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Article

Analysis of the Effects of Organic and Synthetic Mulching Films on the Weed, Root Yield, Essential Oil Yield, and Chemical Composition of *Angelica archangelica* L.

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Abstract: *Angelica archangelica* L. (Garden angelica) is a medicinal and aromatic plant from the *Apiaceae* family, originating from North Europe (Iceland, Greenland, and Scandinavian countries). *A. archangelica* is commonly used in traditional medicine to treat anxiety, insomnia, stomach and intestinal disorders, skin conditions, respiratory problems, and arthritis. This plant is generally cultivated for its root and seed where the essential oil (EO) is concentrated the most. *Angelica archangelica* cultivation has a lot of challenges but the main one is weed control; so, the aim of this study was to investigate the influence of four different mulch types as non-chemical weed control measures on weediness, fresh root yield, and EO chemical composition and yield from *A. archangelica* roots. A field trial was conducted with the following six treatments: two organic mulches, two synthetic mulches, and two controls (regular hand-weeded and weeded). The results show that the most present weeds were *Ambrosia artemisiifolia*, *Chenopodium album*, *Polygonum aviculare*, and *Polygonum lapathyfolium*, but synthetic mulch foils achieved the best weed suppression (100%). These fields also achieved the highest fresh root yield in both of the experimental seasons. The highest EO yield was detected with agrotextile mulch foil at season I (0.41%, v/w) and with the weeded control (0.51%, v/w) at season II, but dominant components at both seasons were α-pinene and β-phellandrene. The results suggest that the agrotextile black and silver–brown mulch foils achieved complete weed suppression, but the agrotextile black mulch foil had a better effect on fresh root yield, EO yield, and its chemical composition.

Keywords: *Angelica archangelica* L.; mulches; weeds; essential oil

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1. Introduction

A high exposure to stress and negative impact of harmful substances from food and the environment have led to the fact that the modern human increasingly turns to the use of natural components whenever possible, especially when it comes to food and disease prevention. Due to this, there is a high market demand for plant raw materials from their natural sources for use in the cosmetic, pharmaceutical, and food industries. The sources of raw materials include the natural collection of medicinal and aromatic plants, which is becoming insufficient due to rising demand. A prominent challenge that comes with gathering natural resources is incorrect identification of medicinal and aromatic plants; one way to overcome that is to cultivate medicinal plants [1]. As a result, medicinal and aromatic plant cultivation is expanding.

Angelica archangelica L. (Garden angelica) is an aromatic medicinal plant whose natural habitat and origin is in the northern region of Europe (Iceland, Greenland, and Scandinavian countries), as well as in the Himalayas, while it is cultivated in most other regions, mainly in Asia, Central Russia, and Thailand [2,3]. *A. archangelica* is planted from seedlings in autumn, while the root harvest is a year later. If the goal of production is a seed, angelica growing takes a year and a half (angelica begins to flower, yield fruit, and produce seeds in the spring of the second year) [2]. An extremely developed root system is characteristic for angelica, where the largest amount of essential oil (EO) is concentrated, which is mostly why this plant is cultivated [3]. The plants from this genus are generally cultivated for their roots (*Angelicae radix*), an official drug according to the European Pharmacopoeia [4]. *A. archangelica* is commonly used in traditional medicine to treat anxiety, insomnia, stomach and intestinal disorders, skin conditions, epilepsy, fever, wounds, respiratory problems, and arthritis [5,6]. Various phytoconstituents were found in the plant, but the most abundant phytoconstituents are EOs and furocoumarins (the most abundant are archangelicin, angelicin, bergapten, imperatorin, and xanthotoxin) in various parts of the plant, but they are mostly concentrated in the root [7]. *A. archangelica* also represents a multilateral source of many other bioactive metabolites, including polysaccharides, phenolics, alkaloids, steroids, lignins, resins, tannins, etc. [8]. Many researchers have reported about angelica EOs' antioxidant, antimicrobial, antiviral, antimutagenic, anticancer, anti-inflammatory, and immunomodulatory activities [7,9–12]. The published reports revealed that angelica root EOs mainly consist of monoterpene hydrocarbons. The chemical composition of EOs is highly influenced by various parameters, such as harvesting time, growing season, environmental conditions, plant maturity, genetic diversity, nutritional status, drying methods, extraction, and analysis techniques [13,14]. According to previous research, the main EO components are the following: α-pinene, δ-3-carene, limonene, β-phellandrene, α-phellandrene, and p-cymene [5,10,15,16].

Cultivation of medicinal plants has a lot of challenges, and the main one is weed control [17–20]. Uncontrolled interaction between weeds and the crop can result in a reduction in yield by up to 45% [17]. Matković et al. (2016) [18] reported that weeds have caused the loss of aboveground biomass of *Mentha* × *piperita* by up to 89% in field production in Serbia. On the other hand, Carrubba and Militello (2013) [21] reported that weeds have caused a 79.6% seed yield loss of *Foeniculum vulgare*. Considering the potentially large damage that weeds can cause, *A. archangelica* production on large areas is much more practical with the use of herbicides in order to control them, but the application of herbicides in this kind of crop has a lot of risks. Medicinal plants are employed in pharmaceutical, cosmetic, and medical fields, while pesticides residues in raw material or final product are considered very dangerous and harmful. The aim of this study was to investigate one of the most prospective non-chemical weed control measures—mulching and its influence on weediness—on *A. archangelica* fresh root yield, *A. arcahgelica* EO yield, and chemical composition. Mulching might be performed either by the use of biodegradable mulching materials or with various mulch films. This weed control method can be useful for multiple reasons: mulching enacts a direct mechanical pressure on the ground [22] and prevents or postpones weed's seed germination and emergence, thus providing crops with a competitive advantage by creating favorable conditions for their development. Meanwhile, it indirectly regulates the soil pH and humidity, prevents temperature oscillations, and reduces pest and disease incidence [23–25]. Also, mulch usage is recognized as an effective crop production cultivation strategy used in the face of climate change-related extreme weather conditions (increasing air temperatures, relatively little precipitation, and heavy rainfalls) [26,27]. Its efficiency depends on the type of the material used for mulching (organic or synthetic) and its thickness and durability within the application period [19,20,28,29], so two organic and two synthetic mulches were included in this study.

Having in mind the challenges in weed control in medicinal and aromatic plants, where herbicide application is not recommended, the main aim of this study was to estimate the best mulch solution for weed management. An additional aim was to estimate selected mulches' effect on fresh root yield and EO yield and chemical composition.

2. Materials and Methods

2.1. Field Trial

The field trial was conducted in Kujavica village (N: 4947855; E: 404266), near the city of Šabac (Vladimirci municipality, northwest Serbia), on semi-clay soil (chemical analysis was conducted before planting, Table 1). The experiment was carried out during two consecutive years: the first experimental season (season I: 29 November 2019–27 October 2020) and the second experimental season (season II: 27 November 2020–3 November 2021). The closest weather station provided monthly mean meteorological data and was located in Sremska Mitrovica (<50 km), and it is shown in Table S1 (Supplementary Materials).

Table 1. Soil chemical analysis results before planting.

pH		$CaCO_3$ (%)	Humus (%)	N (%)	P_2O_5 (mg/100 g)	K_2O (mg/100 g)
H_2O	KCl					
6.20	5.50	0.00	2.24	0.15	63.10	128.00

The previous crop in the first experimental season was strawberry, and in the second experimental season it was winter wheat. The experimental field was prepared in the following way: ploughing was preformed to a depth of 30 cm (in the end of September) with a plow "IMT 754"; pre-sawing soil preparation was carried out with a heavy-duty rotary tiller (model: "FPM 619") one day before planting (in the end of November). Regarding soil properties, fertilization was carried out in spring at the beginning of vegetation period with ammonium nitrate (34% N, commercial name: Genezis) at a rate of 250 kg ha^{-1}.

A. archangelica seedlings were produced in open field conditions via hand sowing in summer (at the beginning of August) at a soil depth of 5–7 cm. The seeds originated from a commercial farm in Serbia engaged in the production of *A. archangelica*. This farm received *A. archangelica* seed from a seed collection at the Institute for Medicinal Plant Research "Dr Josif Pančić" for starting their production. The seeds were collected in the beginning of June from the central part of the inflorescence and stored in a dark and dry place for ripening. After ripening, the seeds were stored in a freezer at a temperature of −20 °C. In November, the seedlings were ready for planting at the experimental field. Transplantation was performed with a 70 cm distance between rows and 33–35 cm between plants in the row.

The experiment was carried out with a completely randomized block design (CRBD) with the following six treatments: two organic (mixture of acacia and oak sawdust and wheat straw) and two synthetic (agrotextile water-permeable black foil and silver–brown foil produced by Ginegar Plastic Products Ltd. (Ginegar, Israel), Kibbutz Ginegar 3658000 Israel mulches and two controls (regular hand-weeded and weeded) in three replicates. Each plot was 11.2 m^2 (4 m × 2.8 m). The treatment layouts are presented in Table S2 (Supplementary Materials) and Scheme 1.

Mixture of acacia and oak sawdust and wheat straw were applied at a thickness of 10 cm on the surface of the whole plot (between rows and between plants in rows). Also, mulch foils were applied to the whole plot. All mulches were set up in early spring before weeds sprouted.

Scheme 1. Experimental field assay.

2.2. Weed Flora, Density, and Total Dry Weed Biomass

In the weeded control (WCT) and in treatments infested by weeds due to insufficient mulch efficacy (S and SW), weeds were collected at the end of the angelica growing season. It was conducted a few days before root harvesting from the whole elementary plot (2.8 m × 4 m) during both years to obtain weed flora, weed density, and biomass values. All parameters were calculated per m^2 area. After harvesting, all weeds were determined and counted. For weed biomass, collected weeds were dried in an oven at 105 °C for 48 h. The average total dry weed biomass (TDWB) per plot was measured and expressed in grams per unit of soil surface ($g\ m^{-2}$). The effect of the applied mulches on the weeds at the end of growing season was estimated as a percentage of TDWB reduction in comparison to WCT based on the following formula:

$$TWDBr\ (\%) = 100 - TDWBt/TWDBc \times 100, \quad (1)$$

where TWDBr is TWDB reduction, TDWBt is TWDB in the mulch treatment, and TWDBc is TWDB in the control.

2.3. Roots Harvesting

At the end of first year vegetation period (autumn, November), mechanical harvesting of angelica's roots was performed with a single-furrow plow. After harvest, the roots were cleaned of soil and other impurities and measured to calculate the total yield per ha. Cleaned fresh roots, after measurement, were collected and dried naturally at a temperature of 23 °C in the dark for two weeks. Dried samples were frozen and stored until the moment of laboratory analysis.

2.4. Essential Oil Extraction and Chemical Compound Identification

Angelica root essential oil was obtained via hydrodistillation in a Clevenger-type apparatus. Chemical characterization of the essential oil was performed using gas chromatography (GC) equipped with two types of detectors. Quantitative analysis was conducted using an Agilent GC 7890A model (Agilent, 5301 Stevens Creek Blvd. Santa Clara, CA, USA) equipped with a split/splitless injector, HP-5 capillary column (30 m 0.32 mm i.d. 0.25 µm film thickness), and flame ionization detector (FID). Injector and detector temperatures were set to 250 °C and 300 °C, respectively, while the nitrogen flow rate was 1 mL min^{-1}. The column temperature was linearly programmed to rise from 50 °C to 250 °C at 4 °C min^{-1} before holding for 10 min. Qualitative analyses were performed on the Varian CP-3800 GC (Varian, Inc. 2700 Mitchell Drive, Walnut Creek, CA, USA) gas chromatograph equipped with a Saturn 2200 mass spectrometer (MS) as a detection device. The column type, Injector, and column temperatures were the same as for GC-FID analysis. Helium was the carrier gas, and the flow rate was 1 mL min^{-1}, while the ion trap and transfer line temperatures were set to 250 °C and 280 °C, respectively. The mass detector was operated in the electron impact (EI) mode (70 eV; 40–600 m/z range). In both cases, the essential oil solution in n-hexane (1% v/v) was injected in the split mode (1:20).

Essential oil components were identified by comparing the obtained experimental retention indices (RIs) with literature data [30] and their mass spectra with those from the Wiley 7.0 mass spectral library. RI values were determined concerning a homologous series of n-alkanes (C6–C28), analyzed via both GC-FID and GC-MS under identical operating conditions as for the essential oils. Quantitative data were expressed as area percent obtained via the GC-FID analysis.

2.5. Statistical Analysis

All statistical analysis was performed using IBM SPSS Statistics version 25.0 for Windows. Logarithmic transformation of the raw data was used for checking homogeneity of the analyzed groups. One-way ANOVA was applied to the data and was performed to test the effect of four mulch treatments and two controls and their interactions. Multiple comparisons were made using Duncan's test to detect significant differences between arithmetic means of weed biomasses and root yields ($p < 0.05$).

3. Results

3.1. The Mulches' Effect on Weediness

In both experimental seasons, the treatments with synthetic mulch foils (ATF and SBF) achieved complete weed suppression and there were no detected weeds as well as at WFC. In weed infested treatments (SW, S, and WCT), the total number of detected species was 27 in season I, and 18 in season II, but broadleaf weed species were more numerous (season I: 22; season II: 15) than grasses (season I: 5; season II: 3) (Table 2, Scheme 2). In experimental season I, the most abundant broadleaf weed species for all infested treatments was *Ambrosia artemisiifolia* (SW: 29.05 plants m^{-2}; WCT: 19.05 plants m^{-2}; S: 15.33 plants m^{-2}), while *Agropyrum repens* (SW: 55.18 plants m^{-2}; S: 83.93 plants m^{-2}) and *Carex myosuroides* (S: 54.46 plants m^{-2}) were the most numerous grass weed species. Beside them, very dominant weeds were *Setaria viridis* (SW: 24.15 plants m^{-2}), *Polygonum aviculare* (WCT: 10.63 plants m^{-2}), *Polygonum lapathifolium* (S: 9.11 plants m^{-2}), *Echinocloa crus-galii* (SW: 7.95 plants m^{-2}), and *Cirsium arvense* (SW: 15.67 plants m^{-2}). In experimental season II, *Ambrosia artemisiifolia* was also one of the most dominant weeds (WCT: 22.92 plants m^{-2}) followed by *Chenopodium album* (WCT: 21.96 plants m^{-2}; SW: 10.89 plants m^{-2}) and *Cirsium arvense* (S:10.71 plants m^{-2}). The rest of the detected weed species were much less numerous.

The highest value of TDWB at the end of experimental season I was found for the WCT treatment (426.14 g m^{-2}). In S (365.51 g m^{-2}) and SW (384.39 g m^2), TDWB values were significantly lower in comparison to WCT, but between them, there were no significant differences (Figure 1). Also, in experimental season II the highest TDWB value was measured for WCT (1114.14 g m^{-2}) (Figure 2). The treatments with the two organic mulches (S: 405.79 g m^{-2} and SW: 664.27 g m^{-2}) resulted in lower TDWB values in regard to WCT due to weed suppression. The S treatment achieved significantly better weed suppression than SW, which was not evaluated a year ago. Generally, in comparison to experimental season I, the two organic mulches in season II achieved better weed suppression. Significant differences between SW and WCT were also detected, as well as in experimental season I (Figure 2). Although a lower number of weed species were detected in experimental season II (Table 2), their TDWB was higher (Figure 2).

Table 2. Weed composition and density (number of plants per m^2) on the field at the end of the first and second experimental seasons.

Weed Species	Season I			Season II		
	SW	S	WCT	SW	S	WCT
Abutilon theophrasti	0	0	0	0.09	0	0
Agropyrum repens	55.18	0	4.24	0	0	0
Amaranthus retroflexus	0	0	0	0.09	0	0
Ambrosia artemisiifolia	29.05	15.33	19.05	5.68	6.99	22.92
Anagalis arvensis	0	0.71	0	0	0	0
Artemisia vulgaris	0	0	0.09	0	0	0
Aster litoralis	3.04	1.07	6.43	0	0	0
Avena fatua	0	0	0	0	0	4.91
Capsella bursa-pastoris	0	0	2.23	0	0	0
Carduus acanthoides	0	0.09	0.27	0	0	0
Carex myosuroides	0	54.46	0	0	0	0
Chenopodium album	0.27	1.13	2.08	10.89	3.21	21.96
Cichorium intybus	0.45	0	0.45	0.27	0.18	0.51
Cirsium arvense	15.67	0	0	0.09	10.71	0
Convolvulus arvensis	0	0	0	1.34	0	1.92
Datura stramonium	0	0	0	0.18	0	0
Daucus carota	1.73	0.09	0.36	0	0	0
Echinocloa crus-galii	7.95	0	0	0.27	0	0
Erigeron canadensis	0	0.27	0.71	0	0.09	0.09
Fragaria vesca	1.52	0.54	0.31	0	0	0
Lactuca serriola	0	0	0.39	0	0	0.31
Lolium multiflorum	0	0	3.13	0	0	0
Mentha longifolia	1.96	0	0	0	0	0
Pastinaca sativa	0	0.18	0	0	0	0
Picris hieracoides	0.09	0	0	0	0	0
Plantago major	0	0.27	0.58	0	0	0
Polygonum aviculare	9.26	7.11	10.63	0.22	0.09	3.72
Polygonum lapathyfolium	7.17	9.11	4.49	0	0	0.18
Setaria viridis	0	0	0	2.05	0.80	0
Solanum nigrum	0	0	0	0	0	0.09
Taraxacum officinale	0.36	1.61	0.54	0	0	0
Trifolium pratense	0	0	0	0.18	0	0
Trifolium repens	0	0	0.18	0	0	0
Triticum vulgare	0	6.70	0	0	0	0
Vicia sativa	0.18	0	0	0	0	0
Xanthium strumarium	0	0	0	0.09	0	0.09

S—straw; SW—sawdust; WCT—weeded control.

It is noticeable that the best weed suppression (100%) was achieved with synthetic mulches (ATF and SBF) in both seasons (Table 3). In season I, TDWB reduction via organic mulches was significantly lower (S: 14.22% and SW: 9.79%) in comparison to mulch foils. In season II, TDWB reduction via organic mulches was better than in the previous year: 63.58% and 40.38%, respectively.

Scheme 2. Weediness of *A. archangelica* experimental field.

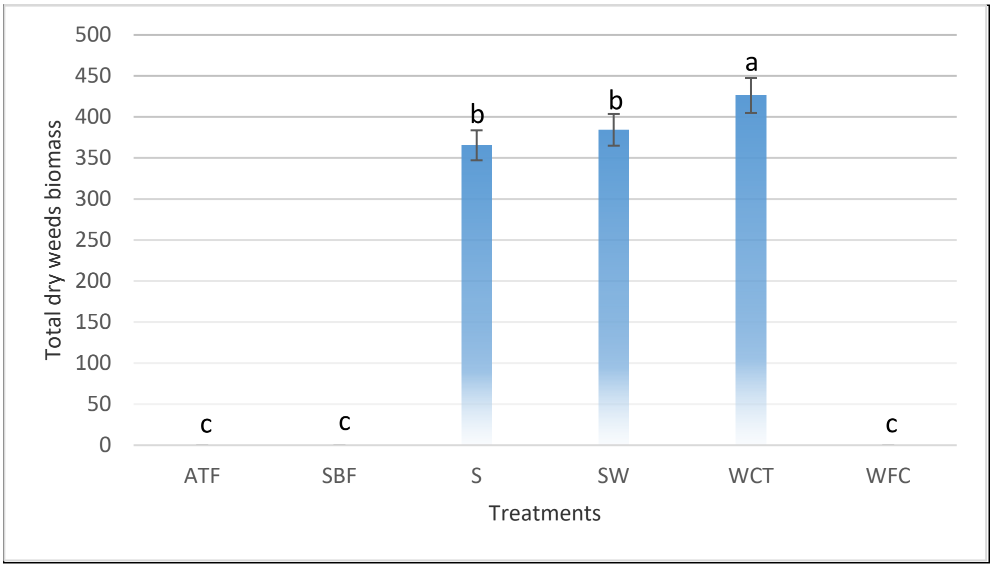

Figure 1. Total dry weed biomass (TDWB; g m^{-2}) in the first experimental season. Letters on bars (a–c) refer to the statistical evaluation of the sum of the dry weed biomass illustrated by stacked bars in the diagram ($p < 0.05$ Duncan's test). Synthetic mulches: ATF—agrotextile foil; SBF—silver–brown foil. Organic mulches: S—straw; SW—sawdust. Controls: WCT—weeded control; WFC—weed-free control.

Table 3. TDWB reduction via mulches.

Experimental Season	ATF	SBF	S	SW
season I	100%	100%	14.22%	9.79%
season II	100%	100%	63.58%	40.38%

Synthetic mulches: ATF—agrotextile foil; SBF—silver–brown foil. Organic mulches: S—straw; SW—sawdust.

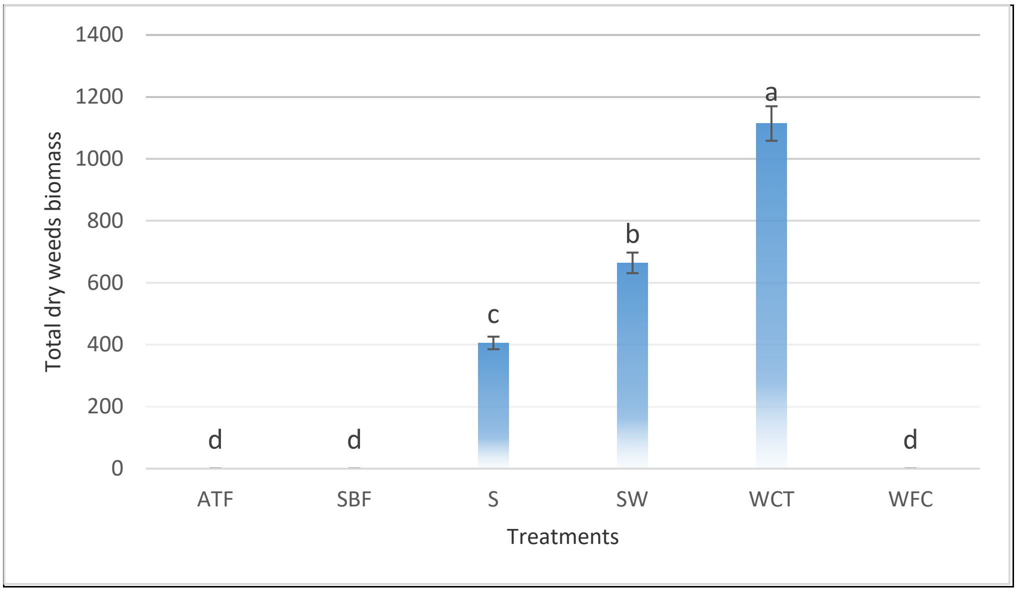

Figure 2. Total dry weed biomass (TDWB; g m^{-2}) in the second experimental season. Letters on bars (a–d) refer to the statistical evaluation of the sum of the dry weed biomass illustrated by stacked bars in the diagram ($p < 0.05$ Duncan's test). Synthetic mulches: ATF—agrotextile foil; SBF—silver–brown foil. Organic mulches: S—straw; SW—sawdust. Controls: WCT—weeded control; WFC—weed-free control.

3.2. *A. archangelica Fresh Root Yield*

In season I, the highest fresh root yield (Figure 3, Scheme 3) achieved with ATF (14.39 t ha^{-1}) followed by SBF (11.98 t ha^{-1}) whereby the yields in those two treatments were higher than the yield with WFC (10.60 t ha^{-1}). Both of the synthetic mulches achieved statistically significant higher fresh root yield than those achieved for both controls and both organic mulch treatments. The S mulch achieved similar yield (9.64 t ha^{-1}) as well as WFC (10.60 t ha^{-1}), but SW showed lower fresh root yield (6.34 t ha^{-1}) in comparison to the S treatment. Similar trend of fresh root yield was observed in season II (Figure 4). Again, the highest yield (13.18 t ha^{-1}) was achieved for ATF without statistical differences with SBF (11.40 t ha^{-1}). Also, there were no observed statistical differences between SBF (11.40 t ha^{-1}) and S (9.82 t ha^{-1}), as well as between S and WFC (9.70 t ha^{-1}). The lowest yield was observed in WCT: 2.14 t ha^{-1}.

3.3. *A. archangelica Essential Oil Yield and Its Chemical Composition*

Essential oil quantity is in direct correlation with fresh root yield. The outcome of different weed control measures was assessed on essential oil chemical yield and composition. Total EO yield in season I was different depending on the weed control. The highest EO yield was observed for ATF (0.41%) followed by S and SBF (0.34% and 0.30%, respectively). The EO yields for the controls (WFC: 0.32% and WCT: 0.31%) were similar, but the fresh root yields were different (9.70 t ha^{-1} and 2.14 t ha^{-1}). For SBF and S, similar EO yields (0.30% and 0.34%, respectively) were observed. The lowest EO yield was in the treatment with sawdust (0.18%). The highest total EO yield in season II was recorded for WCT (0.51%) followed by ATF (0.43%) and S (0.41%). Slightly lower yields were recorded at SW and SBF (0.37% and 0.32%, respectively).

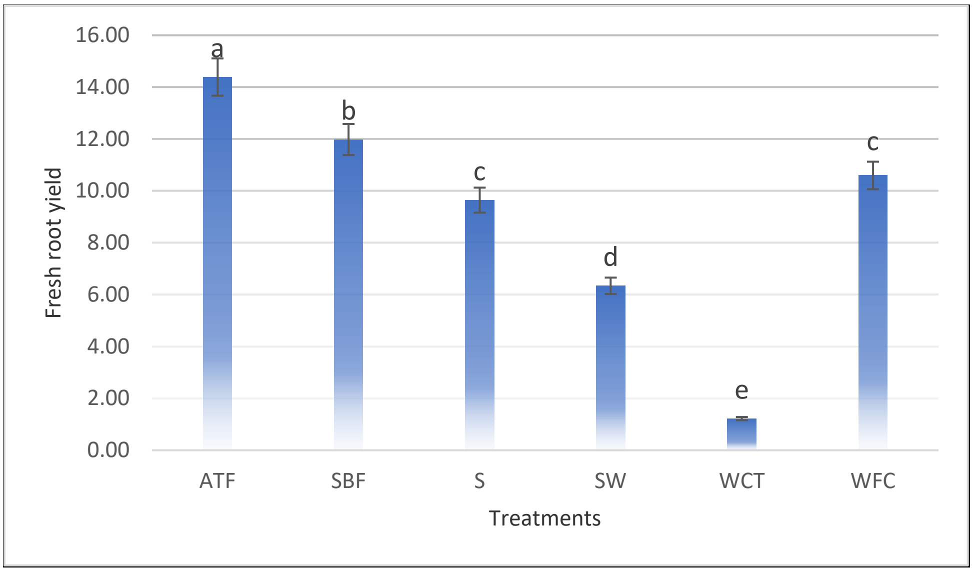

Figure 3. *A. archangelica* fresh root yield (t ha^{-1}) in the first experimental season. Letters on bars (a–e) refer to the statistical evaluation of the sum of the fresh root yield illustrated by stacked bars in the diagram ($p < 0.05$. Duncan's test). Synthetic mulches: ATF—agrotextile foil; SBF—silver–brown foil. Organic mulches: S—straw; SW—sawdust. Controls: WCT—weeded control; WFC—weed-free control.

Scheme 3. *A. archangelica* roots.

Overall, the analysis of EO identified many components from different chemical groups, but dominant ones in season I (Table 4) were β-phellandrene (from 6.71% at SW to 17.23% at S), α-pinene (from 7.80% at SW to 13.13% at S), and δ-3-carene (from 4.41% to 14.09% at SBF) followed by p-cymene, mircen, α-copaen, (2E,4E)-decadienal, α-phellandrene, and (E)-β-ocimen. Similar to the season I, major EO compounds for season II (Table 4) were monoteprene hydrocarbons (β-phellandrene, α-pinene, δ-3-carene, and p-cymene). The highest concentration of α-pinene and δ-3-carene was recorded for the organic straw treatment (28.20% and 12.52%, respectively), and the lowest one of these components was recorded for WCT (14.20%) and SW (9.54%), respectively. β-phellandrene was dominant for WFC (29.69%), and the lowest concentration of this compound was detected for S (18.85%). Content of p-cymene ranged from 4.03% (S) to 9.23% (WFC). The highest content of mircene was recorded for SW (6.80%), but the lowest one was recorded for S (3.37%). For SW, the highest content of (E)-β-ocimen was detected, but the lowest was for WFC (4.03%). Content of α-copaen ranged from 1.71% (ATF) to 2.95% (WCT).

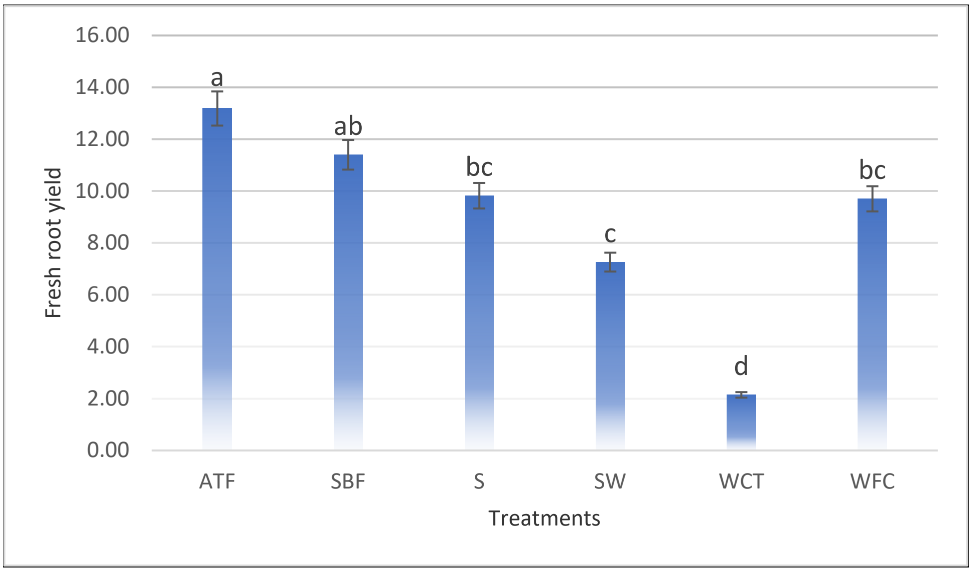

Figure 4. *A. archangelica* fresh root yield (t ha^{-1}) in the second experimental season. Letters on bars (a–d) refer to the statistical evaluation of the sum of the fresh root yield illustrated by stacked bars in the diagram ($p < 0.05$. Duncan's test). Synthetic mulches: ATF—agrotextile foil; SBF—silver–brown foil. Organic mulches: S—straw; SW—sawdust. Controls: WCT—weeded control; WFC—weed-free control.

Table 4. Major components of essential oil (%) and total essential oil yield (%, *v*/*w*) in different treatments in the first (A) and the second (B) experimental season.

			A			
Components	**ATF**	**SBF**	**S**	**SW**	**WCT**	**WFC**
α-pinene	11.89	9.57	13.13	7.80	13.05	9.07
mircene	2.44	4.69	2.75	/	3.36	2.03
α-phellandrene	3.01	0.55	1.61	/	1.43	1.01
δ-3-carene	6.45	14.09	7.37	4.41	9.3	8.32
p-cymene	7.97	6.44	9.51	10.25	8.73	6.61
β-phellandrene	13.01	11.47	17.23	6.71	13.53	10.79
(E)-β-ocimen	1.43	1.63	1.61	/	1.48	1.09
α-copaen	4.63	3.30	3.33	7.05	2.99	2.78
(2E.4E)-decadienale	6.77	3.03	5.49	1.46	3.19	2.27
Total yield	0.41	0.30	0.34	0.18	0.31	0.32
B						
Components	**ATF**	**SBF**	**S**	**SW**	**WCT**	**WFC**
α-pinene	19.42	16.34	28.20	16.70	14.20	16.21
mircene	4.42	5.08	3.37	6.80	4.35	5.9
α-phellandrene	7.91	12.67	8.14	9.32	10.13	4.91
δ-3-carene	10.22	11.54	12.52	9.54	10.55	10.23
p-cymene	6.18	5.07	4.03	4.59	6.80	9.23
β-phellandrene	27.36	22.79	18.85	23.10	26.45	29.69
(E)-β-ocimen	3.71	5.27	4.12	6.86	4.89	4.03
α-copaen	1.71	2.92	2.43	1.90	2.95	2.13
Total yield	0.43	0.32	0.41	0.37	0.51	0.32

Synthetic mulches: ATF—agrotextile foil; SBF—silver–brown foil. Organic mulches: S—straw; SW—sawdust. Controls: WCT—weeded control; WFC—weed-free control.

4. Discussion

Weed control via mulching is the object of the numerous studies, especially in organic systems of crop production. This kind of weed control is very acceptable in medicinal and aromatic plants [31], but there is no research that have investigated the possibilities of mulching in *A. archangelica*. In addition to weeds, a great influence on angelica growth and development is climate condition (especially in this region, which is not native for growing angelica), so mulches can affect soil moisture and temperature [20].

4.1. Mulching Effects on Weediness

Our results show that synthetic mulch foils achieved the best weed suppression for *A. archangelica*. In both experimental seasons, mulch foils completely suppressed the weeds contrary to organic mulches. These results are in accordance with many other studies which confirmed complete weed suppression via synthetic mulches [19,20]. The mulch's effects on weed suppression are achieved via mechanical pressure on soil and prevention of sunlight penetration through it, which is necessary for weeds' germination and sprouting [22,32]. Organic mulches allow a certain percentage of sunlight penetration which is enough for some weeds' germination and sprouting. Our previous research [19] on this topic is in compliance with these results because agrotextile mulch foil completely suppressed weeds. Dragumilo et al. (2023) [20], who were researching different mulches in another medicinal plant (*Mentha* × *piperita* L.) which is also cultivated in rows like *A. archangelica*, also reported very high efficacy of synthetic mulches which reduced total weed dry biomass in the range of 84.6–100%. This investigation validates our findings that synthetic mulch foils showed the best weed suppression compared to organic ones. Mzabri et al. (2021) [33] report the same results, but the research was conducted with saffron. Testing different weed control measures, Asil et al. (2023) [34] reported 100% effectiveness with textile mulch, too. In our research, the TWDBr was very high in both seasons for treatment with silver–brown foil (season I: 100%; season II: 100%), similar to an investigation in cucumber where the efficacy of the same mulch foil was 98% [35]. Wheat straw (14.22% and 63.58% in season I and II, respectively) achieved a higher TWDBr than sawdust (9.79% and 40.38% in season I and II, respectively). This is supported by Jodaugiene et al. (2006) [36] who also reported better weed suppression with straw in comparison to sawdust with an equal-thickness layer of 10 cm. Many studies [37,38] are in agreement with our results for organic mulches; total weed dry biomass was greater for treatment with sawdust in comparison to the treatment with wheat straw in a corn crop [4] and in black mung beans [38]. The effect of these organic mulches in suppressing weeds depend on the moment of evaluation for black mung beans [38] and *Mentha* × *piperita* [20], too. On the other hand, the evaluation of the effect of weed management effect on weediness with an *A. archangelica* crop occurs at the end of the growing season. The differences in weed infestation and detected species between seasons I and II could be caused by the following factors: different weather conditions, different experimental field (we applied crop rotation because it is not recommended to perform angelica production in monoculture), experimental field history, different weed control measures applied before field trial conduction, and different crops which were cultivated on the fields.

4.2. Mulching Effects on Fresh Root Yield

As expected, due to the good effect of synthetic mulch foils on weed suppression, the highest fresh root yield was found for these treatments, especially ATF. The soil conditions for the growth of medicinal plant's roots are better under black agrotextile mulch foil [39–41] which is water permeable, and the soil is more humid for a longer time than under SBF, which is waterproof. Black agrotextile foil achieved a higher yield of *Gentiana lutea* roots compared to synthetic silver foil [40]. For cultivation of *A. archangelica* at its highest levels, it requires wet and undammed soil free from weed competition, which are conditions that our study's foil treatments produced. A positive effect of black agrotextile foil and silver–brown foil on *Mentha* × *piperita* yield was reported by Dragumilo et al. (2023) [20].

They achieved significantly higher *Mentha* × *piperita* yield with this synthetic mulch in comparison to organic mulches and a weed-free control. Hoeberechts et al. (2004) [42] reported a very positive effect of polyethylene mulch foil for lavender (*Lavandula officinalis*) and rosemary (*Rosmarinus officinalis*) and indicated it as the most suitable type of mulch for use in these crops, because the measured crop parameters (height and width) were the fastest growing on this type of mulch compared to the other examined mulches.

Organic mulches also showed a positive influence on *A. archangelica* root yield, especially for S. Our results show no significant difference between the yield for S and WFC. The reason could be that straw contains organic carbon (40–45%), nitrogen (0.6–1%), phosphorus (0.45–2%), and potassium (14–23%) as well as microelements necessary for plant growth and development [43]. In the process of straw decomposition, a certain amount of these nutrients are available to be used by crop from the soil [44]. Also, straw retains soil moisture which is maybe a crucial benefit of this type of mulch for successful and better *A. archangelica* growth. Despite the fact that straw did not suppress weeds at a high percentage compared to WFC, there are many other benefits from this kind of mulch which had an influence on root yield. SW achieved a lower root yield in comparison to the S treatment. The reason could be that sawdust has an influence on the pH reaction of the soil (where sawdust results inlower pH values) [45]. Also, sawdust affects soil compaction and the amount of easily available nitrogen which could have a negative influence on crop development [46,47].

4.3. Mulching Effects on EO Chemical Composition and Yield

A reasonably good agreement can be seen when the EO chemical composition extracted from angelica roots is compared with published data. Some variations in the chemical composition and content of individual components can be attributed to the various geo-climatic conditions in which angelica grows. That α-pinene, p-cimene, β-phellandrene, and/or δ-3-carene are the most abundant components of garden angelica EO originated from Lithuania was confirmed by Nivinskienė et al. (2005) [15]. They investigated two locations in Lithuania and two locations showed α-pinene (15.7–20.8%) as the most abundant compound, while at one location in addition to α-pinene (11.4–15.0%), β-phellandrene (13.8–18.5%) also was in high concentration. Aćimović et al. (2017) [11] indicated that EO extracted from *A. archangelica* roots from Serbia is the richest in the contents of α-pinene, β-phellandrene, and δ-3-carene which is in agreement with our results. Also, α-pinene and δ-3-carene are the most abundant components in EO [5], while α-pinene, δ-3-carene, and lemonene are the most abundant compounds in EO extracted from *A. archangelica* roots from Urbino, Italy [16]. Fraternale (2014) [10] reported that α-pinene (21.3%), δ-3-carene (16.5%), limonene (16.4%), and α-phellandrene (8.7%) were the most abundant compounds in EO distilled from *A. archangelica* roots. In our research, α-pinene content was in the range 9.07% (WFC, season I)–28.20 (S, season II), and the β-phellandrene content was in the range 6.71% (SW, season I)–29.69% (WFC, season II). The differences in composition of essential oils and the percentages of compounds can be explained as consequences of different microclimate conditions (soil humidity, soil temperature, pH, etc.) under different mulches. Differences for the same factors in two experimental seasons are the result of the influence of meteorological conditions on the microclimate under different mulches.

5. Conclusions

Based on the presented results, the main conclusions are the following:

- Agrotextile black and silver–brown mulch foils have the best effect on weed suppression (100%);
- Agrotextile black mulch foil had the best effect on *A. archangelica* fresh root yield, EO yield, and its chemical composition;
- The effect of wheat straw and sawdust on weediness was not satisfactory;
- Wheat straw had a positive effect on EO yield and the content of some compounds.

According to the obtained results in this study, the agrotextile black foil can be recommended as the best mulch for weed control. This foil achieved complete weed suppression and the highest angelica fresh root yield. In addition, the highest essential oil yield was obtained with this treatment, which indicates the positive effect of this mulch on the crop.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/horticulturae10111199/s1, Table S1. Meteorological data: monthly mean temperature, precipitation and humidity; Table S2. Treatments layout.

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