Cinnamoyl Esters of Lesquerella and Castor Oil: Novel Sunscreen Active Ingredients

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ABSTRACT: Lesquerella and castor oils were esterified with cinnamic acid (CA) and 4-methoxycinnamic acid (MCA). Esterification of the hydroxy oils reached 85% completion with CA and 50% conversion with MCA. The hydroxy oils were esterified at 200°C under a nitrogen atmosphere within a sealed system. Unreacted CA and MCA were removed from the reaction mixtures by sublimation at 100°C under vacuum. The resultant methoxycinnamic oils possessed a broader, more blue-shifted UV absorbance, 250 to 345 nm with a λ_{max} of 305 nm, compared with the cinnamic oils, which absorbed from 260 to 315 nm, λ_{max} of 270 nm. The methoxycinnamic oils provide better UV-B absorption and thus are better candidates to be used as sunscreen active ingredients. Esterifications of the hydroxy oils with MCA at 200°C resulted in conversion of 40% of the MCA to undesirable by-products. Esterifications with MCA performed at 175°C in the presence of a tin catalyst resulted in similar percent conversions to product without degradation of MCA. Esterifications of lesquerella oil with MCA at 175°C resulted in higher conversions, 43%, than analogous esterifications with castor oil, 29%. The hydroxyl groups of the lesquerella and castor oils provide their excellent emolliency, lubricity, and noncomedogenicity in skin and personal-care products. Therefore, reactions that convert only 50% of the available hydroxyl groups of the lesquerella oil to cinnamoyl-esters are preferred.

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KEY WORDS: Castor oil, cinnamic acid, esterification, lesquerella oil, methoxycinnamic acid, sunscreens.

Lesquerella fendleri, a winter annual oil seed crop native to the desert Southwest of the United States, has recently garnered much attention as a potential rotational crop throughout the rest of the United States. Lesquerella seeds consist of 25 to 30% oil, which contains 55 to 64% hydroxy fatty acid (FA) (1). This makes lesquerella oil (LO) an attractive replacement for castor oil (CO), which is mostly imported into the United States and is associated with the phytotoxin ricin.

The hydroxy FA of LO, lesquerolic (55 to 60%) and auricolic (2 to 4%) (2), are mainly located at the 1- and 3-position of the TG (3). The distribution of the lesquerella TG is 10% nonhydroxy, 15% monolesquerolin, and 73% dilesquerolin (2). Therefore, LO in essence contains two moles of hydroxy functionality per mole of triglyceride (TG).

The hydroxy functionality of the FA of the TG can be exploited by esterification to form estolides. The majority of research has focused on the estolides of hydroxy FA and TG formed with oleic acid. The esterification of hydroxy TG and free lesquerolic acid with oleic acid using a cobalt catalyst (4) or a lipase catalyst (5) has been reported. Also, the acid-catalyzed formation of estolides from CO and LO with oleic acid has been patented (6). Recently, a detailed study of the effect of oleic acid concentration and temperature on catalyst-free TG–estolide formation was reported (7).

This study focuses on the ester formation of naturally occurring hydroxyl-containing TG with cinnamoyl acids. Our intent was to functionalize the hydroxy TG with UV-absorbing moieties without the use of a solvent or catalyst. Jojoba wax has been similarly modified with the assistance of an acid catalyst; however, the unsaturated jojoba wax must first be hydroxylated through a multistep, acid-catalyzed process involving mercury acetate, acetic acid, sodium bromide, sodium hydroxide, and the solvents THF and chloroform (8). We conducted experiments to establish the feasibility of a solventless, noncatalytic modification of LO and CO with cinnamoyl acids. Hydrogenated CO possesses excellent emolliency, lubricity, and noncomedogenicity (tendency to create "blackheads" or other skin blemishes) and is often used in cosmetic formulations and personal-care products (9,10). Domestically produced LO is an ideal substitute for CO in cosmetic formulations. The resulting cinnamoyl lesquerella esters described herein are intended to provide the formulation benefits of a hydroxy TG with the added benefit of UV protection, all in a single, naturally based, active ingredient (11).

EXPERIMENTAL PROCEDURES

Materials. LO was obtained from cold-pressed *L. fendleri* seed. The oil was charcoal-bleached and filtered through Celite. CO, cinnamic acid (CA), 4-methoxycinnamic acid (MCA), tin(II) ethylhexanoate, BF_3·methanol complex (BF_3·MeOH, ~50 wt% BF_3 in methanol), hexane, THF (<0.005% water in Sure/Seal® bottles), and HPLC-grade methanol were purchased from Sigma-Aldrich (St. Louis, MO) and used as obtained. Water used for HPLC analysis was purified using a Barnstead International (Dubuque, IA) NanoPure Diamond Pack filtration system. The 3-Å molecular

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sieves were obtained from Fisher Scientific Co. (Fair Lawn, NJ) and activated at 200°C under vacuum for 48 h.

TG-cinnamoyl ester synthesis. All syntheses were performed under a nitrogen atmosphere using standard Schlenk line techniques. Degassed LO (1.0 mL, 0.975 mmol) or degassed CO (1.0 mL, 1.0 mmol), varying molar equivalents of either CA or MCA, and activated 3-Å molecular sieves (650.0 mg) were reacted in a 5-mL glass ampule (Kimble Glass, Inc., Vineland, NJ). The desired cinnamoyl acid was transferred to the ampule, containing the sieves, as 4 mL solutions in THF. The THF was evaporated under a stream of nitrogen, then the sample was dried under vacuum at 80°C. LO or CO was added, and the ampule was sealed under a stream of nitrogen using a Bernz-O-Matic propane torch (Medina, NY). The ampule was placed in a stainless-steel beaker, which was covered by a larger, inverted stainless-steel beaker. The beakers, containing the ampule, were placed in a Cole-Parmer (Chicago, IL) laboratory oven and heated to the desired temperature. The ampule was periodically agitated to ensure a homogeneous reaction mixture. After a prescribed time the ampul was allowed to cool to ambient temperature, the seal was broken, and the contents were extracted with three 2-mL portions of hexane. The combined extract was filtered through a bed of Celite. The bed was then rinsed with three portions of 1 mL of hexane, and the washings were combined with the filtrate. The solvent was removed from the filtrate under vacuum, and the final residue was dried *in vacuo* at 75°C for 18 h. Each esterification reaction was replicated at least three times, and the average yields were reported. The largest standard deviation (SD) of the yields reported in Table 1, as determined by ^{1}H NMR, was ±3.7%.

HPLC analysis. Samples of the TG-cinnamoyl ester reactions were analyzed by HPLC, mostly following previously published procedures (12). A Thermo Separation Products (San Jose, CA) HPLC was equipped with a UV-vis detector and a Prodigy C8 column (Phenomenex, Torrance, CA). For quantification of residual cinnamoyl acids, a water/methanol gradient elution regime was used (12). Samples were prepared by diluting untreated reaction mixtures to 10 mL with THF in volumetric flasks, followed by a further 2,000-fold dilution using THF. The eluate was monitored at 280 nm. The detector response was calibrated with CA (280 nm) and MCA (280 nm) using known concentrations to establish a calibration curve. Responses were linear for both species. The sample injection volume was 10 μL.

NMR. ^{1}H and ^{13}C NMR spectra were recorded on a Bruker ARX-400 (Karlsruhe, Germany) with a 5-mm dual proton/carbon probe (400 mHz ^{1}H/100.61 mHz ^{13}C).

^{1}H NMR of the lesquerella moiety for compounds **1** and **2** ($CDCl_3$) were as follows: δ 5.47–5.23 (*m*, 8.7H, –C*H*=C*H*– and (–O–CH_2)$_2$–C*H*–O–), 4.89 (*p*, *J* = 6.2 Hz, 1.2H, –(CH_2)$_2$–C*H*–(O–CO–R), 4.28 [*dd, J* = 4.3 and 11.8 Hz, 2H, (–O–CH_2)$_2$–CH–O–], 4.14 [*dd, J* = 5.9 and 11.8 Hz, 2H, (–O–CH_2)$_2$–CH–O–], 3.55 [*m*, 1H, –C*H*(OH)–], 2.79 [*m*, 1.9H, –(CH=CH)–CH_2–], 2.36–2.25 (*m*, 9.8H, –CH_2–CO_2R and –CH=CH–CH_2–CHO–), 2.05 (*m*, 8.1H, –CH=CH–CH_2–), 1.63–1.46 (*m*, 9.7H, –CH_2–), 1.30–1.26 (*m*, 54.6H,

TABLE 1
Chemical Properties of Cinnamoyl Esters from Lesquerella and Castor Oils

Entry	Oil	Acid[a]	Acid equivalent[b]	Sieves (mg)	Temperature (°C)	Time (h)	Conversion to ester (%)	Residual acid[c] (%)	EN[d] (NMR)
A	Lesquerella	CA	2	650	100	24	18	—	0.34
B	Lesquerella	CA	2	650	200	4	56	—	0.82
C	Lesquerella	CA	2	650	200	24	76	12	1.44
D	Lesquerella	CA	2	650	200	48	75	11	1.41
E	Lesquerella	CA	3	650	200	24	83	—	1.58
F	Lesquerella	CA	1	650	200	24	19	72	0.36
G[e]	Lesquerella	CA	2	650	175	48	50	50	0.92
H	Lesquerella	CA	2	1000	200	24	74	16	0.75
I	Lesquerella	MCA	2	650	175	24	11	78	0.21
J	Lesquerella	MCA	2	650	200	24	44	12	0.84
K	Lesquerella	MCA	3	650	200	24	42	—	0.81
L[e]	Lesquerella	MCA	2	650	175	24	43	55	0.73
M	Castor	CA	3	650	100	24	34	—	0.91
N	Castor	CA	3	650	200	24	86	21	2.28
O	Castor	CA	3	1000	200	24	85	17	2.25
P[e]	Castor	CA	3	650	175	24	57	36	1.53
Q	Castor	MCA	3	650	175	24	22	—	0.58
R	Castor	MCA	3	650	200	24	42	12	1.12
S	Castor	MCA	3	650	200	48	50	9	1.34
T	Castor	MCA	4	650	200	24	46	—	1.23
U[e]	Castor	MCA	3	650	175	24	29	38	0.78

[a]CA, cinnamic acid; MCA, 4-methoxycinnamic acid.
[b]Acid equivalents based on 2 mol of –OH groups available per mol of lesquerella oil and 3 mol of –OH groups available per mol of castor oil.
[c]The amount of residual acid was determined by HPLC.
[d]Ester number (EN) values determined by H_{14} (lesquerella) and H_{12} (castor) integration.
[e]Tin(II) ethylhexanoate catalyst (10 μL) was added to the reaction.

TABLE 2
^{1}H and ^{13}C NMR Data for the Cinnamoyl Moieties of the Lesquerella and Castor TG-Cinnamoyl Esters

C/H Atom[a]		Lesquerella-cinnamoyl esters		Castor-cinnamoyl esters	
		δ_H ppm, *J* (Hz)	δ_C ppm	δ_H ppm, *J* (Hz)	δ_C ppm
		1[b]		**3**[b]	
1	C	—	134.6	—	134.6
2	CH	7.51 *m*	128.3	7.52 *m*	128.3
3	CH	7.36 *m*	129.3	7.36 *m*	129.0
4	CH	7.36 *m*	130.1	7.36 *m*	130.4
5	CH	7.36 *m*	117.3	7.36 *m*	118.3
6	CH	7.51 *m*	129.3	7.52 *m*	127.3
α	CH	6.41 *d* (16)	118.7	6.41 *d* (16)	118.6
β	CH	7.65 *d* (16)	144.5	7.64 *d* (16)	144.5
C=O	C	—	170.2	—	171.2
		2[b]		**4**[b]	
1	C	—	127.1	—	127.5
2	CH	6.93 *m*	129.9	6.82 *m*	130.1
3	CH	7.65 *m*	114.3	7.40 *m*	115.1
4	C	—	162.1	—	163.2
5	CH	7.65 *m*	114.3	7.40 *m*	115.1
6	CH	6.93 *m*	129.9	6.82 *m*	130.0
α	CH	6.33 *d* (16)	116.0	6.22 *d* (16)	116.5
β	CH	7.65 *d* (16)	145.7	7.54 *d* (16)	147.1
C=O	C	—	172.1	—	174.4
OCH_3	CH_3	3.89 (*s*)	55.3	3.72 (s)	56.1

[a]See Scheme 1 for hydrogen and carbon atom assignments of the cinnamoyl structures.
[b]NMR obtained in $CDCl_3$.

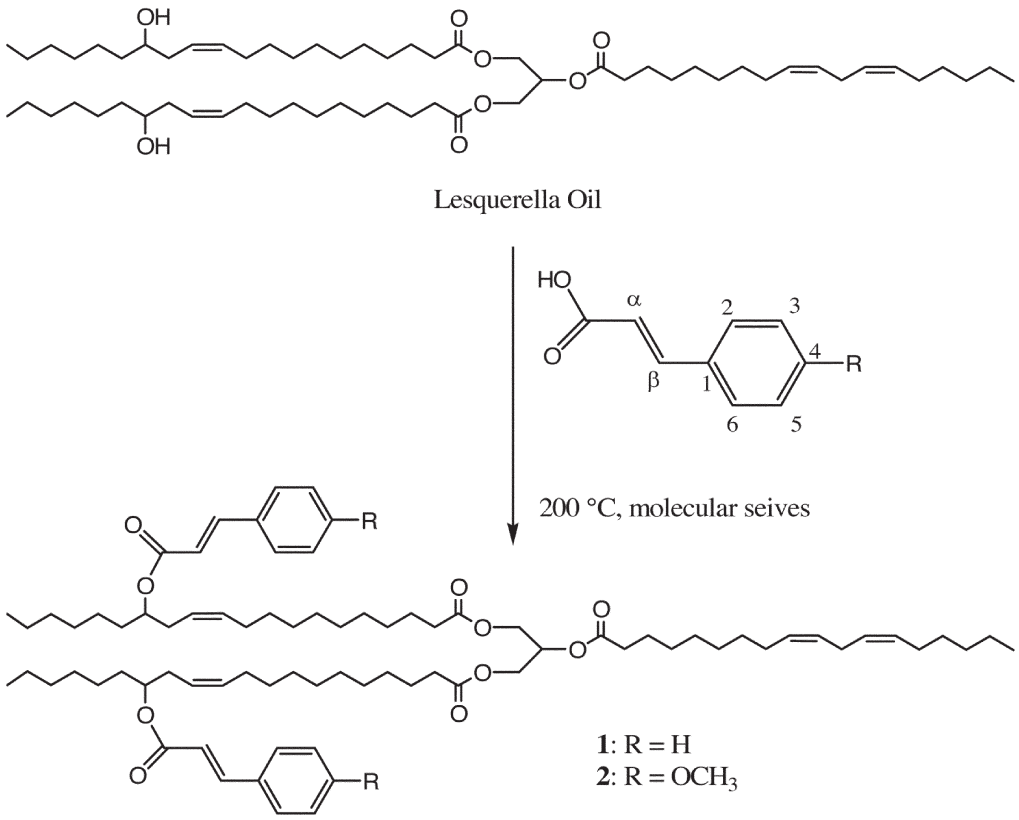
–CH_2–), 0.87 ppm (*m*, 9.2H, –CH_2). ^{1}H NMR ($CDCl_3$) data for the cinnamoyl moieties of compounds **1** and **2** are presented in Table 2. ^{13}C NMR ($CDCl_3$) of the lesquerella moiety for compounds **1** and **2**: δ 173.6 (*s*, –*C*=O), 173.4 (*s*, –*C*=O), 132.7 (*d*, –C=*C*–CH_2CH–O–), 130.2 (*d*, –C=C–), 129.0 (*d*, –C=C–), 128.1 (*d*, –C=C–), 125.7 (*d*, –*C*=C–CH_2CH–O–), 73.7 [*d*, –*C*H(OH)–], 71.6 (*d*, –*C*H–O–), 68.9 [*t*, (–OCH_2)$_2$–*C*H–O–), 62.2 [*d*, (–O*C*H$_2$)$_2$–CH–O–], 36.9 (*t*, –*C*H$_2$–), 35.4 (*t*, –*C*H$_2$–), 34.3 (*t*, –*C*H$_2$–), 34.1 (*t*, –*C*H$_2$–), 31.9 (*t*, –*C*H$_2$–), 29.8 (*t*, –*C*H$_2$–), 29.7 (*t*, –*C*H$_2$–), 29.6 (*t*, –*C*H$_2$–), 29.5 (*t*, –*C*H$_2$–), 29.5 (*t*, –*C*H$_2$–), 29.4 (*t*, –*C*H$_2$–), 29.4 (*t*, –*C*H$_2$–), 29.3 (*t*, –*C*H$_2$–), 29.3 (*t*, –*C*H$_2$–), 29.2 (*t*, –*C*H$_2$–), 29.1 (*t*, –*C*H$_2$–), 27.5 (*t*, –*C*H$_2$–), 27.2 (*t*, –*C*H$_2$–), 25.8 (*t*, –*C*H$_2$–), 24.9 (*t*, –*C*H$_2$–), 22.8 (*t*, –*C*H$_2$–), 22.7 (*t*, –*C*H$_2$–), 14.2 ppm (*q*, –CH_3). ^{13}C NMR ($CDCl_3$) data for the cinnamoyl moieties of compounds **1** and **2** are presented in Table 2.

^{1}H NMR of the castor moiety for compounds **3** and **4** ($CDCl_3$) were as follows: δ 5.46–5.33 [*m*, 7.3H, –C*H*=C*H*– and (–O–CH_2)$_2$–C*H*–O–], 4.88 [*p*, *J* = 6.2 Hz, 2.7H, –(CH_2)$_2$–C*H*–(O–CO–R)], 4.28 [*dd, J* = 4.3 and 11.8 Hz, 2H, (–O–(CH_2)$_2$–CH–O–], 4.14 [*dd, J* = 5.9 and 11.9 Hz, 2H, (–O–(CH_2)$_2$–CH–O–], 3.61 [*m*, 1H, –C*H*(OH)–], 2.29–2.19 (*m*, 11.4H, –CH_2–CO_2R and –CH=CH–CH_2–CHO–), 2.07–2.02 (*m*, 5.9H, –CH=CH–CH_2–), 1.62–1.17 (*m*, 47H, –CH_2–), 0.88 ppm (*m*, 8.5H, –CH_3). ^{1}H NMR ($CDCl_3$) data for the cinnamoyl moieties of compounds **3** and **4** are presented in Table 2. ^{13}C NMR ($CDCl_3$) of the castor moiety for compounds **3** and **4**: δ 173.7 (*s*, –*C*=O), 173.3 (*s*, –*C*=O), 133.8 (*d*, –C=*C*–CH_2CH–O–), 125.8 (*d*, –*C*=C–CH_2CH–O–), 73.9 [*d*, –*C*H(OH)–], 72.1 (*d*, –CH–O–), 69.4 [*t*, (–OCH_2)$_2$–*C*H–O–], 62.6 [*d*, (–O*C*H$_2$)$_2$–CH–O–], 36.9 (*t*, –*C*H$_2$–), 35.4 (*t*, –*C*H$_2$–), 34.7 (*t*, –*C*H$_2$–), 33.8 (*t*, –*C*H$_2$–), 32.1 (*t*, –*C*H$_2$–), 32.1 (*t*, –*C*H$_2$–), 32.0 (*t*, –*C*H$_2$–), 31.9 (*t*, –*C*H$_2$–), 31.8 (*t*, –*C*H$_2$–), 29.7 (*t*, –*C*H$_2$–), 29.6 (*t*, –*C*H$_2$–), 29.4 (*t*, –*C*H$_2$–), 29.3 (*t*, –*C*H$_2$–), 29.3 (*t*, –*C*H$_2$–), 29.2 (*t*, –*C*H$_2$–), 29.2 (*t*, –*C*H$_2$–), 27.5 (*t*, –*C*H$_2$–), 27.4 (*t*, –*C*H$_2$–), 25.8 (*t*, –*C*H$_2$–), 25.5 (*t*, –*C*H$_2$–), 25.4 (*t*, –*C*H$_2$–), 25.1 (*t*, –*C*H$_2$–), 24.9 (*t*, –*C*H$_2$–), 22.7 (*t*, –*C*H$_2$–), 14.2 ppm (*q*, –CH_3). ^{13}C NMR ($CDCl_3$) data for the cinnamoyl moieties of compounds **3** and **4** are presented in Table 2.

RESULTS AND DISCUSSION

This paper details the esterification of LO and CO with CA and MCA in neat solutions at elevated temperatures. LO and CO mostly contain 1,3-dihydroxyacyl and trihydroxyacyl TG, respectively. The FA compositions of both hydroxyl oils used in this study have been published previously (7). LO contains 1.9 mol of hydroxyl groups, whereas castor oil contains 2.7 mol of hydroxyl groups per mol of oil. These functional hydroxyl sites (secondary alcohols) are subject to esterification with carboxylic acids *via* condensation. The condensation can be catalyzed at moderate temperatures (135°C) or proceed directly at more elevated temperatures (200°C). Scheme 1 depicts the neat, noncatalyzed condensation reaction of LO with cinnamoyl acids to form lesquerella-cinnamoyl esters. CO undergoes the same condensation reaction to form castor-cinnamoyl esters (Scheme 2).

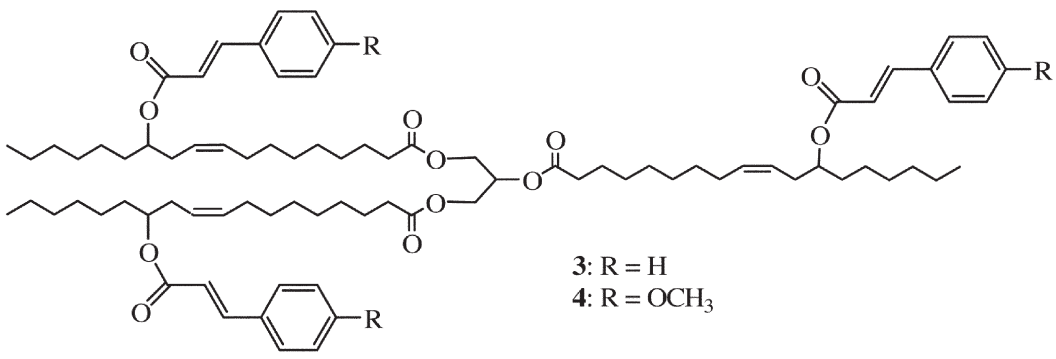
The high-temperature, noncatalytic esterification of the hydroxy TG with cinnamoyl acids was adapted from previously published methods (7). The condensation of LO and CO with



SCHEME 1

oleic acid to form TG estolides was performed under a dynamic vacuum at 200°C. The resulting water was evaporated from the reaction, driving the esterification to completion. The physical properties of CA (m.p. 133–134°C) and MCA (m.p. 170–173°C) did not allow for an analogous synthesis. Attempts to perform the esterification of LO and CO with CA and MCA at 200°C under vacuum resulted in the acids being sublimed from the reaction mixture and condensed at the top of the reaction flask. Consequently, we devised a method in which the oil and acid were sealed in an ampule, which was heated in an oven with agitation to ensure reactant mixing. Since the resultant water could not be evaporated from the closed system, molecular sieves were used to scavenge the water produced from the reaction. The CA and MCA could not accurately be placed directly into the ampules, but instead were quantitatively transferred as solutions in anhydrous THF. The THF was removed under a stream of dry nitrogen at 60°C, then under vacuum for 1 h at 60°C. It was essential to remove all solvent since residual THF produced pressures that caused the ampules to explode upon heating. Esterifications of LO and CO were performed at various CA and MCA concentrations, temperatures, and lengths of time (Table 1).

The lesquerella- and castor-cinnamoyl esterification yields (Table 1) were determined using ^{1}H NMR spectroscopy. Esterification numbers (EN), analogous to previously reported



SCHEME 2

TABLE 1
Chemical Properties of Cinnamoyl Esters from Lesquerella and Castor Oils

Entry	Oil	Acid[a]	Acid equivalent[b]	Sieves (mg)	Temperature (°C)	Time (h)	Conversion to ester (%)	Residual acid[c] (%)	EN[d] (NMR)
A	Lesquerella	CA	2	650	100	24	18	—	0.34
B	Lesquerella	CA	2	650	200	4	56	—	0.82
C	Lesquerella	CA	2	650	200	24	76	12	1.44
D	Lesquerella	CA	2	650	200	48	75	11	1.41
E	Lesquerella	CA	3	650	200	24	83	—	1.58
F	Lesquerella	CA	1	650	200	24	19	72	0.36
G[e]	Lesquerella	CA	2	650	175	48	50	50	0.92
H	Lesquerella	CA	2	1000	200	24	74	16	0.75
I	Lesquerella	MCA	2	650	175	24	11	78	0.21
J	Lesquerella	MCA	2	650	200	24	44	12	0.84
K	Lesquerella	MCA	3	650	200	24	42	—	0.81
L[e]	Lesquerella	MCA	2	650	175	24	43	55	0.73
M	Castor	CA	3	650	100	24	34	—	0.91
N	Castor	CA	3	650	200	24	86	21	2.28
O	Castor	CA	3	1000	200	24	85	17	2.25
Pe	Castor	CA	3	650	175	24	57	36	1.53
Q	Castor	MCA	3	650	175	24	22	—	0.58
R	Castor	MCA	3	650	200	24	42	12	1.12
S	Castor	MCA	3	650	200	48	50	9	1.34
T	Castor	MCA	4	650	200	24	46	—	1.23
U[e]	Castor	MCA	3	650	175	24	29	38	0.78

[a]CA, cinnamic acid; MCA, 4-methoxycinnamic acid.
[b]Acid equivalents based on 2 mol of –OH groups available per mol of lesquerella oil and 3 mol of –OH groups available per mol of castor oil.
[c]The amount of residual acid was determined by HPLC.
[d]Ester number (EN) values determined by H_{14} (lesquerella) and H_{12} (castor) integration.
[e]Tin(II) ethylhexanoate catalyst (10 μL) was added to the reaction.

estolide numbers (7), are a measure of the amount of available hydroxyl groups in the oil that have been capped (esterified) by a carboxylic acid moiety during the reaction. For the lesquerella reactions, the ratio of the integrated hydroxy methine proton (3.55 ppm), after assigning the integration of the glycerin's α-methylene protons (4.28 and 4.14 ppm) a value of 4, is used to calculate the EN_{lesq}. The same method, employing the hydroxy methine protons (3.61 ppm) and the α-methylene protons (4.28 and 4.13 ppm), is used for calculating the EN_{castor}.

$$EN_{lesq} = 1.89 - H_{14} \quad [1]$$

$$EN_{castor} = 2.67 - H_{12} \quad [2]$$

The constants 1.89 and 2.67 used for calculating the lesquerella- and castor-cinnamoyl ester EN, respectively, represent the maximum EN value possible based on the number of moles of hydroxyl groups available in each oil (7).

The conversion of LO to the lesquerella-cinnamic ester, **1**, reached a maximum EN of 1.58 (trial E, Table 1), which corresponds to 83% of the available hydroxyl groups esterified by the CA. Reaction temperature, reaction time, and cinnamic acid equivalents were found to influence the esterification yields. Reactions performed at 100°C produced conversions lower than 20%, resulting from the heterogeneous reaction conditions due to the unmelted cinnamic acid. Esterifications performed at 200°C with 2 equiv of CA reached 75% conversion after 24 h (trial C, Table 1) and did not proceed further with longer reaction times. Shorter reaction times at 200°C produced significantly lower yields. Using an excess of CA (trial E, Table 1) shifted the equilibrium of the reaction and increased the conversion to 83%. The amount of CA incorporated into **1** was confirmed based on the ratio of the integrated protons (7.51 ppm) at positions 2 and 6 of the cinnamoyl ring (Scheme 1) to the α-methylene protons (4.28 and 4.14 ppm) of the glyceride backbone. The maximum ratio of the cinnamoyl ring protons (positions 2 and 6) to the α-methylene protons would be 1:1 based on a 100% conversion of hydroxyl groups to esters (EN_{lesq} = 1.89). After the unreacted CA was removed from the reaction mixture by sublimation at 75°C under vacuum, the ratio of the 2 and 6 protons of the cinnamoyl ring to the α-methylene protons was 0.76:1 for trial D (Table 1). This correlates well with the percent conversion, 75%, calculated based on an EN_{lesq} of 1.41.

For comparison, analogous esterifications of CO with CA were performed. CO contains *ca.* 3 mol equiv of hydroxyl groups per mol of oil; therefore, a minimum of 3 equiv of CA was used. The conversion of CO to the castor-cinnamic ester, **3**, using 3 equiv of CA at 200°C after 24 h (trial N, Table 1) resulted in an EN_{castor} = 2.26 (86% conversion). The reaction was similarly dependent on temperature and reaction time. Excess CA did not result in higher EN values for compound **3**.

The TG-cinnamic esters, **1** and **3**, exhibit UV absorptions similar to those of CA, which absorbs between 250 and 310 nm with a λ_{max} of 270 nm. The cinnamoyl structure allows for the delocalization of an electron throughout the molecule

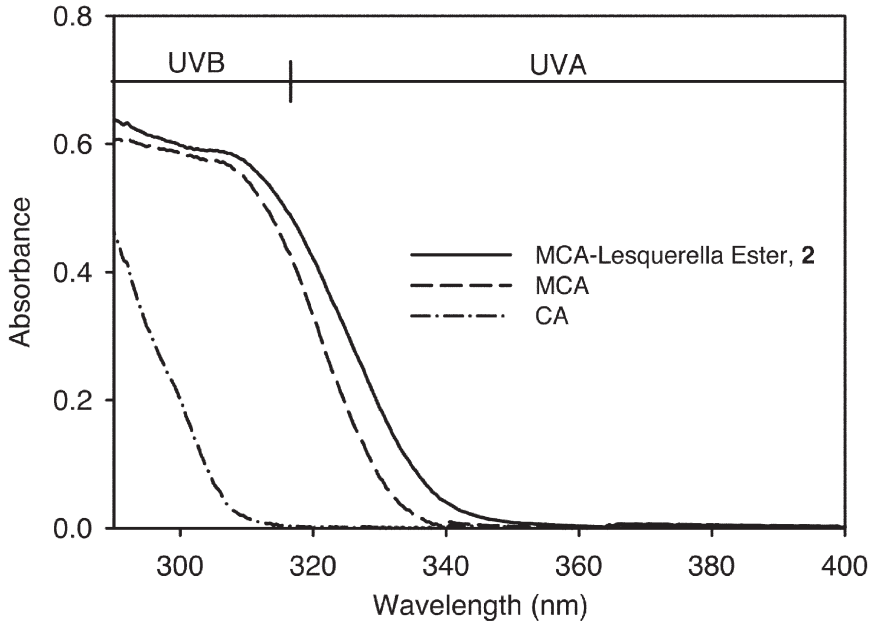


FIG. 1. Absorbance spectra of 5 µM THF solutions of cinnamic acid (CA), 4-methoxycinnamic acid (MCA), and lesquerella-MCA ester (**2**) in the UV-B (290 to 320 nm) and the UV-A (320 to 400 nm) regions.

upon absorption of a photon. The CA absorbs only the lowest wavelengths of the ultraviolet-B (UV-B) region (Fig. 1) but possesses a large molar extinction coefficient (>23,000) (13). Substituted CA, such as MCA, that possesses an electron-releasing group (e.g., $–OCH_3$) in the *para*-position have superior UV-B absorption characteristics compared to the unsubstituted CA (Fig. 1). Our previous studies focused on using the ethyl ester of naturally occurring ferulic acid (4-hydroxy-3-methoxy cinnamic acid) to modify soybean oil to produce an all-natural sunscreen active ingredient, SoyScreen™ (14,15). Attempts to esterify the hydroxylacylglycerides with ferulic acid at 200°C under dehydrating conditions resulted in the polymerization of the ferulic acid *via* a condensation reaction of its *p*-hydroxy group with its carboxylic acid group. MCA possesses UV absorption properties similar to those of ferulic acid, although the MCA spectrum is blue-shifted. MCA is substituted with a single *p*-methoxy group instead of a *p*-hydroxyl and an *m*-methoxy group and does not polymerize at 200°C under dehydrating conditions. Thus, its capacity to form UV-B-absorbing lesquerella- and castor-methoxycinnamic esters was investigated.

The conversion of LO to the lesquerella-methoxycinnamic ester, **2**, reached a maximum EN of 0.84 at 200°C and 24 h (trial J, Table 1). MCA melts at 173°C, and reactions below that temperature did not proceed. The lesquerella esterification with MCA performed at 175°C for 24 h resulted in very low percent conversions (trial I, Table 1). Excess MCA did not shift the equilibrium of the reaction (trial K, Table 1). The esterification of CO with MCA at 200°C for 24 h to form **4** resulted in slightly higher percent conversions, 50%, than the analogous lesquerella esterifications. HPLC analysis of the hydroxylacylglycol esterification reactions with MCA showed that there were unidentified by-products in addition to unreacted MCA. ^{1}H NMR spectroscopy revealed proton signals (multiplets) at δ = 7.20, 7.15, and 6.79—at a ratio of 1:1:2—and a singlet at 3.84 (3 protons), none of which can be attributed to a 4-, 3-, or 2-methoxycinnamoyl moiety. The by-products account for approximately 40% of the MCA consumed in the reactions performed at 200°C for 24 h. Much less of the MCA is converted to these unidentified by-products when the reactions are conducted at 175°C; however, the formation of **2** is less (trial I, Table 1). The residual MCA was easily removed from these reactions by sublimation at 100°C under vacuum whereas the by-product was not. Attempts to increase the conversion of LO (trial L, Table 1) and CO (trial U, Table 1) to **2** and **4** at 175°C by using a tin catalyst significantly reduced the amount of by-product formed while increasing the yield to 43% for the lesquerella reaction. The analogous CO reaction did not proceed as efficiently, i.e., the yield was 29%. Reactions that were attempted using $BF_3{\cdot}CH_3OH$ and H_2SO_4 as catalysts resulted in severely discolored reactions and lower yields (data not shown). Previous studies have shown that hydroxyljojoba wax, which must be synthesized from jojoba wax, can be converted to methoxycinnamic esters (78% yield); however, the reactions involve diethyl ether/acetone/petroleum ether solutions in the presence of 30% H_2O_2 and 20% HCl (8). Although the esterifications described herein produce lower lesquerella- and castor-methoxycinnamic ester yields, our reactions have the advantage of a natural hydroxyltriacylglyceride source and need no solvent. Overall, we can obtain a 43% conversion of lesquerella to **2** with a minimal amount of MCA degradation at 175°C with the use of a tin catalyst. Similar percent conversions, 44%, of lesquerella to **2** can be obtained

without the use of a catalyst at 200°C; however, the amount of MCA degradation is significantly increased.

The UV spectra of **2** and **4** were similar to that of MCA. The UV spectrum of **2** is shown in Figure 1. The λ_{max} of **2** and **4** are red-shifted from that of **1** and **3** well into the UV-B region (290 to 320 nm), making them better candidates for UV-B-absorbing active ingredients. Focusing on the lesquerella-cinnamoyl oils, the percent conversions to **1** (83%) were double that of conversions to **2** (44%). However, because **2** absorbs much more in the UV-B region, it is the preferred compound for use as a UV-B-absorbing active ingredient. The lower percent conversion to **2** is not a critical issue. The desired lesquerella-cinnamoyl active ingredient must retain the emolliency and beneficial cosmetic properties of a hydroxyltriacylglyceride; therefore, only one hydroxyl group per mole of oil must be esterified. Thus, a reaction that provides nearly 50% conversion is adequate. Since conversions of LO with 1 mol equiv of CA resulted in one-fifth of the available hydroxyl group being esterified after 24 h (trial F, Table 1), the use of 2 mol equiv of MCA to reach 50% conversion with the subsequent removal of unreacted MCA under vacuum was the preferred method. It would be more desirable to have a process that does not use a catalyst; however, a tin catalyst provided 50% conversion to **2** without a significant loss of MCA to by-products. The unreacted MCA can be collected by sublimation and recycled into subsequent reactions. Additionally, using the tin catalyst requires lower energy input since the reaction can be carried out at lower temperatures.

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REFERENCES

1. Carlson, K.D., A. Chaudry, and M.O. Bagby, Analysis of Oil and Meat from *Lesquerella fendleri* Seed, *J. Am. Oil Chem. Soc. 67*:438–442 (1990).
2. Carlson, K.D., A. Chaudry, and R.E. Peterson, Chromatographic Isolation of Hydroxy Acids from *Lesquerella fendleri* and *L. godonii* Seed Oils, *Ibid. 67*:495–498 (1990).
3. Hayes, D.G., and R. Kleiman, Recovery of Hydroxy Fatty Acids from Lesquerella Oil with Lipases, *Ibid. 69*:982–985 (1992).
4. Erdem-Senatalar, A., E. Ereneck, and A.T. Erciyes, Mechanism and Kinetics of $CoCl_2$-Catalyzed Esterification Reaction of Castor Oil with Oleic Acid, *Ibid. 72*:891–894 (1995).
5. Hayes, D.G., and R. Kleiman, Lipase-Catalyzed Synthesis and Properties of Estolides and Their Esters, *Ibid. 72:*1309–1316 (1995).
6. Lawate, S.S., Triglyceride Oils Thickened with Estolides of Hydroxy-Containing Triglycerides, U.S. Patent 5,427,704 (1995).
7. Isbell, T.A., and S.C. Cermak, Synthesis of Triglyceride Estolides from Lesquerella and Castor Oils, *J. Am. Oil Chem. Soc. 79*:1227–1233 (2002).
8. Touitou, E., and L. Bergelson, Products for Preventing Penetration into the Skin, International Patent Application WO 02/079121 A2 (2002).
9. Hurd, P.W., The Chemistry of Castor Oil and Its Derivatives, *Natl. Lubr. Grease Inst. 60*:14–23 (1996).
10. Lower, E.S., Hydrogenated Castor Oil, *Riv. Ital. Sostanze Grasse 70*:87–92 (1993).
11. Compton, D.L., T.A. Isbell, and R.E. Harry-O'kuru, Novel Sunscreen Reagents from Hydroxy-Substituted Acylglycerides, U.S. Patent Application 10/462,882 (2003).
12. Compton, D.L., J.A. Laszlo, and M.A. Berhow, Synthesis of Ferulate Esters, *J. Am. Oil Chem. Soc. 77*:513–519 (2000).
13. Shaath, N.A., Evolution of Modern Sunscreen Chemicals, in *Sunscreens: Development, Evaluation, and Regulatory Aspects*, 2nd edn., edited by J.L. Nicholas, N.A. Shaath, and M.A. Pathak, Marcel Dekker, New York, 1997, pp. 3–33.
14. Compton, D.L., and J.A. Laszlo, Novel Sunscreens from Vegetable Oil and Plant Phenols, U.S. Patent 6,346,236 (2002).
15. Laszlo, J.A., D.L. Compton, F.J. Eller, S.L. Taylor, and T.A. Isbell, Packed-Bed Bioreactor Synthesis of Feruloylated Monoacyl- and Diacylglycerols: Clean Production of a "Green" Sunscreen, *Green Chem. 5*:382–386 (2003).

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