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Integration of soil-applied herbicides at the reduced rates with physical control for weed management in fennel (*Foeniculum vulgare* Mill.)

Ali Reza Yousefi*, Mohammad Reza Rahimi

Department of Agronomy and Plant Breeding, College of Agriculture, University of Zanjan, Zanjan, Iran

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A B S T R A C T

Fennel has been widely used in traditional medicine for their antimicrobial effects. Since fennel is long duration crop and have slow initial growth, it protection from weed is essential. Experiments were conducted for two consecutive seasons to evaluate the efficacy of soil-applied herbicides at the reduced rates in combination with physical control for weed management and optimizing the yield of fennel. Treatments were type of herbicide (trifluralin and pendimethalin), application dose (recommend dose (R), 75% R, 50% R, and 0% R) and physical weed control (none, one hand-weeding at 50 day after planting (DAP), wheat straw mulch). Weed-free control treatment was also included in each year. The results showed that the use of soil-applied herbicides resulted in reduced weed biomass but did not provide season long weed control without an additional physical control. In both seasons, pendimethalin provided better weeds control than trifluralin. Reduced herbicide rates were found to be more effective when herbicides application followed by hand-weeding than when were used alone or combined with mulch. Experimental results also showed that one time increasing in herbicide rates increased seed yield by 17.5 and 7.5% in 2012 and 16.5 and 6.3% in 2013, when one hand-weeding and mulching were used as supplemental control, respectively. Overall, the 75% of the labeled recommended rate of herbicides followed by one hand-weeding at 50 DAP produced consistently high yields and less weed biomass, reflecting both superior weed control and crop safety.

1. Introduction

Fennel (*Foeniculum vulgare* Mill. var. vulgare) has been cultivated as a medicinal and spice plant for a long time in different areas of Iran (Omidbaigi, 2007). Essential oil of fennel is also used as a flavor and aromatic agent in breads, soups, and other food products. Aromatherapy and pharmaceutical industries utilize fennel essential oil. The main constituents of fennel essential oil are trans-anethole, estragole, fenchone and limonene. Trans-anethole, often the most prevalent constituent, counts for the anise taste, fenchone provides the bitterness and estragole (methyl-chavicol) the sweetness (Guillen and Manzanos, 1994). The most important bioactive components of fennel essential oil are anethole and fenchone (Reichardt and Pank, 1993).

Weed management in fennel is one of the main production concerns for growers as fennel (especially at the first year of establishment) has a short stature and slow growth and therefore is not a competitive plant with weeds. Moreover, wider row spacing and frequent use of water favors growth of weeds. To keep the field weed free, about 3–4 hand-weeding are required (Parthasarathy et al., 2008). Hand-weeding is only practical on small farms, because it is highly labor intensive, time-consuming, expensive and needs to be repeated often (Elkola et al., 2004). Use of appropriate weed management practice such as chemical and physical weed control can reduce weed competition and mitigate yield losses. Weed interference in fennel can reduce seed yield and can interfere with harvest efficiency and may cause staining and reduce seed quality (Omidbaigi, 2007). There is limited number of registered herbicides for fennel production in Iran. More research is needed to identify herbicides that provide broad-spectrum weed control in this important medicinal plant.

Recommended herbicide rates are selected to ensure a high level of weed control over a wide range of environmental conditions, weed growth stages, and weed species with different degrees of susceptibility. The industry recognizes that there are situations where herbicide efficacy can be maintained at reduced rates,

* Corresponding author. Tel.: +98 9127441934; fax: +98 2412283202.
E-mail address: yousefi.alireza@znu.ac.ir (A.R. Yousefi).

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although these situations are difficult to predict (Blackshaw et al., 2006). Increasing public awareness and concern about the impact of herbicides on the environment, development of herbicide-resistant weeds and the high economic cost of herbicides have increased the need to reduce the amount of herbicides used in agriculture (Kim et al., 2001). The economically optimal dose of herbicides is strongly influenced by weed infestation levels and weed size. Yousefi et al. (2012) found that optimal doses of imazethapyr for *Amaranthus reroflexus* control were always markedly lower than the recommended dose. Indeed, herbicides at reduced rates are often sufficient to control weed density at or below the threshold levels and below-labeled herbicide rates in combination with some mechanical weed control have proven to be an effective way of reducing herbicide input to agricultural systems (Barros et al., 2005). The combination of management practices, such as mulching with herbicide could improve weed control efficacy of reduced rates (Zhang et al., 2000). Mulches can control weeds by preventing light from reaching weed seeds and creating a physical barrier that prevents seedling emergence and early growth. Cereal straw mulch has been shown to suppress weeds in orchard and rice (Rowley et al., 2011; Singh et al., 2007). Mulches can also have positive secondary impacts, such as increasing the biodiversity of arthropods (Brown and Tworkoski, 2004), or decreasing evaporation from the soil surface (Monks et al., 1997). Wood chip mulch has been shown to improve tree growth during orchard establishment (Smith et al., 2000).

Limited information is available on control of weeds in fennel as important medicinal plant. To our knowledge, there is no information about utilizing combinations of herbicides at the reduced rates and physical methods (mulches or hand-weeding) for weed suppression in fennel. Using a combination of physical control and herbicides at reduced rate may increase the efficacy of both treatments while reducing the cost of the weed control program and environmental impact of over reliance on herbicide applications. Therefore, the objective of this study was to evaluate the effects of reduced rates of the trifluralin and pendimethalin alone and in combination with mulch and one hand-weeding on the growth of weed and grain yield of cultivated fennel.

2. Materials and methods

2.1. Site description and field procedures

Two field experiments were conducted at the Research Farm of the University of Zanjan, Zanjan, Iran, in 2012 and 2013. This region is characterized by a semi-arid cool climate, with an annual mean temperature of 11 °C and mean precipitation of 293 mm for the past 30 years. Mean monthly temperature and rainfall data during the growing season, recorded near the experimental area, are given in Table 1. The soil type was a sandy loam (31% clay, 27% silt and 42% sand), with a pH of 8.1, and soil organic matter of 1.21%. In both years, seedbed preparation included deep plowing (20–25 cm) with a moldboard plough in fall, followed by disking in spring. Based on soil analysis, fertilizers were applied prior to planting or as a topdressing. Fertilizer inputs were 37 kg ha^{-1} P (triple superphosphate) before planting and 92 kg ha^{-1} N (urea) in three splits, 1/3 each at planting, stem elongation and flowering times.

Fennel was planted at 10 seeds m^{-2}, at 0.5 m row spacing, on May 6, 2012 and April 15, 2013. Plot size was 2 m wide by 5 m long. Drip irrigation was used on all plots. Irrigation at 3 days interval was used in the experiment for first 30 days after sowing to get optimum plant stand and then weekly irrigation was applied for reset of the season in each year.

Table 1
Average monthly air temperatures (°C) and rainfall (mm) during the fennel growing season in 2012 and 2013.

Month	Temperature (°C)						Rainfall (mm)	
	Mean		Maximum		Minimum			
	2012	2013	2012	2013	2012	2013	2012	2013
April	9.0	10.6	15.4	18.2	2.6	3.1	94.3	7.3
May	14.7	12.7	22.3	19.8	7.2	5.7	55.0	11.6
June	18.9	19.0	26.7	27.6	11.1	10.3	17.7	3.0
July	22.0	22.3	30.2	31.6	13.7	13.1	33.4	0.0
August	24.3	23.2	32.8	31.8	15.8	14.7	5.4	2.0
September	21.2	21.5	29.1	31.0	13.4	11.9	6.0	3.0
October	15.7	14.0	24.4	22.6	6.9	5.3	5.7	0.4
November	9.8	7.8	15.6	13.0	4.0	2.5	58.2	24.6

2.2. Treatment and data collection

The experiments were carried out with a completely randomized factorial design. Factors were type of herbicide (trifluralin and pendimethalin), application dose (recommend dose (R), 75% R, 50% R, and 0% R) and physical weed control (none, one hand-weeding, mulching). Weed-free control treatment was also included in each year. All treatments were replicated three times. The recommended doses of trifluralin and pendimethalin were 1440 and, 1320 g ai ha^{-1}, respectively. The recommended doses of these two herbicides were determined according to their registration information in Iran (Yousefi et al., 2007). In the mulch treatments, wheat straw were spread evenly after fennel planting at the rate of 2 kg m^{-2} which created about 10 cm thickness mulch on the soil surface. Wheat straw was obtained from a local farm supply store. In the weed control treatments which one hand-weeding used as supplemental physical control, a hand-weeding was performed at 50 day after planting (DAP), where weeds were allowed to grow before and after the hand-weeding. Weeds in the weed-free plots were removed by hand-weeding every week throughout the growing season. In the weedy control, no weeding was done.

Trifluralin (Treflan,EC, 480 g L^{-1}, Dow Agro Sciences) was applied pre-plant and incorporated into the top 5 cm of the soil by raking within 1 h of herbicide application (PPI), while pendimethalin (Stomp, EC, 330 g L^{-1}, BASF) was applied pre-emergence (PRE) soon after planting. Herbicide treatments were applied with a backpack sprayer fitted with Flood-jet nozzle, calibrated to deliver 280 L ha^{-1} at 180 kPa. At fennel maturity, 149 and 165 days after planting in 2012 and 2013, respectively, weeds were harvested from a 0.5 m^2 (two quadrats per plot) area. Weed were cut at the stem base close to the soil surface, placed in paper bags, dried in an oven for 48 h at 75 °C and biomass was recorded.

For assessing the effect of the treatments on fennel seed yield a 2-m^2 centre area of the plots was harvested manually on November 5, 2012 and October 17, 2013 at the end of season.

2.3. Statistical analysis

Data were subjected to an analysis of variance using PROC GLM in SAS Software (Version 9.1, SAS Institute Inc., Cary, NC). Before analyzing the data, the assumption of a homogenous variance was tested using residual plots and the Kolmogorov-Smirnov normality test. The data of treatments effect on the broadleaf and grass weed biomass were directly analyzed, while data of treatments effect on the total weed biomass (only 2012 data) and fennel seed yield were $\log_{10}$ transformed prior to analysis. If the analysis of variance indicated statistical significant differences, the means were compared using a Fisher's Protected Least Significance Difference test ($P \leq 0.05$).