.027					
Methyl bromide +	261	PRE	10.6 a	8.8 a	17.0 a	36.4 a
chloropicrin	129					
Weed-free control	-	-	12.1 a	11.7 a	20.6 a	44.4 a
Non-treated control	-	-	1.1 c	0.8 b	1.9 b	3.8 c

[a] Treatment means within a column followed by the same letter are not different based on Fisher's protected LSD at α = 0.05. Mean separation based on Log10 transformation.

[b] Marketable bell pepper yield according to the USDA grade and the total early yield.

[c] PRE herbicides applied at 3 d before transplanting, and POST herbicides applied at 4 wk after transplanting bell pepper.

[d] Total yield determined by summation of four harvests for 2010 and 2011, respectively.

Table 13. Estimated preharvest cost based on input for tomato production in low-density polyethylene mulched system[a].

Production inputs[b]	Cost
	---$ ha^{-1}---
A. Variable costs:	
Mulch cleanup	332.33
Lime and fertilizer	809.83
Machinery (raise bed, mulch laying, spraying pesticide)	262.50
Fuel (Diesel)	197.84
Drip tape	435.00
Seed/transplant	1,220.15
Labor	
Hand labor (transplanting, fertigation, staking, tying, unallocated labor)	587.25
Operator labor (tractor, implement)	411.43
Irrigation	1,111.65
Insecticide	623.15
Fungicide	431.13
Herbicide for row middles	72.57
Stakes and string	2,913.60
Repair and Maintenance	
Implements	182.40
Tractor	16.72
Interest on operating capital	288.22
Total preharvest variable cost (A)	9,895.77
B. Fixed costs:	
Implements	339.47
Tractor	102.55
Irrigation setup	1,011.86
Total preharvest fixed cost (B)	1,453.88
Total preharvest cost (A + B)	11,349.65

[a] Preharvest cost includes all the inputs cost except weed management and marketing and harvesting cost.

[b] Preharvest costs consist inputs required for plasticulture tomato and production input are adopted from traditional vegetables 2012 planning budgets developed by Department of Agricultural Economics at Mississippi State University.

Table 14. Estimated weed management cost for PRE-applied imazosulfuron and *S*-metolachlor fb POST-applied trifloxysulfuron plus halosulfuron, methyl bromide, and weed-free control in low-density polyethylene mulched tomato production.

		Cost[a]			
Treatments	Rate	Chemical[b]	LDPE mulch[c]	Labor[d]	Total[e]
	kg ai ha^{-1}	$ ha^{-1}			
Imazosulfuron fb	0.112	23.12	720.25	0	831.65
trifloxysulfuron +	0.008	37.64			
halosulfuron	0.027	50.64			
Imazosulfuron fb	0.224	46.25	720.25	0	854.78
trifloxysulfuron +	0.008	37.64			
halosulfuron	0.027	50.64			
Imazosulfuron fb	0.336	69.38	720.25	0	877.91
trifloxysulfuron +	0.008	37.64			
halosulfuron	0.027	50.64			
S-metolachlor fb	1.6	50.41	720.25	0	858.94
trifloxysulfuron +	0.008	37.64			
halosulfuron	0.027	50.64			
Methyl bromide + chloropicrin	390	5,062.20	720.25	0	5,782.45
Weed-free control	-	0	720.25	2,018.87	2,739.12
Non-treated check	-	0	720.25	0	720.25

[a] Weed management cost includes the cost of all the inputs applied for weed control.

[b] Chemcial cost is the cost of herbicides or methyl bromide. In weed-free control and non-treated check chemicals were not applied.

[c] LDPE mulch cost is the cost of low density polyethylene mulch.

[d] Labor cost is the cost of hand weeding in weed-free control plots. Hand weeding was done only in weed-free control plots.

[e] Total cost is the summation of chemical, LDPE mulch and labor costs required for weed management.

Table 15. Estimated total cost, gross return, net return, and net return relative to methyl bromide for PRE-applied imazosulfuron and *S*-metolachlor fb POST-applied trifloxysulfuron plus halosulfuron, methyl bromide, and weed-free control in low-density polyethylene mulched tomato production.

Treatment	Preharvest Cost	Weed management cost	Harvesting and marketing cost[a]	Total cost[b]	Gross return[c]	Net return[d]	Net return relative to methyl bromide[e]
	--	--	--	-----$ ha^{-1}-----	--	--	--
Imazosulfuron (0.112) fb trifloxysulfuron + halosulfuron	11,349.65	831.65	5,123.60	17,304.90	13,349.60	-3,955.30	-8,385.41
Imazosulfuron (0.224) fb trifloxysulfuron + halosulfuron	11,349.65	854.78	3,458.53	15,662.96	8,746.00	-6,916.96	-11,347.08
Imazosulfuron (0.336) fb trifloxysulfuron + halosulfuron	11,349.65	877.91	5,593.81	17,821.37	14,543.60	-3,277.76	-7,707.88
S-metolachlor fb trifloxysulfuron + halosulfuron	11,349.65	858.94	9,945.71	22,154.30	25,912.80	3,758.50	-671.61
Methyl bromide + chloropicrin	11,349.65	5,782.45	13,396.18	30,528.28	34,958.40	4,430.116	0
Weed-free control	11,349.65	2,739.12	13,624.17	27,712.94	35,668.80	7,955.86	3,525.75
Non-treated check	11,349.65	720.25	4,190.86	16,260.76	10,657.60	-5,603.15	-10,033.27

[a] Harvesting and marketing cost includes the cost of harvesting labor, materials for harvesting, grading and packing labor, hauling, and transportation to the terminal market. Harvesting and marketing cost was calculated based on a fixed charge of $5.36 per 11.23-kg box of tomato, therefore, harvesting and marketing cost differed with the varying yield.

[b] Total cost is the summation of preharvest cots, weed management cost, and harvesting and marketing cost.

[c] Gross return is the summation of returns from all the tomato grades.

[d] Net return is the difference between gross return and total cost.

[e] Net return relative to methyl bromide for a treatment was calculated by subtracting net return of methyl bromide from net return of a particular treatment.

Table 16. Estimated preharvest cost for bell pepper production in low-density polyethyle mulched system[a].

Production inputs[b]	Cost
	---$ ha^{-1}---
A. Variable costs:	
Mulch cleanup	332.33
Lime and fertilizer	809.83
Machinery (raise bed, mulch laying, spraying pesticide)	262.50
Diesel fuel	176.80
Drip tape	435.00
Seed/Transplant	4,022.64
Labor	
Hand labor (transplanting, fertigation, unallocated labor)	1,641.51
Operator labor (tractor, implement)	345.04
Irrigation water	1,215.24
Insecticide	54.93
Fungicide	431.13
Herbicide for row middles	72.57
Repair and Maintenance	
Implements	21.24
Tractors	15.95
Interest on operating capital	295.10
Total preharvest variable cost (A)	10,131.81
B. Fixed costs:	
Implements	53.25
Tractor	97.96
Irrigation setup	1,011.86
Total preharvest fixed cost (B)	1,163.07
Total preharvest cost (A + B)	11,294.88

[a] Preharvest cost includes all the inputs cost except weed management and marketing and harvesting cost.

[b] Preharvest costs consist inputs required for plasticulture bell pepper and production input are adopted from traditional vegetables 2012 planning budgets developed by Department of Agricultural Economics at Mississippi State University.

Table 17. Estimated weed management cost for PRE-applied imazosulfuron and *S*-metolachlor fb POST-applied trifloxysulfuron plus halosulfuron, methyl bromide, and weed-free control in low-density polyethylene mulched bell pepper production.

Treatment	Rate	Cost[a]			
		Chemical[b]	LDPE mulch[c]	Labor[d]	Total[e]
	kg ai ha^{-1}	----------$ ha^{-1} ----------			
Imazosulfuron fb	0.112	23.12	720.25	0	831.65
trifloxysulfuron +	0.008	37.64			
halosulfuron	0.027	50.64			
Imazosulfuron fb	0.224	46.25	720.25	0	854.78
trifloxysulfuron +	0.008	37.64			
halosulfuron	0.027	50.64			
Imazosulfuron fb	0.336	69.38	720.25	0	877.91
trifloxysulfuron +	0.008	37.64			
halosulfuron	0.027	50.64			
S-metolachlor fb	1.600	50.41	720.25	0	858.94
trifloxysulfuron +	0.008	37.64			
halosulfuron	0.027	50.64			
Methyl bromide + chloropicrin	390	5,062.20	720.25	0	5,782.45
Weed-free control	-	0	720.25	2,619.41	3,339.66
Non-treated check	-	0	720.25	0	720.25

[a] Weed management cost includes the cost of all the inputs applied for weed control.

[b] Chemcial cost is the cost of herbicides or methyl bromide. In weed-free control and non-treated check chemicals were not applied.

[c] LDPE mulch cost is the cost of low density polyethylene mulch.

[d] Labor cost is the cost of hand weeding in weed-free control plots. Hand weeding was done only in weed-free control plots.

[e] Total cost is the summation of chemical, LDPE mulch, and labor costs required for weed management.

Table 18. Estimated total cost, gross return, net return, and net return relative to methyl bromide for PRE-applied imazosulfuron and *S*-metolachlor fb POST-applied trifloxysulfuron plus halosulfuron, methyl bromide, and weed-free control in low-density polyethylene mulched bell pepper production.

Treatments	Pre harvest cost	Weed management cost	Harvesting and marketing cost[a]	Total cost[b]	Gross return[c]	Net return[d]	Net returns relative to methyl bromide[e]
				$/ha			
Imazosulfuron (0.112) fb trifloxysulfuron + Halosulfuron	11,294.88	831.65	2,183.72	14,310.25	7,010.00	-7,300.25	-17,038.96
Imazosulfuron (0.224) fb trifloxysulfuron + Halosulfuron	11,294.88	854.78	1,301.10	13,450.76	4,266.67	-9,184.09	-18,922.80
Imazosulfuron (0.336) fb trifloxysulfuron + Halosulfuron	11,294.88	877.91	2,238.12	14,410.91	7,100.00	-7,310.91	-17,049.62
S-metolachlor fb trifloxysulfuron + Halosulfuron	11,294.88	858.94	9,630.80	21,784.62	31,696.67	9,912.05	173.34
Methyl bromide + chloropicrin	11,294.88	5,782.45	11,723.96	28,801.29	38,540.00	9,738.71	0
Weed-free control	11,294.88	3,339.66	14,297.93	28,932.47	46,913.33	17,980.86	8,242.15
Non-treated check	11,294.88	720.25	1,222.22	13,237.35	4,010.00	-9,227.35	-18,966.06

[a] Harvesting and marketing cost includes the cost of harvesting labor, materials for harvesting, grading and packing labor, hauling, and transportation to the terminal market. Harvesting and marketing cost was calculated based on a fixed charge of $4.82 per 13.63-kg box of bell pepper, therefore, harvesting and marketing cost differed with the varying yield.

[b] Total cost is the summation of preharvest cots, weed management cost, and harvesting and marketing cost.

[c] Gross return is the summation of returns from all the bell pepper grades.

[d] Net return is the difference between gross return and total cost.

[e] Net return relative to methyl bromide for a treatment was calculated by subtracting net return of methyl bromide from net return of a particular treatment.

CONCLUSION

The ban on ordinary agricultural use of MeBr and unavailability of suitable MeBr alternatives are serious concern for weed management and profitable harvest in commercial tomato and bell pepper production. Soil fumigation and herbicide application as MeBr alternatives were evaluated in the current research. This research demonstrated the superiority of metam sodium over allyl ITC for weed control in LDPE-mulched tomato and bell pepper. Metam sodium at 360 kg ha^{-1} did not injure the crops, controlled a broad spectrum of weeds effectively, and provided optimal yield comparable to MeBr in tomato and bell pepper production. Therefore, metam sodium at 360 kg ha^{-1} is a potential replacement for MeBr for weed control in plasticulture tomato and bell pepper. For herbicide application, *S*-metolachlor applied PRE provided broad-spectrum weed control early in the season. Furthermore, POST-applied trifloxysulfuron plus halosulfuron extended effective weed control throughout the season in *S*-metolachlor-applied tomato and bell pepper plots. In addition, the *S*-metolachlor herbicide program added a net return ≥\$3,758.50 ha^{-1} in tomato and bell pepper production. This herbicide program was also more profitable than an application of MeBr by \$173.34 ha^{-1} in LDPE-mulched bell pepper production. Based on findings from this experiment, it is suggested that PRE-applied *S*-metolachlor fb POST-applied trifloxysulfuron plus halosulfuron (applied at 4 WATP) is a potential herbicide alternative to MeBr for weed control in LDPE-mulched tomato and bell pepper.