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INTEGRATED WEED MANAGEMENT STRATEGIES IN PEANUT CULTIVATION: AN EVALUATION OF BENTAZONE + IMAZAMOX AND ESSENTIAL OILS

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Abstract

Integrated weed management systems are crucial to effectively address the growing challenges of herbicide resistance and environmental degradation, and to maintain the sustainability and productivity of our food systems. As the global agricultural community grapples with these pressing issues, this innovative research explores eco-friendly strategies for controlling weeds in peanut farming.

This study evaluated a traditional synthetic herbicide (Bentazon + Imazamox) in comparison with the potent essential oils of thyme and eucalyptus.Trial was conducted in the peanut-rich Aegean region of Türkiye during the 2022-2023 growing season, by using a randomized complete block design to ensure accurate and reliable results. Ten treatments were administered, including eight plant-based foliar sprays crafted from essential oils and hydrosols, one treatment with the commercial herbicide Bioxam, and a control was left untreated. The researchers carefully assessed the effectiveness of pinus, thyme, and eucalyptus essential oils in suppressing weeds when applied after emergence at the critical 2-4 leaf stage.

While the synthetic herbicide Bioxam achieved a remarkable 90% weed control, its success came at a cost: mild phytotoxicity, which impacted the peanut plants. This trade-off raises important questions about the long-term sustainability of chemical-based approaches. In contrast, the plant-based treatments offered a more solution, with the Pinus EO and Thyme EO treatments statistically rivaling Bioxam's effectiveness while preserving the health of the peanut plants. While, the highest yields are achieved with Bioxam herbicide applications, averaging 4,596.33 kg ha^{-1}. The natural compounds yielded a higher yield—ranging from 3.4% to 34%—compared to the control plots.

These findings suggest that integrating natural plant compounds with traditional herbicide approaches can be introduce new sustainable techniques for weed management in peanut farming, paving the way for a more sustainable and environmentally conscious agricultural.

Key words: Peanut, Weed control, Essential oils, hydrosols, Sustainable agriculture

Introduction

Integrated weed management embodies a comprehensive and environmentally strategy for weed control, integrating multiple methods to reduce weed competition with crops, proactively tackle herbicide resistance, and decrease reliance on synthetic herbicides (Abigail *et al.,* 2017; Fawad *et al.,* 2022). Despite its recognized value, the implementation of integrated weed management remains limited, possibly due to current systems not meeting growers' performance expectations (Young *et al.,* 2017). The urgency to diversify weed management practices in cropping systems is evident, especially in light of increasing herbicide resistance and the growing demand for sustainable agriculture (Owen *et al.,* 2015). Herbicide application is the dominant method of weed control in farming, exceeding other inputs, which highlights the critical role of effective weed management in successful agricultural systems (Mortensen *et al.,* 2012). Moving beyond traditional methods, integrated weed management emphasizes the integration of non-chemical strategies, particularly considering the drawbacks of relying solely on herbicides (Kurstjens, 2007; Nawab *et al.,* 2011). Integrated pest management involves a coordinated use of various tactics to optimize pest control in an ecologically and economically sustainable way (Damos, 2014). This approach stands in contrast to conventional methods that often rely heavily on single tactics, like pesticides(Shankar Raman *et al.,* 2024). Integrated weed management incorporates a range of control methods, including zero tillage, diverse crop rotations, competitive cultivars, increased crop seed rates, targeted fertilizer management, and cover crops, alongside limited herbicide use (Blackshaw *et al.,* 2008). Peanuts are a crop with low competitive ability during the early growth stage, which allows weeds to quickly become dominant. In particular, the first 4–8 weeks following emergence are identified as the most sensitive period to weed competition (Everman *et al.,* 2008). If weed control is not maintained during this period, yield losses can reach up to 70% (Wilcut *et al.,* 1995). It has been reported that the critical period for weed competition in groundnuts is longer than in many other arable crops (Knezevic *et al.,* 2002). This necessitates the implementation of control strategies at an earlier stage and with with greater precision. . Furthermore, as peanut fruits grow underground, they are vulnerable to mechanical control methods. (Wilcut *et al.,* 1995) and the use of selective herbicides are also quite risky (Grichar *et al.,* 2012). For this reason, weed control in groundnuts is a more complex and critical process compared to other arable crops, due to the plant's morphological

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characteristics (geocarpy), the long critical competition period, and the limited range of herbicide options. In this context, the development of sustainable and environmentally friendly alternatives, such as allelopathic plant extracts, is of strategic importance both for reducing yield losses and for resistance management.

Imazamox, an herbicide that inhibits acetolactate synthase, is an effective option for post-emergence weed control in peanut fields, targeting a wide variety of broadleaf and grass weeds (Umina *et al.,* 2015). However, relying solely on imazamox may create selection pressure, potentially leading to the emergence of resistant weed biotypes, underscoring the need for integrated strategies Khalil, 2012). Bentazone has been used for selective POST control of broadleaf weeds and sedges in alfalfa, asparagus, cereals, clover, digitalis, dry peas, flax, garlic, grass, green lime beans, mint, onions, potatoes, snap beans for seeds, sorghum, soybeans, and sugarcane(Herrmann *et al.,* 2017; Iqbal *et al.,* 2027).

Bentazone is a contact herbicide that interferes with susceptible plants' ability to use sunlight in producing survival energy through photosynthesis. Bentazone is absorbed by leaves upon application as a foliar spray, accompanied by rapid break-down or metabolism into natural plant components and metabolites in resistant plants, such as starch, protein, lignin, amino acid, and cellulose (Ali *et al.,* 2020).

The use of essential oils, derived from various plant species, in weed management strategies offers a promising path for more sustainable weed control. These oils can function as bioherbicides, applied pre- or post-emergence, or as adjuvants to improve the effectiveness of synthetic herbicides. Their diverse modes of action and relatively lower environmental impact make essential oils appealing alternatives to synthetic herbicides (Soesanto *et al*., 2020). Understanding the biology and ecology of target weeds is crucial for developing effective integrated weed management programs, where recognizing critical periods for weed control and executing timely interventions are essential (Strek, 2014).

Non-chemical weed management is a valuable alternative as it enables sustainable agricultural practices, provides cost-effective alternatives that improve crop quality and marketability, and is easy to implement (Pavlović *et al.,* 2022; Alluri & Saha, 2024; Raza *et al.,* 2025).

Integrating essential oils into peanut cropping systems is an effective approach to managing weeds by leveraging allelopathic effects and competition. For non-chemical integrated weed management to succeed, it's important to accurately identify weed species, assess their density, and time of herbicide applications. Therefore, the effectiveness of this management strategy relies on creating solutions that are economically viable for farmers while also being environmentally friendly and socially responsible, promoting sustainable agricultural productivity and ecological integrity.

Therefore, in this study, it was aimed to compare the efficacy of both synthetic chemical herbicides and plant-based essential oils, their effects on weed growth periods and crop yield and to determine the results of the applications that can be applied.

Material and Methods

The experiment took place in the Aegean region of Türkiye during the 2022–2023 peanut growing season, under field conditions. The site featured clay loam soil with moderate fertility, and the region is characterized by a Mediterranean climate, receiving an average annual rainfall of 700 mm. The field trial employed a randomized complete block design (RCBD) with three replications and a total of eleven treatments. These treatments comprised eight plant-based foliar sprays, one commercial herbicide (BİOXAM, which contains 480 g/l Bentazone and 22.4 g/l Imazamox), and a control. Each plot was 20 m² in size (4 m x 5 m).

Preparation of plant extracts: Thyme (*Thymus vulgaris* L.), Scots pine (*Pinus sylvestris* L.), and Eucalyptus (*Eucalyptus obliqua* L'Hér.) leaves were ground and stored at room temperature until needed. To prepare the aqueous extract, 40 grams of thyme powder were mixed with 200 cm³ of distilled water in a conical flask. The mixture was stirred with a magnetic blender for 30 minutes and then centrifuged for 15 minutes. The solution was heated in an electric furnace at 35°C until the extract was ready, from which we prepared 25% solutions.

Gas chromatography-mass spectrometry (GC-MS) analysis: The chemical compositions of the samples were determined using a Thermo Scientific Trace GC1310-ISQ mass spectrometer with a direct capillary column TG-5MS. Column oven temperature was programmed as follows: 50°C initial temperature, 5°C/min ramp to 230°C, 2-minute hold, 30°C/min ramp to 290°C, and 2-minute hold. Injector and MS transfer line temperatures were set to 250°C and 260°C. Helium carrier gas flowed at 1 mL/min. After a 3-minute solvent delay, an Autosampler AS1300 injected 1 µL of each diluted sample into the GC system in split mode. Mass spectra were acquired using electron ionization at 70 eV, scanning m/z 40-1000. Ion source temperature was 200°C. Components were identified by matching retention times and mass spectra to NIST 11 database entries.

Treatments were applied at the 2–4 leaf stage of crop and weed development using a backpack sprayer calibrated to deliver 300 L/ha at 3 atm pressure. Weed assessments were conducted at 30 and 60 days after treatment (DAT), measuring weed density with 1 m^{-2} quadrats, biomass (dry weight at 65°C for 72 hours), and visual phytotoxicity ratings (scale 0–10). Crop parameters, including plant height, pod count, and yield (kg/ha), were collected at harvest. Statistical analysis was performed using one-way ANOVA and LSD tests (α=0.05) in R software (v4.2.0), with percentage data arcsine-transformed for variance stabilization prior to analysis.

Trial applications: The experiment utilized a randomized complete block design featuring two types of weed interference treatments: plots with weeds and plots without weeds at different time intervals (Ghamari, 2015). Research underscores the importance of early-season weed control to optimize yield (Mulder & Doll, 1994; Lee *et al.,* 2022). The weed-free and weedy periods were managed by manually removing or introducing weeds at various crop growth stages.

When selecting the study area, it is essential to consider factors such as weed pressure, soil properties, and cropping history. The experimental design should reflect these considerations to ensure accurate and reliable results.

To preserve the quality of the experimental data, sprayers were calibrated to ensure a consistent delivery rate of treatment solutions across all plots.

Additionally, it is important to monitor environmental conditions during herbicide applications, including temperature, humidity, and wind speed, as these factors can significantly impact herbicide effectiveness and crop safety.

Herbicide applications were conducted post-emergence when weeds reached the 2–4 leaf stage. Regular visual assessments of weed control efficacy were performed at intervals (e.g., 14, 21, and 28 days after treatment) using a standardized rating scale from 0% (no control) to 100% (complete control).

For example, in herbicide trials using a randomized block design, sprayers were calibrated to apply herbicides evenly across 20 m² plots at a pressure of 3 atm, delivering 30 L of water per acre (Price *et al.*, 2021). Weed control and crop response assessments were conducted by counting weed densities in 1 m² quadrats and visually rating phytotoxicity.

Results and Discussion

GS-MS plant extract analysis results: 1,8-cineol is known to have a pretty significant effect on plants, its ability to inhibit root growth. Studies have shown that this compound significantly reduces root length in a dose-dependent manner (Koitabashi *et al.*, 1997). The fact that roots are affected more than hypocotyls and shoots is explained by the fact that root development depends on both cell division and cell elongation (Yoshimura *et al.*, 2011). Limonene and pinene are volatile monoterpenes commonly found in many aromatic plants (particularly in the Lamiaceae, Myrtaceae and Pinaceae families). These compounds are defined as allelochemicals that play a significant role in interplant competition (Cheng & Cheng, 2015). It has been demonstrated in numerous studies that these volatile compounds, when released into the environment, inhibit the growth of neighbouring plants and, in particular, inhibit seed germination (Singh *et al.*, 2002). It has been reported that geraniol and citronellol exertgrowth-inhibiting effects and that this effect stems from monoterpene alcohols, including citronellol (Dudai *et al.*, 1999; Kordali *et al.*, 2007). It is known that nerol exerts allelopathic effects on surrounding plants (Dudai *et al.*, 1999; Cheng & Cheng, 2015). Thymol, γ-terpinene and p-cymene suppress the root and hypocotyl development of plants exhibiting strong allelopathic properties (Abd-ElGawad *et al.*, 2020; Vokou *et al.*, 2003).

The concentrations of allelopathic compounds present in the plant extracts used in the trial were determined (Table 1).

Weed suppression: Table 2 summarizes the key weed species identified in the peanut field trial, along with their density per square meter, fresh biomass, and dry biomass. These figures represent average values from four replicates.

Additionally, the table presents a statistical analysis of weed biomass, weed control percentages, phytotoxicity ratings, and yield performance for selected treatments in peanut cultivation. The data clearly shows differences in effectiveness and crop safety among the treatments.

The results indicated that pinus + thyme, pinus, thyme, eucalyptus essential oils significantly reduced fresh weed biomass compared to the control and hydrosol treatments, achieving weed control percentages of 74.2%, 66.2%, 64.3% and 64.1%, respectively. The commercial herbicide Bioxam provided the highest effectly reduction on fresh weed weight at 89.7%, significantly outperforming all essential oil and hydrosol treatments. In contrast, rose and sage hydrosols offered modest fresh weed weight, with reductions in fresh weed biomass of 35.3% and 41.0%, respectively, and were statistically similar to the control (Table 2).

Statistical analysis of the treatments' effects on weed dry weights indicated significant differences. Bioxam (90.1%) proved to be the most effective treatment for reducing weed dry weight, while essential oils also significantly decreased weed biomass. The reductions were notable, with Pinus EO + Thyme EO at 75,6%, Pinus EO 66.0%, Thyme EO at 63.2%, and Eucalyptus EO at 62.4% (Table 2).

Table 1. The concentrations of compounds in plant extracts.

Compounds	***Rosa damascena* Mill. (Rose Hydrosol)**	***Salvia officinalis* L. (Sage Hydrosol)**	***Eucalyptus globulus* Labill. (Eucalyptus EO)**	***Thymus vulgaris* L. (Thymues EO)**	***Pinus sylvestris* L. (Pinus EO)**
Citronellol	30.0 – 40.0%				
Geraniol	8.0 – 15.0%				
Nerol	3.5 – 10%				
Phenylethyl alcohol	15.0 – 30.0%				
Limonene	0.6 – 2.5%		2.0 – 10.0%		5.5 – 13.0%
P-cymene	0.5 – 1.8%		3.0 – 10.0%	12.0 – 25.0%	
Eugenol	0.3 – 1.2%				
Linalool		15.0 – 30.0%		3.0 – 6.0%	
Linalyl acetate		10.0 – 25.0%			
1,8-cineole		10.0 – 20.5%	52.0 – 70.0%		
Camphor		3.0 – 12.0%			2.0 – 5.0%
α-thujone		7.5 – 15.5%			
β-thujone		4.5 – 10.0%			
α-pinene			5.0 – 15.0%		30.0 – 35.0%
γ-terpinene			1.0 – 3.0%	8.0 – 15.0%	
α-terpineol			4.0 – 8.0%		
Thymol				22.0 – 42.0%	
Carvacrol				7.0 – 30.0%	
β-pinene					9.0 – 18.0%
Sabinene					4.6 – 10.0%
Terpinen-4-ol					3.4 – 7.0%

Table 2. Weed suppression effects of treatments.

Treatment	Fresh weight ($g\ m^{-2}$)	Dry weight ($g\ m^{-2}$)	Fresh weed control (%)	Dry weed control (%)
Control	575.66 a	272.79 a	0.0	0.0
Rose Hydrosol	372.20 b	184.89 b	35.3	32.2
Sage Hydrosol	339.76 c	162.32 c	41.0	40.5
Eucalyptus EO	206.83 d	102.61 d	64.1	62.4
Thyme EO	205.67 d	100.41 d	64.3	63.2
Pinus EO	111.54 d	92.73 d	66.2	66.0
Pinus EO + Thyme EO	148.07 e	66.65 e	74.2	75.6
Bioxam ()	59.02 f	26.98 f	89.7	90.1
F ($p<0.05$)	***	***		

Table 3. Average number of weeds in treatment plots (weed m^{-2}).

	Treatment	Control	Rose hydrosol	Sage hydrosol	Eucalyptus EO	Thyme EO	Pinus EO	Pinus + Thyme EO	Bioxam
Weed species	*Amaranthus retroflexus*	12.75	6.25	7.52	4.58	4.03	1.59	2.25	1.21
	Chenopodium album	6.00	3.85	3.54	2.15	1.90	0.75	1.15	0.75
	Cyperus rotundus	18.45	10.95	8.86	6.65	3.85	1.25	2.35	1.90
	Echinochloa crus-galli	11.25	7.25	6.64	4.00	3.56	1.75	0.25	1.75
	Portulaca oleraceus	7.50	4.55	3.45	2.60	2.35	0.75	1.30	0.70
	Solanum nigrum	5.25	3.40	1.10	1.00	1.66	0.65	0.75	0.54
	Xanthium strumarium	6.45	4.10	3.80	2.50	2.04	0.25	1.35	0.35

Table 4. Yield and phytotoxide effects of treatments in the trial field.

Treatment	Crop phytotoxicity (0–10)	Grain yield ($kg\ ha^{-1}$)
Control	0.0	3124.67 d
Rose Hydrosol	0.0	3231.50 d
Sage Hydrosol	0.0	3271.00 d
Eucalyptus EO	0.0	3540.83 cd
Thyme EO	0.0	3857.83 bc
Pinus EO	0.0	4019.33 b
Pinus EO + Thyme EO	0.0	4187.83 ab
Bioxam (480 g L Bentazone + 22.4 g L Imazamox)	2.0	4596.33 a
F ($p<0.05$)		***

Upon analysing the weed densities in the treatment plots on the 14th, 21st, and 28th days, the control plots exhibited the highest density. The weed densities in the Bioxam, Pinus, and Thyme EO treatments were notably low. Although weeds were managed effectively in these plots, new emerging weeds were also observed (Table 3).

Crop yield: In our investigation of phytotoxicity from weed control treatments on peanuts, only Bioxam herbicide made its presence known, registering a phytotoxicity value of 2.0 during the crucial 6-8 leaf stage. However, the persisting symptoms disappeared within two weeks. In analyzing the impact of treatments on peanut yields, we found significant differences at the 5% level. Control plots, constantly left with weed, yielded the least. In contrast, the treatments with Bioxam herbicide, Pinus EO + Thyme EO, Pinus EO, and Thyme EO achieved the highest yields, all nestled in the same statistical category. Specifically, these treatments generated yields that were roughly 1.47, 1.34, 1.28, and 1.23 times greater than the control (continuous weedy plots). Furthermore, Eucalyptus EO and Hydrosol applications also found their place in the same statistical cluster, reflecting their strong performance in comparison (Table 4).

Discussion

The findings of the study emphasized the effectiveness of certain essential oils, particularly eucalyptus and thyme, in controlling weed growth in peanut fields. This was consistent with earlier research that highlights the herbicidal properties of essential oils (Tworkoski, 2002). Essential oils disrupted to weed membranes and induced oxidative stress, as indicated by increased electrolyte leakage, proline levels, and lipid peroxidation (Khare *et al.*, 2019). To overcome the limitations of essential oils, nanoformulation can protect them from degradation and allow for controlled release, thereby improving their effectiveness and usability González *et al.*, 2014). The phytotoxic effects of these oils were largely due to their high content of monoterpene hydrocarbons (Almarie & Almarie, 2020; Kochti *et al.*, 2024). In a study by Hazrati *et al.*, (2018) and Ibáñez & Blázquez (2020), basil essential oil was tested on common weeds in tomato crops, resulting in a weed biomass reduction of up to 70%, which suggests its potential as a natural herbicide. Additionally, thyme essential oil was found to significantly reduce weed growth in sunflower fields, achieving a 65% reduction in biomass, indicating its effectiveness in weed management while being safe for the crop (Ramezani *et al.,* 2008).

Cinnamon essential oil (EO) effectively reduces the water content in the leaves of *Trifolium incarnatum* and *Lolium perenne* when compared to the control group. At concentrations of 3% and 6%, the essential oil decreased water content by approximately 56% and 63% for *T. incarnatum*, and by 24% and 36% for *L. perenne*, respectively (Ben Kaab *et al.,* 2024). Another study indicated that peppermint EO was the most effective treatment for corn and weeds, surpassing any mixtures. Oilseed rape fatty acid methyl esters (FAME) showed the best overall performance, resulting in less than 10% injury to corn while causing over 84% injury to barnyard grass and 50% injury to common lambsquarters (Synowiec *et al.,* 2017).

For peppermint essential oil nanoemulsions (PNs), a concentration that caused 10% damage to maize was 2.2%, while doses leading to 50% and 90% damage to barnyard grass were 1.1% and 1.7%, respectively. PNs at 5% or 10% concentration caused significant reductions in relative water content in leaves and Chlorophyll a fluorescence 72 hours after application. In conclusion, peppermint nanoemulsion with Eco-Polysorbate 80 at a 2% concentration presents a viable option for the selective control of barnyard grass in maize (Rys *et al.,* 2022). In our study, pistachio plants did not suffer any damage from plant extracts. In Pinus and Pinus+Thyme extracts, damage ranging from 10% to 40% was observed on the leaves of broad-leaved weeds such as *A. retroflexus* and *C. album.*

The minimal phytotoxicity observed with BIOXAM emphasized the importance of evaluating herbicide selectivity to ensure crop safety. Essential oils, with their complex mixtures of volatile compounds, offer multiple action pathways, potentially reducing the risk of resistance compared to synthetic herbicides that focus on single targets.

This study also points to commercial opportunities for essential oils (Adukwu *et al.,* 2016). However, it is necessary to investigate the forms that can be applied in their pure forms and as nanoemulsions to increase the bioavailability and stability that will increase the effectiveness of essential oils.

Conclusion

In summary, the study demonstrates that both synthetic herbicide and plant-based essential oil treatments significantly influence weed suppression and peanut yield under field conditions. The commercial herbicide (Bentazone + Imazamox) achieved the highest weed control efficiency, reaching 89.7% (fresh biomass) and 90.1% (dry biomass reduction), and resulted in the maximum yield (4596.33 kg ha^{-1}). However, this treatment caused temporary phytotoxicity (score: 2.0), highlighting potential risks associated with sole reliance on chemical control.

Among plant-based treatments, Pinus EO + Thyme EO combination emerged as the most effective alternative, providing 74.2% fresh and 75.6% dry weed control, with no phytotoxic effects, and achieving yields statistically comparable to the herbicide treatment (4187.83 kg ha^{-1}). Individual applications of Pinus EO (66.2–66.0%) and Thyme EO (64.3–63.2%) also demonstrated strong weed suppression and yield improvements over the control. In contrast, hydrosol treatments showed limited effectiveness and were not significantly different from the control in some parameters.

These findings confirm that essential oils can provide substantial weed suppression while ensuring crop safety, although they are slightly less effective than synthetic herbicides in absolute control levels. Importantly, the absence of phytotoxicity and their multi-target modes of action make essential oils promising tools for reducing herbicide dependency and mitigating resistance development.

From an integrated weed management (IWM) perspective, the results indicate that combining essential oils with reduced herbicide doses or other cultural practices can optimize both efficacy and sustainability. This approach can maintain high yield performance while lowering environmental impact and chemical input.certain essential oils, like pinus, eucalyptus and thyme, are promising and eco-friendly alternatives to synthetic herbicides for managing weeds in peanut fields. These oils not only provided effective weed control but also ensured the safety of the crops, making them a practical choice for sustainable agriculture. Furthermore, their intricate mechanisms and biodegradability make them appealing options for reducing reliance on synthetic herbicides and lessening environmental impacts. Due to these properties, it can provide great benefits as ingredients that should be included in the management of less herbicide-resistant weeds and herbicide resistance.

From an Integrated Weed Management (IWM) perspective, this study suggests that these plant extracts can be effectively combined with cultural practices (such as crop rotation and cover crops), mechanical methods (like early cultivation), and chemical approaches. This integration can improve system resilience by addressing weeds at various life stages and minimizing reliance on any single control method (Swanton & Weise, 1991). Long-term strategies should involve repeated applications across seasons, monitoring seedbank density, and assessing cumulative impacts on weed community structure. Future research should focus on multi-year field trials to measure seedbank depletion rates, changes in species composition, and potential synergistic effects when reducing herbicide usage.

More research is needed to refine application techniques, assess the long-term effects on weed populations, and investigate how essential oils can be combined with other integrated weed management methods to boost their effectiveness and sustainability. Additionally, exploring nanoformulations of essential oils could enhance their stability, bioavailability, and overall effectiveness in agricultural use. Future research should also examine the synergistic and antagonistic interactions among the components of essential oils.

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