1995

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Journal of Essential Oil Research

ISSN: 1041-2905 (Print) 2163-8152 (Online) Journal homepage: http://www.tandfonline.com/loi/tjeo20

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To cite this article: Denys J. Charles , James E. Simon & Mark P. Widrlechner (1995) Characterization of Essential Oil of Dill (Anethum graveolens L.), Journal of Essential Oil Research, 7:1, 11-20, DOI: 10.1080/10412905.1995.9698456

To link to this article: http://dx.doi.org/10.1080/10412905.1995.9698456

Published online: 28 Nov 2011.

Characterization of Essential Oil of Dill (*Anethum graveolens* L.)

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Received: April 1994
Revised: July 1994

ABSTRACT: The genetic variability of the major essential oil constituents in a germplasm collection of dill (*Anethum graveolens* L.) from the National Plant Germplasm System was characterized. The oil content in the dill herb ranged from 0.10% to 0.30% (v/fresh weight), and in the dill seed from 1.75% to 4.0% (v/dry weight). The three major constituents in the dill herb oil were α-phellandrene, β-phellandrene, and 3,9-oxy-p-menth-1-ene (dill ether) comprising 90% to 97% of the total oil constituents. Of these three constituents, α-phellandrene comprised 51.1% to 64.7% of the total oil. The major constituents in dill seed oil were carvone and dihydrocarvone comprising 68% to 83% of the total oil constituents. The other major constituent was limonene, which ranged from 14.18% to 21.43%. Carvone was not detected in the herb oil; and dill ether could not be detected in the seed oil.

KEY WORD INDEX: *Anethum graveolens*, Apiaceae, α-phellandrene, β-phellandrene, 3,9-oxy-p-menth-1-ene, dill ether, carvone, dihydrocarvone, limonene, seed oil, leaf oil, herb oil, Umbelliferae.

INTRODUCTION: Dill (*Anethum graveolens* L.), which is an annual plant of the Apiaceae (Umbelliferae) family, is native to Europe and commercially produced in subtropical and temperate regions such as India, Pakistan, Egypt, United States, Hungary, England, Germany and Holland, as well as in northern temperate zones near the Arctic Circle in Finland (1).

Dill seed and herb are used as flavorings in salads, sauces, soups, seafoods, potatoes and especially in pickled vegetables. In Finland, the fresh dill herb is used before bud formation or during flowering. In the United States, the foliage is harvested prior to flowering and marketed as fresh dill, dried or frozen. However, the oil distilled from the fresh herb, dill

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1041-2905/95/0001-0011$04.00/0—

weed (leaves and flowering tops), and ripe seeds, are preferred over the fresh product by the food industry in Europe and the United States. Dill oil has been shown to have antifungal activity (2,3) and to inhibit several species of bacteria (4-7).

Two species of dill have been of commercial interest: European dill (*Anethum graveolens* L.) and Indian dill (*Anethum sowa* Roxb.). The carvone content of the European dill seed oil is higher than that of Indian dill seed oil (8). The Indian dill seed oil contains high levels of dillapiole, a compound reputed to be toxic (9). The two major components of dill seed oil are carvone and limonene, comprising 70-95% of all compounds (8,10,11). However, the three major components of the essential oil of dill herb are α- and β-phellandrene and dill ether, which together comprise about 80% of the oil (12). Dill herb oil, seed oil and weed oil have been previously studied and reviewed (13-15). Recently, Halva et al. (16,17) studied the effect of light levels and light quality on the growth and essential oil in dill and reported that dill growth and oil accumulation increased with increased light level.

The present study was conducted to characterize the genetic variability of the major oil constituents in dill, grown under identical conditions for both fresh dill herb and dry seeds. The origin of the seed used in this study was the US National Plant Germplasm collection.

MATERIALS AND METHODS: ***Plant Material, Growing Conditions and Harvest*** —Seed samples of the entire dill germplasm collection (56 accessions) held at the North Central Regional Plant Introduction Station (NCRPIS) were direct seeded into a Nicollet loam soil (18) at the NCRPIS research farm southwest of Ames, Iowa on 5 May 1992. Based on prior germination tests, from 200 to 2,000 seeds per accession were planted in single 7.5 meter rows. Plots were weeded by hand and thinned to 200 plants per row. Plots were irrigated weekly in May and June. A few plants exhibiting symptoms of aster yellows were rogued from the field in June.

Leaf samples were harvested by hand during the late mornings of 14 and 15 July 1992, when umbels were first noticeable. Leaves were sampled randomly from each plant, including foliage from all locations on each plant. They were harvested from all plants from each accession, placed in plastic mesh bags, and held under refrigeration until they could be weighed. All samples in excess of 150 g (fresh weight) were shipped by refrigerated, overnight express to Purdue University for oil extraction and analysis. Samples less than 150 g were not analyzed for oil content and composition.

After leaf harvest, plants were allowed to bolt. On 18 and 24 September 1992, all mature umbels were cut by hand, placed in fine-mesh cloth bags, and dried at 30°C for 72 h. Clean seed samples were prepared by rubbing the dried umbels by hand, separating the seeds with a Clipper air-screen cleaner and an air-column separator, and cleaning by visual inspection and hand-picking. Seed samples were weighed and those in excess of 16 g were shipped by overnight express to Purdue University for seed oil extraction and analysis.

Essential Oil Extraction and Isolation—Essential oil was extracted by both hydrodistillation and solvent extraction, and statistically compared in order to determine the potential influence of extraction methodology on oil composition. For hydrodistillation, fresh chopped dill herb was placed in a 2000 mL round-bottomed boiling flask with 400 mL distilled-deionized water and distilled for 1 h and 15 min using a modified Clevenger trap (19). Dried dill seeds were placed in a 2000 mL round-bottomed boiling flask with 1000 mL distilled-deionized water and distilled for 3 h using the modified Clevenger trap (19). The essential oil content was determined on an oil volume to tissue weight basis (20). Oil samples were stored in Varian autosampler vials at 2°C in the dark.

For solvent extraction, 2 g samples of freshly chopped dill herb were ground in a

mortar containing dichloromethane and anhydrous Na_2SO_4 and extracted four times with dichloromethane to give a total volume of 20 mL of extract. The extract was concentrated under a gentle stream of air in a fume hood at room temperature and was then centrifuged (20).

Essential Oil Identification and Quantification by GC—Hydrodistilled oil samples and dichloromethane extract samples were analyzed by GC using a Varian 3700 gas chromatograph equipped with FID and a Varian 4270 electronic integrator (Varian, Walnut Creek, CA). A fused silica capillary column (12 m x 0.22 mm) with an OV101 bonded phase (Varian, polydimethylsiloxane) was used to separate the oil constituents. A 1 µL oil sample was injected with helium as the carrier gas and 100:1 split-vent ratio. The oven temperature was held isothermal at 80°C for 2 min and then programmed to increase at 3°C/min to 180°C to give complete elution of all peaks. The injector and detector temperatures were 180° and 300°C, respectively. Oil constituents were identified on the basis of retention time and by co-injection with standard compounds. The relative peak area for individual constituents was determined by a Varian 4270 integrator (20).

GC/MS Analysis—Pure standards (α-thujene, α-pinene, α-fenchene, β-pinene, myrcene, α- and β-phellandrene, α-terpineol, apiole, cymene, limonene, dihydrocarvone and carvone) and essential oil constituents were verified by GC/MS. A Finnigan (San Jose, CA) GC (9610) and MS (4000) hooked on-line to a Data General Nova/4 data processing system, used electron impact analysis as previously described (21,22). The GC conditions were as follows: direct injection of 1.0 µL sample diluted 10:1 with MeOH; fused silica column (30 mm x 0.25 mm) with DB-1 bonded phase (polydimethylsiloxane) (J&W Scientific, Folsom, CA); helium as a carrier gas with a column pressure of 72.2 kPa (10.5 psi) and split vent of 40 mL/min; oven program, 80°C at 2 min rising to 180°C at 2°C/min; injector temperature, 225°C. The MS conditions were as follows: ionization voltage, 70 eV; emission current, 40 µA; scan rate, 1 scan/s, mass range, 40-500 Da; ion source temperature, 160°C.

The identification of oil constituents was accomplished by matching the mass spectra of each compound with standards or different MS compound libraries for best fit (23-26).

RESULTS AND DISCUSSION: ***Essential Oil Content***—Each of the dill accessions are listed by number, country of origin, and oil content in Table I. The oil content of herb oil ranged from 0.10% to 0.30% on a fresh weight basis, while the oil content in dill seed ranged from 1.75% to 4.00% on a dry weight basis. In dill herb, the total oil was recovered in 1 h 15 min, whereas in dill seed, 3 h was required to recover all the oil.

The oil of dill has been studied extensively over many years, but a direct comparison of the total essential oil content and composition among these studies is difficult because of the different methods of isolation and determination, the differences in the geographical origin and environmental growing conditions, the different stages of growth when harvested, and probable variation in the varieties evaluated (29–31). El-Gengaihi and Hornok (32) reported values of 0.24% (fresh weight basis) during the start of stem growth (41 days) and 0.46% (fresh weight basis) during the start of umbel growth (48 days). Zlatev and Balinova-Tsvetkova (33) reported values of 0.68% to 1.40% (dry weight basis) in spring and summer sowed plants, at the initiation of stalks. The range of the oil content of dill reported from other countries varied from 0.16% to 1.50% on dry weight basis. The oil content of dill seed (29) has been reported to vary from 2% to 4% (dry weight basis). In this study, the oil content ranged from 0.10% to 0.30% (fresh weight basis) in the dill herb, and from 1.75% to 4.00% (dry weight basis) in the dill seed. Our results demonstrating a wide range in oil accumulation among accessions apparently due to their wide genetic

Table I. Dill accession number, country of origin and oil content (percentage) from herb and seed

Accession number	Country of origin	Oil content	
		Herb oil (vol/FWT)	Seed oil (vol/DWT)
PI 141556	Iran	0.19	-
PI 141558	Iran	0.10	-
PI 141559	Iran	0.20	-
PI 164935	Turkey	0.26	2.80
PI 165040	Turkey	0.17	-
PI 167083	Turkey	0.20	2.35
PI 167213	Turkey	0.22	-
PI 170225	Turkey	0.22	2.50
PI 170226	Turkey	0.22	2.15
PI 170232	Turkey	0.25	2.10
PI 170233	Turkey	0.20	2.25
PI 171492	Turkey	0.22	-
PI 171493	Turkey	0.15	-
PI 171494	Turkey	0.15	-
PI 171495	Turkey	0.29	-
PI 171496	Turkey	0.20	2.39
PI 172723	Turkey	0.20	-
PI 172724	Turkey	0.26	1.75
PI 173640	Turkey	0.25	2.80
PI 174044	Turkey	0.28	2.67
PI 174047	Turkey	0.29	2.62
PI 174048	Turkey	0.20	2.35
PI 174049	Turkey	0.30	2.67
PI 174214'	Turkey	0.25	3.14
PI 177259	Turkey	0.22	-
PI 193453	Ethiopia	0.25	-
PI 206939	Turkey	0.20	1.85
PI 253151	Iran	0.20	2.50
PI 288284	India	0.20	-
PI 296382	Iran	0.22	2.25
PI 305461	Israel	-	3.17
PI 305462	Israel	0.20	2.86
PI 305463	France	0.25	2.17
PI 305464	Netherlands	0.20	1.95
PI 305465	Hungary	0.30	2.60
PI 307645	India	0.25	-
PI 307647	India	0.17	-
PI 307649	India	0.20	3.20
PI 307650	India	0.22	2.83
PI 307651	India	0.28	2.64
PI 307652	India	0.20	-
PI 307653	India	-	3.33
PI 307654	India	0.28	2.40
PI 325870	Yugoslavia	0.20	2.65
PI 344265	Turkey	0.20	4.00
PI 357322	Yugoslavia	0.22	2.00
PI 357323	Yugoslavia	0.25	2.55
PI 357324	Yugoslavia	0.28	2.45
PI 379082	Yugoslavia	0.24	2.67
PI 414188	US	0.27	2.15
Ames 1666	Unknown	0.22	-
Ames 4714	US	0.29	2.25
Ames 19098	US	0.28	2.50
Ames 19098	US	0.30	-

- = data not collected

Table II. Dill herb accession number and relative percentage of constituents in the hydrodistilled oil

Accession number	Essential oil constituents (relative percentage of total oil)										
	A*	B	C	D	E	F	G	H	I	J	K
PI 141556	0.36	1.81	0.06	0.14	0.71	51.98	17.17	22.88	0.62	0.01	0.06
PI 141558	0.41	2.16	0.07	0.30	0.84	51.28	14.50	18.58	t	t	t
PI 141559	0.27	1.37	0.05	0.23	0.71	57.11	16.82	20.71	0.77	0.04	0.04
PI 164935	0.27	1.43	0.05	0.28	0.67	59.91	11.97	23.23	0.66	0.02	0.05
PI 165040	0.32	1.56	0.05	0.36	0.68	53.79	15.02	25.67	1.01	0.04	0.05
PI 167083	0.27	1.37	0.05	0.26	0.66	55.66	13.85	25.62	0.87	0.02	t
PI 167213	0.23	1.45	0.04	0.22	0.60	53.88	11.88	30.08	0.77	0.01	0.06
PI 170225	0.26	1.28	0.05	0.22	0.67	56.96	13.31	25.32	0.61	0.02	0.04
PI 170226	0.25	1.27	0.04	0.22	0.62	55.89	11.87	28.37	0.79	t	t
PI 170232	0.34	1.75	0.06	t	0.72	54.41	14.90	24.44	0.65	t	0.07
PI 170233	0.27	1.44	0.04	0.27	0.69	54.89	13.90	26.26	0.72	0.03	0.05
PI 171492	0.21	1.06	0.04	0.14	0.61	54.29	12.35	28.61	0.86	0.01	0.05
PI 171493	0.27	1.21	0.05	0.15	0.59	51.09	14.32	28.82	0.97	0.02	0.08
PI 171494	0.21	1.19	0.04	0.18	0.66	54.25	17.56	22.60	t	t	0.03
PI 171495	0.33	1.61	0.06	0.37	0.69	57.11	14.38	22.70	0.70	0.19	t
PI 171496	0.30	1.41	0.05	0.15	0.62	52.50	13.07	28.86	1.26	t	t
PI 172723	0.28	1.44	0.05	0.27	0.70	58.78	13.32	23.97	t	0.03	0.02
PI 172724	0.28	1.41	0.05	0.25	0.64	55.75	13.56	25.65	0.79	0.05	0.03
PI 173640	0.36	1.83	0.06	0.32	0.71	57.02	13.99	23.42	0.56	0.04	0.06
PI 174044	0.24	1.30	0.05	0.16	0.66	57.68	12.83	24.84	0.66	0.01	0.04
PI 174047	0.38	2.00	0.06	0.20	0.74	54.19	16.36	22.66	0.43	0.03	0.06
PI 174048	0.27	1.28	0.05	0.15	0.65	55.00	13.94	25.64	0.81	0.03	0.06
PI 174049	0.23	1.22	0.05	0.25	0.66	58.59	12.46	23.88	0.50	0.03	0.09
PI 174214	0.28	1.46	0.05	0.22	0.64	56.69	12.27	26.30	0.68	0.02	0.04
PI 177259	0.29	1.38	0.05	0.35	0.65	59.41	12.49	23.13	0.82	0.01	0.07
PI 193453	0.32	1.62	0.05	0.25	0.72	60.80	16.00	18.26	0.73	0.01	t
PI 206939	0.35	1.67	0.06	0.28	0.66	53.45	14.21	26.80	0.70	0.06	0.09
PI 253151	0.32	1.51	0.05	0.27	0.66	56.69	13.74	25.09	0.66	t	t
PI 288284	0.24	1.20	0.05	0.25	0.70	61.37	16.93	17.05	0.46	0.06	0.10
PI 296382	0.29	1.48	0.05	0.24	0.72	61.64	14.80	18.99	0.54	0.02	t
PI 305462	0.33	1.74	0.06	0.27	0.77	64.65	13.69	16.62	0.50	0.06	0.04
PI 305463	0.30	1.65	0.05	0.23	0.68	57.82	14.18	23.99	t	0.02	0.02
PI 305464	0.24	1.30	0.04	0.20	0.60	53.46	13.01	29.02	0.65	0.04	0.03
PI 305465	0.29	1.56	0.05	0.20	0.66	58.61	12.65	24.71	t	0.03	0.06
PI 307645	0.21	1.21	0.03	0.25	0.70	58.44	16.91	19.73	1.02	0.07	0.01
PI 307647	0.41	1.97	0.08	0.31	0.74	52.20	19.08	22.91	1.08	t	t
PI 307649	0.33	1.65	0.06	0.27	0.70	62.14	12.75	20.34	0.93	0.03	0.04
PI 307650	0.36	1.90	0.06	0.32	0.76	56.99	16.40	20.22	0.41	0.04	0.08
PI 307651	0.33	1.64	0.06	0.26	0.71	62.48	13.25	19.64	0.62	0.01	0.03
PI 307652	0.29	1.60	0.05	0.21	0.71	60.10	14.94	19.64	0.43	0.05	0.05
PI 307654	0.34	1.74	0.06	0.27	0.73	60.97	13.77	20.60	0.53	0.03	0.10
PI 325870	0.22	1.20	0.04	0.21	0.66	58.62	13.00	24.12	0.63	0.06	0.09
PI 344265	0.23	1.06	0.04	0.21	0.56	52.85	12.10	30.18	0.92	0.02	0.08
PI 357322	0.34	1.81	0.05	0.18	0.72	55.21	15.64	23.21	0.57	0.04	0.93
PI 357323	0.19	1.05	0.03	0.22	0.64	59.48	13.11	23.94	t	0.03	0.07
PI 357324	0.28	1.40	0.05	0.22	0.65	55.60	13.04	27.23	t	t	0.03
PI 379082	0.20	0.98	0.04	0.11	0.62	53.82	16.15	25.09	0.81	0.02	t
PI 414188	0.26	1.22	0.05	0.23	0.61	55.74	12.65	27.09	1.04	0.01	0.02
Ames 1666	0.21	1.08	0.04	0.20	0.63	55.35	13.00	26.92	0.42	t	0.04
Ames 4714	0.29	1.37	0.05	0.23	0.63	55.94	13.16	26.58	0.93	0.02	t
Ames 19098	0.29	1.43	0.05	0.21	0.66	59.67	13.49	22.51	0.50	0.02	0.05
Ames 19098	0.32	1.54	0.06	0.24	0.65	56.19	14.70	23.69	0.19	t	t

*A=α-thujene; B=α-pinene; C=α-fenchene; D=β-pinene; E=myrcene; F=α-phellandrene; G=β-phellandrene; H=dill ether; I=α-terpineol; J=myristicin; K=dillapiole; t=trace (<0.01%)

Table III. Dill seed accession number and relative percentage of constituents in the hydrodistilled oil

Accession number	Essential oil constituents (relative percentage of total oil)						
	A*	B	L	M	N	O	P
PI 164395	2.37	0.72	1.45	14.18	36.64	36.53	1.97
PI 167083	0.45	0.34	0.78	17.72	12.52	67.64	0.34
PI 170225	0.32	0.29	0.66	17.39	2.67	78.10	0.07
PI 170226	2.46	0.85	1.43	17.22	3.02	70.00	0.06
PI 170232	0.56	0.35	0.65	17.48	12.65	65.74	2.07
PI 170233	3.13	1.36	1.91	18.02	4.42	69.34	1.08
PI 171496	0.63	0.19	0.56	15.51	2.45	79.91	0.08
PI 172724	0.36	0.35	0.76	16.72	2.54	78.92	0.13
PI 173640	2.60	0.21	0.61	14.19	35.98	45.74	t
PI 174044	1.65	0.27	0.63	16.78	3.55	76.37	0.09
PI 174047	1.56	0.39	0.82	16.36	5.17	74.36	0.37
PI 174048	1.90	0.23	0.69	17.03	2.56	74.81	2.52
PI 174049	1.32	0.45	1.65	15.37	2.87	77.43	0.17
PI 174214	2.34	0.42	2.17	15.90	2.17	74.52	0.07
PI 206939	2.02	0.93	0.77	16.14	7.56	70.52	1.29
PI 253151	1.94	1.07	1.31	17.81	2.35	75.35	0.05
PI 296382	0.42	0.36	0.79	20.62	2.72	74.77	t
PI 305461	0.15	0.17	0.83	18.29	3.13	74.40	0.11
PI 305462	0.24	0.92	0.93	16.23	6.36	74.93	0.19
PI 305463	0.23	0.32	0.68	17.40	1.57	79.25	0.03
PI 305464	1.46	0.21	0.52	16.55	1.71	79.13	0.02
PI 305465	0.56	0.42	1.02	19.61	1.65	76.72	0.05
PI 307649	1.71	0.40	0.73	18.12	7.88	69.35	0.18
PI 307650	3.54	0.86	1.56	16.42	3.16	73.82	0.47
PI 307651	1.80	0.59	0.76	19.81	9.60	66.06	0.54
PI 307653	1.75	0.29	0.63	16.16	61.69	18.18	0.11
PI 307654	2.36	0.82	1.24	18.96	6.36	66.55	0.02
PI 325870	1.51	0.76	2.05	17.79	3.58	74.17	0.04
PI 344265	0.56	0.79	0.96	19.87	0.17	74.23	0.07
PI 357322	1.57	0.27	0.59	20.24	2.06	74.76	0.09
PI 357323	3.10	0.31	2.09	17.92	22.16	46.30	5.08
PI 357324	0.36	0.35	0.66	21.43	10.97	58.07	6.30
PI 379082	3.10	0.68	1.00	17.46	9.72	66.80	0.27
PI 414188	1.96	0.98	1.23	16.91	1.47	69.51	0.68
Ames 4714	0.45	0.27	0.55	15.39	1.90	80.51	0.06
Ames 19098	1.65	0.32	0.65	14.27	1.80	81.15	0.36

*A=α-thujene; B=β-pinene; L=p-cymene; M=limonene; N=dihydrocarvone; O=carvone; P=dillapiole; t=trace (<0.01%)

variability, are in agreement with, and extend previously reported values.

Essential Oil Composition—The oil constituents of dill herb are listed in Table II. The constituents identified included: α-thujene, α-pinene, α-fenchene, β-pinene, myrcene, α-phellandrene, β-phellandrene, dill ether, α-terpineol, myristicin and dillapiole. The major

Table IV. Comparison of oil constituents obtained by solvent extraction and hydrodistillation of dill herb

Accession number	Essential oil constituents (relative percentage of total oil)							
	Solvent extractions				Hydrodistillation			
	B*	F	G	H	B	F	G	H
PI 167083	10.98	55.34	13.88	11.83	1.37	55.66	13.85	25.62
PI 170225	10.13	58.37	12.79	11.33	1.28	56.96	13.31	25.32
PI 170226	8.28	50.79	14.29	13.04	1.27	55.89	11.87	28.37
PI 170232	7.11	55.36	14.02	11.87	1.75	54.41	14.91	24.44
PI 170233	5.87	51.09	16.07	11.01	1.44	54.89	13.91	26.26
PI 171496	6.61	52.74	14.81	14.71	1.41	52.51	13.07	28.86
PI 172723	6.91	53.52	15.16	12.78	1.44	58.78	13.32	23.97
PI 253151	6.29	55.94	15.55	11.61	1.51	56.69	13.74	25.09
PI 288284	6.28	64.02	13.23	5.95	1.21	61.37	16.93	17.05
PI 296382	6.51	57.11	14.81	10.51	1.48	61.64	14.80	18.99
PI 305462	6.91	58.64	14.72	8.77	1.74	64.65	13.69	16.62
PI 305463	5.83	57.33	14.09	12.55	1.65	57.82	14.18	23.99
PI 305464	9.29	55.98	13.21	14.34	1.31	53.46	13.01	29.02
PI 305465	6.27	55.62	13.77	14.02	1.56	58.61	12.65	24.71
PI 307654	6.11	53.44	15.41	11.32	1.74	60.97	13.77	20.60
PI 325870	6.95	58.30	12.01	11.84	1.21	58.62	13.11	24.12
PI 357324	5.59	56.23	14.65	14.18	1.41	55.60	13.04	27.23
PI 414188	6.45	55.41	13.77	13.57	1.22	55.74	12.65	27.09
Ames 1666	5.13	55.89	15.05	13.19	1.08	55.35	13.11	26.92
Ames 4714	2.42	45.91	15.89	17.10	1.37	55.94	13.16	26.58
Ames 19098	9.41	60.52	14.26	8.62	1.43	59.67	13.49	22.51

	B	F	G	H	No. of observations
Hydro (Mean±SD)	1.42±0.2	57.39±3.0	13.59±1.0	24.46±3.6	21
Solvent (Mean±SD)	6.91±1.9	55.60±3.7	14.35±1.0	12.10±2.4	21

*B=α-pinene; F=α-phellandrene; G=β-phellandrene; H=dill ether

constituent was α-phellandrene, ranging from 51.09% to 64.65%. Three major constituents, α-phellandrene, β-phellandrene, and dill ether comprised 90% to 97% of the oil constituents.

The essential oil constituents of dill seed are listed in Table III. The constituents identified in the dill seed oil included: α-thujene, β-pinene, cymene, limonene, dihydrocarvone, carvone and dillapiole. The major constituents in seed oil were carvone and dihydrocarvone comprising 68% to 83% of the total oil constituents. The other major constituent was limonene, ranging from 14.18% to 21.43%. No dill ether was detected in the dill seed oil.

Two oil isolation procedures, hydrodistillation and solvent extraction, were compared for dill herb oil constituents in 21 dill accessions. Significant differences in the relative amounts of essential oil constituents in the dill oil obtained by hydrodistillation and solvent extraction have been reported (27,28). The relative percentages of the four major constituents (α-pinene, α-phellandrene, β-phellandrene and dill ether) of dill herb oil

produced by both isolation procedures are presented in Table IV. Eleven constituents were identified in the hydrodistilled oil, while only eight constituents could be identified in the solvent extract. The most abundant constituents from both extraction methods were α-phellandrene, β-phellandrene and dill ether, comprising about 85% to 95% of all identified constituents. However, there were differences in the relative percentages of constituents between the two methods of isolation. No significant difference in the relative amounts of α-phellandrene and β-phellandrene was observed. The lower relative amount of dill ether in the solvent extract than in the hydrodistilled oil was matched by higher relative amounts of α-thujene, α-pinene, α-fenchene, β-pinene and myrcene in the solvent extract. Similar results were reported by Huopalahti et al. (27), except that they reported a higher relative amount of β-phellandrene by solvent extract than by steam distillation. Since hydrodistillation gave consistent results and the relative amounts of the constituents were in agreement with those reported previously, we chose hydrodistillation for this study. We tested, but found no effect of storage for two weeks at 10°C of dill herb on the relative amounts of aroma compounds (data not shown). This was unexpected as Cantwell and Reid (34) reported that fresh dill, stored at temperatures from 0°-10°C, maintains a relatively high respiration rate (Q_{10} value of 4.9). However, they also observed that the shelf-life of dill could be maintained at a high market quality for 10-14 days when stored at this temperature range. Our data extends their findings by demonstrating minimal changes in the aroma of stored dill under these storage conditions.

Although 20 to 25 constituents could be resolved by gas chromatography in the dill herb oil, we are reporting on the 11 identified constituents that comprised 95% to 99% of the total oil. The three major constituents were α-phellandrene, β-phellandrene and dill ether comprising 90% to 97% of total oil constituents. Of these three major constituents, α-phellandrene ranged from 51.09% to 64.65%. The total phellandrene content (α- and β-phellandrene) ranged from 65% to 78%. Ihlof (35) found that the typical odor and flavor of the herb oil at an early stage of maturity is due to its high content of phellandrene (63% to 67%). The relative amount of the third major constituent, dill ether ranged from 17.05% to 30.18% and is in agreement with that reported by other workers (12,15,36). Dill ether has been shown to increase markedly at an early stage of maturity and then decrease before visible bud formation (37). The abundance of dill ether in dill herb oil has been reported to exhibit an odor similar to fresh dill herb (12). Limonene and carvone, reported to be present as minor constituents in dill herb oil, could not be detected in the present study, while myristicin and apiole were present in very low amounts. The high levels of α-phellandrene, β-phellandrene, dill ether and the absence of carvone in the herb oil of these populations is consistent with the fact that the plants were harvested at an early stage of maturity.

Of the 10 to 15 constituents resolved by gas chromatography in dill seed oil, seven constituents were identified comprising 95% to 99% of the total oil. The three major constituents comprising about 95% of the identified constituents were limonene, dihydrocarvone and carvone. The relative amount of carvone ranged from 18.18% to 83.15%. The oils low in carvone had higher contents of dihydrocarvone, ranging from 0.17% to 61.69% (Table III). There appears to be an inverse relationship between dihydrocarvone and carvone (Table III). Genetic variability in 2,3-keto-reductase, the enzyme responsible for converting carvone to dihydrocarvone, may be found among these accessions. The other identified constituents included: α-thujene, β-pinene, cymene and dillapiole. Carvone and limonene have been reported to dominate in the seed oil (11,38). The carvone content has been shown to vary from 40% to 55% in dill seed oil (10,11). Whether carvone is synthesized from limonene in dill seed oil, as has been demonstrated in oil of *Mentha spicata* L., warrants examination (39).

Our results indicate a rich diversity in oil constituents of dill herb and dill seed, and an

apparent inverse relationship between dihydrocarvone and carvone in dill seed oil. This germplasm collection could be an important source of genetic material for further selection and breeding based on known comparative relationships among oil constituents.

ACKNOWLEDGMENTS: Journal Paper No. 13,959, Purdue University Agricultural Experiment Station, West Lafayette, IN 47907. We thank Drs. David Rhodes and Robert Joly for reviewing the manuscript. We also thank Kathleen Reitsma for her work to coordinate the field work, sample preparation and shipping. Mention of trademarks, proprietary products, or vendors does not constitute a guarantee or warranty of the product by the USDA or cooperative agencies and does not imply approval to the exclusion of other products or vendors that may also be suitable.

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