Universiti Malaysia Tereggan Journal of Undergraduate Research *ISSN: 2637-1138*
Volume 1 Number 1, January 2019 *©Penerbit UMT*

PHYTOTOXIC ACTIVITY OF GERANIOL-TREATED LEMONGRASS LEAF MULCH AGAINST COMMON WEEDS IN NURSERIES

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Abstract: Hand weeding continues to be one of the most laborious aspects of nursery maintenance. Oxygenated monoterpene, an important group of secondary metabolite found in essential oils, has a potential herbicidal activity that could be exploited as natural herbicide whereas organic mulch could delay weed emergence. Thus, this study aimed to examine the phytotoxicity of geraniol, an oxygenated monoterpene compound, in combination with lemongrass leaf mulch against three common weeds, *Eleusine indica* (grass), *Cyperus distans* (sedge), and *Tridax procumbens* (broadleaf). Greenhouse experiments were carried out by treating 4.0 t/ha lemongrass leaf mulch with 7.5% (v/v) geraniol compound. The pretreated mulch acted synergistically and inhibited the emergence and shoot growth of *T. procumbens* completely. However, the pretreated mulch exhibited a moderate inhibitory effect on *C. distans* emergence and growth. Geraniol-treated lemongrass leaf mulch acted synergistically and inhibited the emergence of *E. indica* by 72%, but it acted antagonistically and caused a 45% reduction of shoot biomass. The present findings suggest that geraniol-treated lemongrass leaf mulch has potent herbicidal activity but its phytotoxic effect is species-dependent.

Keywords: natural herbicide, organic mulch, oxygenated monoterpene

Introduction

Weed control is an important aspect of nursery maintenance from both aesthetic and biological perspectives. Weeds left to grow in nurseries can cause direct or indirect reductions of ornamental crop growth or quality (Atland et al. 2003). Weed management in nursery plantings is often difficult because of the complexity of many plants. Usually, more than one species of plants are planted in the nursery, and there is a mix of annual and perennial ornamentals. Most nursery plantings include turf grass, bedding plants, herbaceous perennials, shrubs, and trees (Wilen, 2007). The choice of a specific weed management programme depends on the weed presence and the types of turf or ornamentals planted in the areas.

Weeds in nurseries are usually controlled by a combination of non-chemical and chemical methods. There are many studies demonstrating the use of herbicide-treated organic mulches for weed control in nurseries (Mathers, 2003), but to date, there are limited studies focussing on the potential of oxygenated monoterpene like geraniol, when combined with organic mulch, for weed control. A previous study has shown that geraniol inhibited the growth of *Aeschynomene indica* and *Abutilon theophrasti* (Choi et al. 2015). Although there are many studies investigating the exploitation of crop residue mulches for weed suppression (Dilipkumar et al. 2015), there is scanty research investigating the potential of lemongrass leaf mulch for weed control. Thus, this study aimed to explore the potency of geraniol in combination with lemongrass leaf mulch for weed inhibition in nurseries under glasshouse conditions.

Materials and Methods
Plant Materials

The compound geraniol was purchased from Sigma-Aldrich, Germany. Seeds of the bioassay species, goosegrass (*Eleusine indica*), *Tridax procumbens* and *Cyperus distans* seeds, were collected from Bukit Kor Marang Terengganu, Malaysia, and propagated in a glasshouse at Universiti Malaysia Terengganu. The seeds were then scarified with sandpapers to remove the seed coats. The seeds were soaked in 0.2% potassium nitrate solution for 24 hours before being used to break seed dormancy. A preliminary viability test was conducted and it was confirmed that the germination rate of the seeds was more than 90%. Empty and undeveloped seeds that floated in tap water were discarded.

Preparation of Mulch

The residue of lemongrass leaf (*Cymbopogon citratus*) was collected from Perak, Malaysia. The plant material was cut into small pieces measuring 6-10 cm in length and dried under direct sunlight for one month and over-dried at 50ºC for 2 days. After it completely dried, the lemongrass leaf residue was ground into powder form (< 2mm) using a mill (MF 10 basic IKA ® WERKE) and stored in chiller (10ºC) prior to use.

Seed Sowing

Topsoil was air-dried and passed through a 2-mm sieve. A 300 g sample of moist soil was filled in a polybag (15 cm diameter) with holes at the bottom. A total of 60 seeds (20 seeds for each bioassay species) were sown evenly per polybag on the soil surface. Water was applied from the bottom of the polybags to stimulate moist conditions for proper growth of weed seedlings. The polybags were then placed in a glasshouse and maintained at a relative humidity of 78 – 80% and a temperature of 20 – 35ºC with 12 hours photoperiod.

Phytotoxicity Test of Lemongrass Leaf Mulch

Lemongrass leaf mulch was applied evenly onto the soil surface at 0, 0.5, 1, 2, and 4 t/ha one day after 20 seeds of each bioassay species were sown in each polybag, respectively. All treatments were arranged as factorial in complete randomized design with five replications. Emerged weed seedlings were counted and recorded one month after treatment. Seedlings were considered emerged when the hypocotyl attained a length of 2 mm. The shoot dry weights of weed seedling were determined by harvesting and weighing above ground tissues remaining of each seedling. All data were expressed as percentages of their respective controls. Non-treated weed seeds were used as control treatment. Inhibitory activity of crop residues was calculated based on rates that gave 50% inhibition of weed growth or emergence.

Phytotoxicity Test of Geraniol

Geraniol was prepared with a series of concentrations from 0, 2.5, 5, 10 and 20 % (diluted using 0.05% Tween 20 w/v) (Choi et al. 2015). Each concentration of geraniol was applied evenly onto the soil surface by using a micropipette one day after 20 seeds of each bioassay species were sown. After one month, the effect of geraniol on weed emergence and growth of weed seedlings was determined. Emerged weed seedlings were counted and recorded. Seedlings were considered emerged when hypocotyle attained a length of 2 mm. The shoot dry weights of weed seedling were determined by harvesting and weighing above ground tissues remaining of each seedling. All treatments were arranged as factorial in complete randomized design with five replications. Non-treated seeds were used as a control treatment. Inhibitory activity of geraniol was calculated based on rates that gave 50% inhibition of weed growth or emergence.

Phytotoxicity of Geraniol-Treated Lemongrass Leaf Mulch

The rates of lemongrass leaf mulch or geraniol which provided 50% inhibition (ED_{50}) of total weed emergence obtained from the dose-response test were further examined in this experiment. The lemongrass leaf mulch at its respective ED_{50} rate was treated with the ED_{50} rate of geraniol, respectively, by using a hand sprayer, delivering a spraying volume at 1000 Lha^{-1}. The lemongrass leaf mulch was dried for 24 hours under glasshouse conditions. Geraniol-treated lemongrass leaf mulch was applied evenly onto the soil surface one day after 60 weed seeds were sown in each polybag, respectively. Non-treated weed seeds were used as control treatment. One month after treatment, the number of seedling emergence was counted and shoot dry weight was measured. Seedlings were considered emerged when the hypocotyl attained a length of 2mm. The data were expressed as percentages of their respective controls. All treatments were arranged as factorial in complete randomized design with five replications.

Statistical Analysis

The data of dose-response test of lemongrass leaf mulch and geraniol were fitted to a log-logistic regression model by using sigma plot programme (SigmaPlot 2006 version 10.0) as follows (Kuk et al. 2002) :

$$Y = a(1 + [\chi/\chi_0]^b)$$

Where, Y is the percentage of shoot emergence or shoot dry weight, a is the coefficients corresponding to the upper asymptotes, χ_0 is the rate of lemongrass leaf mulch/geraniol required to inhibit the shoot emergence or shoot dry weight by 50% relative to untreated seeds and b is the slope of the line. Regression analyses were conducted and the χ_0 was calculated from the regression equations.

All the percentage data in phytotoxicity test of geraniol-treated lemongrass leaf mulch were subjected to independent T-test, at 5% of significant level. Results were presented as the means ± standard deviation. The data were evaluated with SPSS software package version 20.0.

Results

A Single Application of Lemongrass Leaf Mulch against Total Weeds

A series rate of lemongrass leaf residue mulch was set in a range of 0.5 to 4.0 t ha^{-1} in dose-response experiments. Both seedling emergence and shoot biomass of weeds declined progressively with an increase of the lemongrass leaf residue mulch rate. Lemongrass leaf mulch produced a higher inhibitory effect on total weed growth with 54% inhibition and the total emergence of weeds by 50% at the highest rate of 4.0 t ha^{-1} (Figure 1). It is found that the rates required for 50% reduction (ED_{50}) of the total weed emergence and total weed biomass are 4.0 t ha^{-1} and 3.1 t ha^{-1} of lemongrass leaf mulch, respectively. These results suggest that lemongrass leaf mulch could act as a potential shoot and germination inhibitors, respectively.

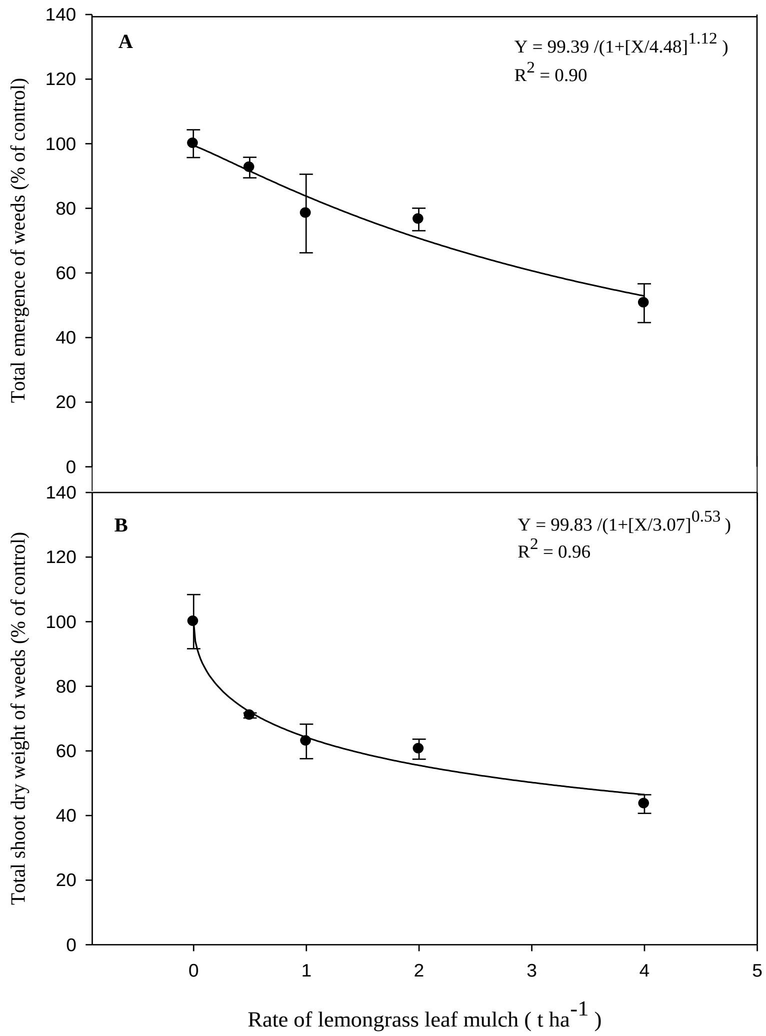

Figure 1: Effects of pre-emergence application of lemongrass leaf mulch on total emergence (A) shoot dry weight (B) of weeds. Vertical bars represent ± standard deviation of mean.

A Single Application of Lemongrass Leaf Mulch against Selected Weeds

Greenhouse experiments were conducted to determine the effects of mulch from the residue of lemongrass leaf on the seedling emergence and shoot biomass of *E. indica*, *C. distans*, and *T. procumbens* as shown in Figure 2. From the results, it shows that the mulch of lemongrass leaf residues exhibited phytotoxic effects on three bioassay weed species at different degrees of potency. The emergence of weeds was inhibited by 46-69% when treated with lemongrass leaf residues at 4 t ha^{-1} but this rate was not able to inhibit the shoot

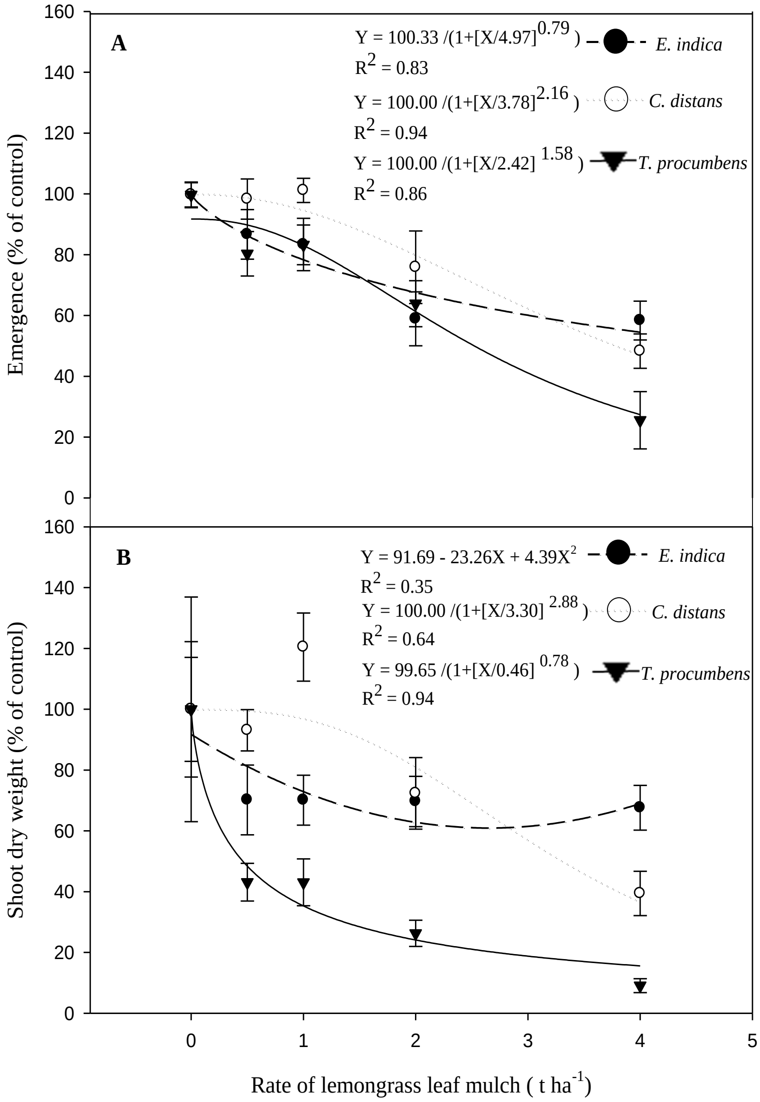

Figure 2: Effects of pre-emergence application of lemongrass leaf mulch on emergence and shoot dry weight of *E. indica*, *C. distans* and *T. procumbens*. Vertical bars represent ± standard deviation of mean.

growth of *E. indica* effectively. In contrast, lemongrass leaf mulch was able to inhibit the shoot growth of *C. distans* and *T. procumbens* by 64-85% at the same rate. These findings imply that *E. indica* is quite tolerant of lemongrass leaf mulch.

ED_{50} values of weed emergence and shoot biomass for different weed species subjected to lemongrass leaf mulch are shown in Table 1. Based on the ED_{50} values of shoot biomass and seedling emergence, it clearly shows that *T. procumbens* was more susceptible than other bioassay species in response to the lemongrass leaf mulch. In addition, lemongrass leaf mulch could inhibit *T. procumbens* shoot growth more effectively than the emergence of this weed species. However, lemongrass leaf mulch exhibited inhibitory effect with ED_{50} values of seedling emergence ranging from 2.4 to more than 4.0 t ha^{-1} among the three weed species. The T-test further shows that lemongrass leaf mulch acted as shoot inhibitor rather than germination inhibitor when being subjected to *T. procumbens*. However, the mulch inhibited both emergence and shoot growth of *C. distans* at a similar degree of potency.

Table 1: ED_{50} values of different types of weeds in relations to lemongrass leaf residue.

Weed Species	*ED_{50} (t ha^{-1})	
	Emergence	Shoot dry weight
Eleusine indica	> 4.0	–
Cyperus distans	3.8	3.3
Tridax procumbens	2.4a	0.5b

* The organic mulching rate that reduces emergence and shoot dry weight of weed by 50%.
** Different letters within a similar row indicate a significant difference between ED_{50} values.
– Cannot be determined due to the insensitivity of bioassay species to the tested rates of organic mulch.

A Single Applications of Geraniol Compound against Total Weeds

The response of weed seeds to the pre-emergence application of geraniol at one month after treatment is shown in Figure 3. Similarly, the total emergence and the shoot biomass of weed seedlings were reduced as the rate of geraniol was increased. Geraniol only provided 60-70% inhibition on the total seedling emergence and shoot growth of weed at a rate of 20% (v/v).

On the other hand, the ED_{50} values of weed emergence were 7.5% (v/v) when being subjected to geraniol, whereas, 12.1% (v/v) of geraniol was needed to provide 50% reduction of overall weed biomass. The t-test shows that there was no significant difference between the ED_{50} values of total weed emergence and biomass, implying that geraniol has a similar degree of potency as shoot or germination inhibitor.

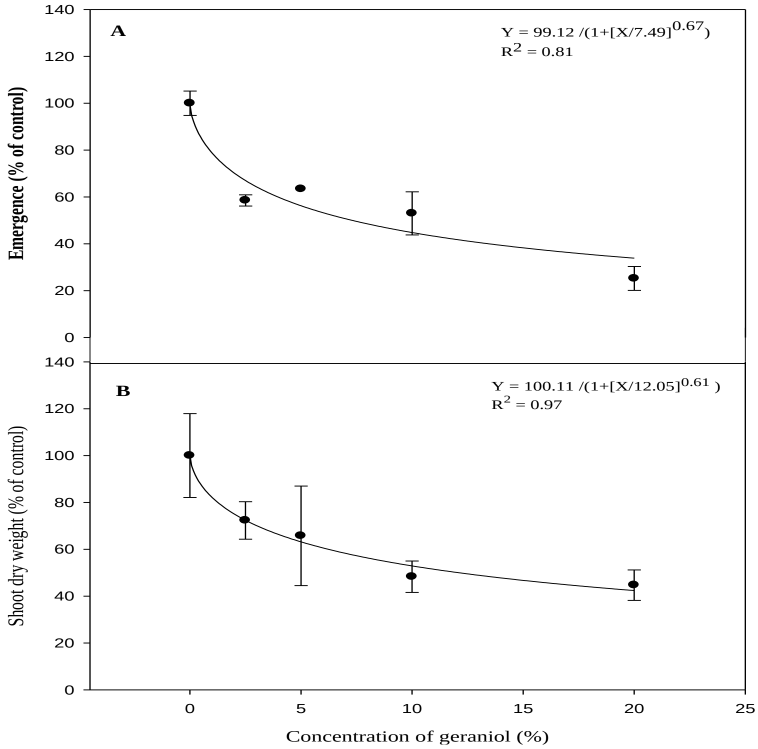

Figure 3: Effects of pre-emergence application of geraniol on total emergence (A) shoot dry weight (B) of weeds. Vertical bars represent ± standard deviation of mean.

A Single Application of Geraniol Compound against Selected Weeds

The greenhouse experiments were conducted using geraniol compound against three types of weeds namely *E. indica*, *C. distans*, and *T. procumbens* as shown in Figure 4. It is interesting to note that the herbicidal activity of tested compound varied enormously against the three weed species, with compound geraniol showing a moderate inhibitory activity on emergence of weed species, but it had a great inhibitory effect on shoot growth of *T. procumbens* at a rate of as low as 2.5% (v/v). Nevertheless, it only gave 10% inhibition of *C. distans* shoot growth even at a rate of as high as 20% (v/v).

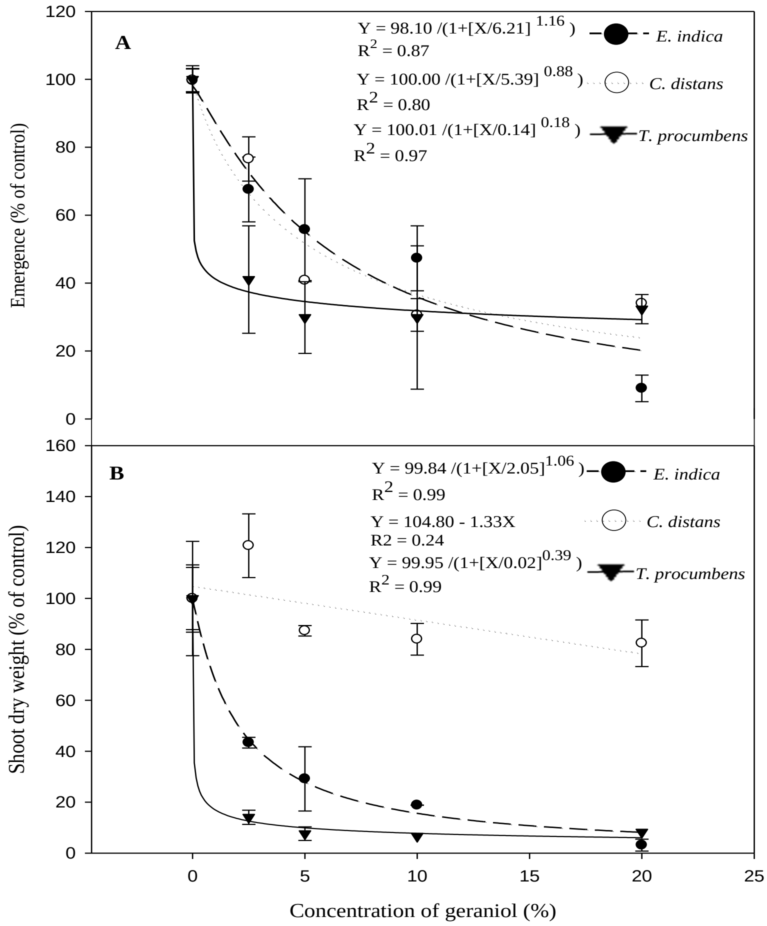

Figure 4: Effects of pre-emergence application of geraniol on emergence (A) and shoot dry weight (B) of *E. indica*, *C. distans* and *T. procumbens*. Vertical bars represent ± standard deviation of mean.

ED_{50} values of weed emergence and weed biomass varied with weed species when subjected to geraniol (Table 2). Among the three species, *T. procumbens* was the most highly susceptible to geraniol with ED_{50} values of seedling emergence and shoot growth being at rates as low as 0.1 and 0.02% (v/v), implying that geraniol could act as a potent shoot inhibitor when being treated on *T. procumbens*. On the other hand, *E. indica* was moderately sensitive to this compound whereas *C. distans* was quite tolerant of geraniol where it needed more than 20% (v/v) to reduce the shoot biomass by 50%.

Table 2: ED_{50} values of different types of weeds in relations to geraniol compound

Weed species	*ED_{50} (%)	
	Emergence	Shoot dry weight
Eleusine indica	6.2	2.1
Cyperus distans	5.4	>20
Tridax procumbens	0.1	0.02

* The geraniol rate in % (v/v) that reduces emergence and shoot dry weight of weeds by 50%.

Phytotoxic Effects of Geraniol-Treated Lemongrass Leaf Mulch against Total Weeds

An application rate of geraniol at more than 20% (v/v) was required to provide 68% inhibition of total weed emergence. Interestingly, geraniol rate was reduced by more than 60% to exhibit the same inhibitory effect when being combined with lemongrass leaf mulch (Table 3). Meanwhile, the combination of geraniol and lemongrass leaf mulch could inhibit total weed biomass by 50% and reduced the rate of geraniol alone by 38%.

Table 3: $ED_{50\text{-}68}$ values of total weed emergence and shoot dry weight for geraniol alone and in combination with lemongrass leaf mulch

	Inhibition (%)	Rate of geraniol applied in combination with lemongrass leaf (%)	Rate of geraniol applied alone (%)	Rate reduction (%)
geraniol-treated lemongrass leaf mulch	Seedling emergence			
	68	7.5	>20	>63
	Shoot dry weight			
	50	7.5	12	38

Phytotoxic Effects of Geraniol-Treated Lemongrass Leaf Mulch against Weeds

Figures 5 shows the phytotoxicity of lemongrass leaf mulch at 4 t ha^{-1} in combination with the 7.5%(v/v) rates of geraniol on the seedling emergence and shoots biomass of *E. indica*, *C. distans*, and *T. procumbens*. Geraniol-treated lemongrass leaf mulch exhibited phytotoxic effects on three bioassay weed species at different degrees of potency.

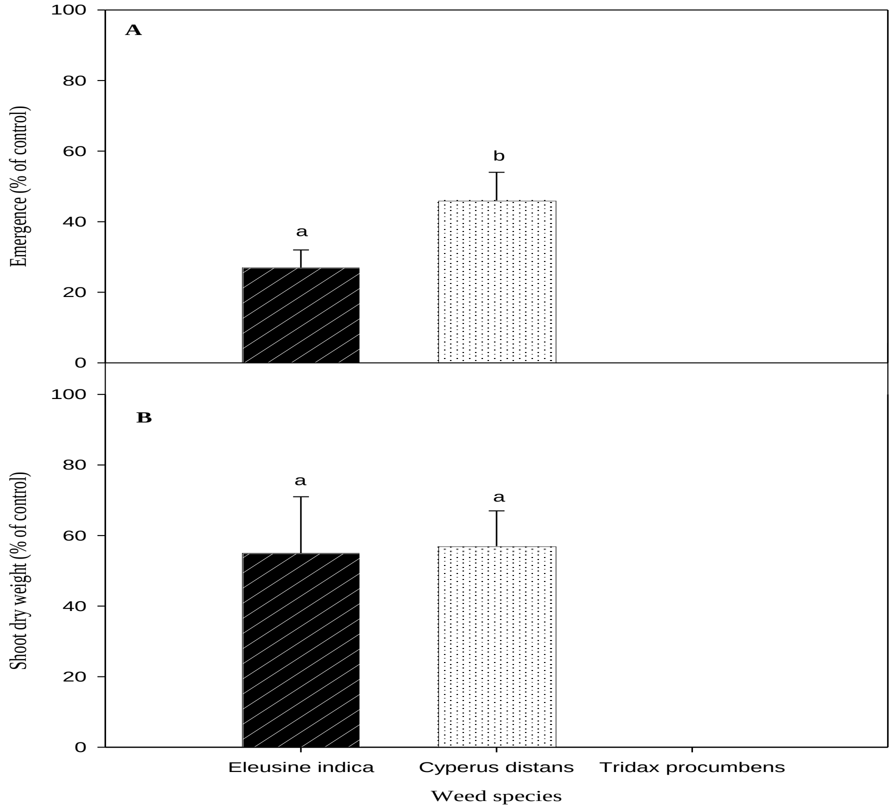

Figure 5: Effects of geraniol-treated lemongrass leaf mulch on the emergence and shoot dry weight of *Eleusine indica*, *Cyperus distans* , and *Tridax procumbens*. Vertical bars represent ± standard deviation of mean.

Table 4: $ED_{43\text{-}100}$ values of weed emergence and shoot dry weight for geraniol alone and in combination with lemongrass leaf mulch

	Weed species	Inhibition (%)	Rate of geraniol applied in combination with lemongrass leaf mulch (%)	Rate of geraniol applied alone (%)	Rate reduction (%)
			Seedling emergence		
geraniol treated-lemongrass leaf mulch	*Eleusine indica*	72	7.5	13.7	45
	Cyperus distans	54		6.4	*
	Tridax procumbens	100		>20	>63
			Shoot dry weight		
	Eleusine indica	45	7.5	1.7	*
	Cyperus distans	43		>20	>63
	Tridax procumbens	100		>20	>63

* Rate reduction cannot be determined because geraniol rate alone is lower than that when combined with lemongrass leaf mulch.

Interestingly, emergence and shoot growth of *T. procumbens* were completely inhibited (Figure 5). Application rate at more than 20% (v/v) of geraniol alone was required to exhibit the same inhibitory effect. Surprisingly, geraniol rate was reduced by more than 60% when being combined with lemongrass leaf mulch (Table 4). On the other hand, the emergence of *E. indica* was more sensitive compared to *C. distans*. A lower rate of geraniol was required to exert the same inhibition of *C. distans* emergence when compared with the rate of geraniol used in combination with lemongrass leaf mulch (Table 4). Geraniol could inhibit shoot biomass of *C. distans* by 20% only at a rate as high as 20% (v/v) (Figure 5). Surprisingly, geraniol at 7.5% (v/v) in combination with lemongrass leaf mulch could inhibit shoot biomass of *C. distans* by 43% (Table 4). Application of geraniol alone at 13.7% (v/v) was required to give 72% inhibition of *E. indica* seedling emergence. Interestingly, this rate was reduced by 45% to provide the same inhibitory effect when combined with lemongrass leaf mulch. The geraniol at 7.5% (v/v) in combination with lemongrass leaf mulch could provide 45% reduction of *E. indica* shoot biomass, but a lower rate of geraniol alone at 1.7% (v/v) was needed to provide the same inhibition.

Discussion

Phytotoxicity of Lemongrass Leaf Mulch in a Single Application

The total emergence of weeds was inhibited by 50% when treated with lemongrass leaf residue at 4 t ha^{-1}. Schonbeck (2012) stated that organic mulch could act as a physical barrier by decreasing light penetration. Furthermore, weeds that germinate may be weakened by even thin layers of mulch that reduce the weed ability to photosynthesize (Crutchfield et al., 1986; Kruidhof et al., 2009; Liebman & Mohler, 2001). A previous study by Cochran et al. (2009) reported that a 2.5 cm layer of pine bark mini-nuggets reduced weed counts of eclipta (*Eclipta prostrate* L.) by 87% and spotted spurge (*Chamaesyce maculata* L.) in container plant production by 90%. On the other hand, the rates required for 50% reduction (ED_{50}) of total weed biomass was 3.1 t ha^{-1} for lemongrass leaf mulch, indicating that the lemongrass leaf mulch is phytotoxic. Crop allelopathy is an important component of weed interference that can affect seed germination, growth and development through the release of allelochemicals into the soil either as exudates from living organ or by decomposition of plant residues (Amri et al.,2013; Belz, 2007; Chalker, 2007). The lemongrass leaf mulch may contain allelochemical constituents that resulted in greater weed biomass reduction. To date, limited information is available on allelochemicals of lemongrass leaf mulch responsible for weed suppression. Further research should be carried out to determine allelochemicals involved in the phytotoxic activity of lemongrass leaf mulch. Based on the ED_{50} values, *T. procumbens* was the most susceptible, followed by *C. distans* and *E. indica* when treated with the mulch. Lemongrass leaf mulch could inhibit the seedling growth of *T. procumbens* more effectively than the emergence of this weed species, with lemongrass leaf mulch being more potent on the reduction of *T. procumbens* seedling growth.

Comparatively, Absinth wormwood mulch residues exhibited no phytotoxicity on the purple nutsedge growth, but it was able to reduce purple nutsedge emergence by 68% (Anzalone et al. 2010). Chauhan and Abugho (2012) reported that amount of 3 t ha^{-1} of rice residue reduced biomass of crowfootgrass (*Dactyloctenium aegyptium* L.) by 36% but the rice residues could increase the seedling biomass of *Echinochloa crus-galli* compared with no-residue treatment. Likewise, the present study showed that seedling growth of *E. indica* could not be inhibited effectively. In contrast, the lemongrass leaf mulch had a similar degree of inhibition on the biomass and emergence of *C. distans*. This study revealed the high potential of lemongrass leaf residues in weed management programme since the lemongrass leaf mulch has the phytotoxic effect and needs a lower rate to reduce the total weed biomass by 50%.

Phytotoxicity of Geraniol Compound in a Single Application

The present study has shown that the tested oxygenated monoterpene compounds caused significant inhibition of weed growth and emergence in a concentration-dependent manner. In this study, it is shown that geraniol only provided 60 to 70% inhibition of total weed emergence and biomass at the rate of 20% (v/v). This compound had moderate inhibitory activity on the emergence of *E. indica* and *C. distans* and poor inhibitory effect on *C. distans* seedling growth. But, it had a great inhibitory effect on shoot growth of *T. procumbens* at a rate of as low as 2.5% (v/v). Similarly, Gouda et al. (2016) found that at the concentration of >2mM, geraniol caused complete inhibition of *Echinochloa crus-galli* germination, with 53% inhibition at a low concentration of 1mM. This previous study also showed that geraniol exhibited a greater inhibitory effect on seedling growth (EC_{50} of root growth = 0.15mM and EC_{50} of shoot growth = 0.78mM) than on seed germination (EC_{50} = 0.98mM) of *E. crus-galli*. The other previous study by Choi et al. (2015) documented that geraniol suppressed the growth of *Aeschynomene indica* and *Abutilon theophrasti* at the lowest concentration of 2.5% after 14 days of spray treatment. Phytotoxic effects of monoterpenes such as geraniol might be caused by the changes in anatomical and physiological of plant seedlings probably due to the accumulation of lipid globules in cytoplasm, reduction in organelles including mitochondria and nuclei, inhibition of DNA synthesis, or disruption of membranes and suppression of metabolic enzymes activity that involved in glycolysis (Nishida et al., 2005; Zunino and Zyagadlo, 2004).

Phytotoxic Effects of Geraniol-Treated Lemongrass Leaf Mulch against Total Weeds

Combinations of lemongrass leaf mulch and geraniol examined in this study give synergistic effects in which the rate of geraniol that is used in this combination is much lower than the rate of geraniol used alone but it could achieve the same inhibitory effect. For instance, geraniol inhibited the total weed emergence and total weed biomass by 68% and 50% when combined with lemongrass leaf mulch. The rate of geraniol was reduced by more than 60% compared to the rates of geraniol when used alone.

Phytotoxic Effects of Geraniol-Treated Lemongrass Leaf Mulch against Weeds

Mathers (2003) has reported that mulches can act as slow release-carriers and produce positive, sometimes synergistic interaction with herbicide. The present study showed mixed results from antagonistic to synergistic interaction of lemongrass leaf mulch and geraniol. Several combinations examined in this study give synergistic effects. For instance, geraniol-treated lemongrass leaf mulch acted synergistically on the *T. procumbens*, with more than 60% reduction of geraniol rates. In agreement with these results, Teasdale et al. (2005) demonstrated that the incorporation of S-metolachlor at 10 g a.i ha^{-1} and hairy vetch (*Vicia villosa*) residue at 5 t ha^{-1} gave synergistic interaction by inhibiting smooth pigweed emergence by 86%, compared with single S-metolachlor at 1000g a.i ha^{-1} to achieve the same inhibitory effect. Plants can detoxify herbicide by conjugation with glucose or glutathione (Anonymous, 2002), a step that would require an adequate supply of carbohydrate within the growing seedling. Synergism may be due to seedlings that partition carbohydrate to hypocotyl elongation in response to light deprivation within mulch would have diminished capacity to detoxify herbicide (Teasdale et al. 2005). The synergism between lemongrass leaf residue and geraniol observed in this experiment could be explained by carbohydrate deprivation of etiolated seedlings that prevented sufficient detoxification of this compound.

In contrast, geraniol-treated lemongrass leaf mulch provided 54% inhibition on emergence of *C. distans*, but application of geraniol alone needed a lower rate which is 6.4 %(v/v) instead of using 7.5%(v/v) when combined with lemongrass leaf mulch. Similarly, a lower rate of geraniol alone was needed to achieve the same inhibitory effect. This result indicated that occurrence of antagonism between the combination of geraniol and lemongrass leaf mulch. According to Chauhan and Abugho (2012), no rice flatsedge (*Cyperus iria* L.) emerged when herbicides were applied in the absence of rice residue. However, seedlings emerged when herbicides were applied in the presence of rice residue which the plant survived when oxadiazon at 0.5 kg ha^{-1} was applied in the presence of 3 t ha^{-1}. Teasdale et al. (2003) reported that herbicide and mulch alone reduced emergence of fall panicum (*Panicum dichotomiflorum*) by 72% and 50%, but the combination of pre-emergence with hairy vetch only provided 24%, indicating an antagonistic interaction between pre-emergence metolachlor and hairy vetch. This antagonism might be due to the fact that herbicide intercepted by surface residue can be lost through several mechanisms, including biodegradation, and volatilization (Locke & Boryson, 1997).

Conclusion

Geraniol at 7.5% (v/v) in combination with lemongrass leaf mulch at a rate of 4.0 t ha^{-1} inhibited the total weed emergence and weed growth by 68 and 50%, respectively. Emergence and shoot growth of *T.*

procumbens were completely inhibited by geraniol-treated lemongrass leaf mulch. The geraniol rate used in the mixtures was reduced by more than 60% as compared to the rate of geraniol when applied alone to provide the same inhibition, indicating synergistic effects between the geraniol and lemongrass leaf mulch on *T. procumbens*. Meanwhile, for emergence of *E. indica* and shoot growth of *C. distans*, the rate of geraniol applied alone was lower compared to the rate when combined with lemongrass leaf mulch. Thus, this result suggests the occurrence of antagonism when combined with the lemongrass leaf mulch. Future research can be extended to evaluate the phytotoxicity of geraniol-treated lemongrass leaf mulch on ornamental plants and other weed species in landscapes and nurseries. Besides, studies on the mixture of two oxygenated monoterpene compounds with lemongrass leaf mulch should be conducted to increase the efficacy and broaden the spectrum of weed control.

Acknowledgements

The authors would like to thank the School of Food Science and Technology for providing the facility.

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