Syntheses of 12-Aminododecanoic and 11-Aminoundecanoic Acids from Vernolic Acid

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ABSTRACT: 12-Aminododecanoic acid and 11-aminoundecanoic acid, monomer precursors for nylon-12 and nylon-11, respectively, have been synthesized from vernolic (*cis*-12,13-epoxy-*cis*-9-octadecenoic) acid *via* a reaction sequence that includes the formation of 12-oxododecanoic acid oxime. Saponification of vernonia oil, followed by a low-temperature recrystallization at –20°C, gave 51% vernolic acid (97% purity, m.p. 23–25°C). Hydrogenation afforded *cis*-12,13-epoxystearic acid (m.p. 52–54°C, lit. m.p. 52–54°C), which upon oxidation with periodic acid in tertiary butyl alcohol gave 12-oxododecanoic acid with an isolated yield of 71.0%. Reaction of the oxoacid with hydroxylamine hydrochloride gave 12-oxododecanoic acid oxime, which was catalytically reduced to give 12-aminododecanoic acid with a yield greater than 85% and a melting point of 184–186°C (lit. m.p. 185–187°C). 11-Aminoundecanoic acid was prepared from the 12-oxododecanoic acid oxime *via* a three-step reaction sequence that involved a Beckmann rearrangement, Hofmann degradation, and hydrolysis. Thus, the aldoxime acid was hydrolyzed in the presence of nickel acetate tetrahydrate to give 11-carbamoylundecanoic acid (48% yield, m.p. 129–131°C, lit. m.p. 129–130°C). The amide was then treated with a solution of sodium methoxide and bromine at 70–80°C to give 11-(methoxycarbonylamino)undecanoic acid at 75% yield (m.p. 84–86°C; elemental analysis, calculated for $C_{13}H_{25}NO_4$: C, 60.19; H, 9.73; N, 5.40; O, 24.68%; found C, 60.02; H, 9.81; N, 5.26; O, 24.91%), which upon alkaline hydrolysis and subsequent neutralization gave 11-aminoundecanoic acid at 34% yield (m.p. 189–192°C, lit. m.p. 190°C). Mass spectrometric and ^{13}C nuclear magnetic resonance data of the previously unreported 11-(methoxycarbonylamino)undecanoic acid is provided.
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KEY WORDS: Aldoxime, 12-aminododecanoic acid, 11-aminoundecanoic acid, Beckmann rearrangement, *cis*-12,13-epoxy-*cis*-9-octadecenoic acid, 12,13-epoxystearic acid, 12-oxododecanoic acid, 12-oxododecanoic acid oxime, vernolic acid, vernonia oil.

Current interest in *Vernonia galamensis* seed oil (vernonia oil) derives from its naturally epoxidized triglyceride fatty acids, giving it potential as a unique oil for industrial raw materials used in plastic formulations, adhesives, chemical coatings, plasticizers, stabilizers, and syntheses of industrial chemical intermediates (1–3). Vernolic acid, the major acid component of vernonia oil (VO), was first characterized from *V. anthelmintica* oil by Gunstone (4) as *cis*-12,13-epoxy-*cis*-9-octadecenoic acid. Bharucha and Gunstone (5) also demonstrated the presence of the acid in *Cephalocroton cordofanus* oil, and Chisholm and Hopkins (6) indicated occurrence of the acid in the oil of *Hibiscus esculentus*. Isolation and identification of vernolic acid from *V. anthelmintica* seed oil was earlier reported by Smith, *et al.* (7), Krewson (1), and by Chisholm and Hopkins (8).

In the present work, we report the syntheses of 12-aminododecanoic acid and 11-aminoundecanoic acid, monomer precursors for nylon-12 and nylon-11, respectively. Nylon-12 is an engineering polyamide used as a curing agent for epoxy resins or as modifiers for polyester (9). This polymeric material also has applications in the automobile industry for the preparation of oil- and gasoline-resistant hoses. Other applications of nylon-12 include its use in hydraulic systems, electrical cable, metal coatings, ship propellers, screws, injection syringes, sterilized films and bags for medical purposes, and for sausage skin (10). Furthermore, modification of these nylon-12 products can be effected by the addition of some polyamide additives such as plasticizers, pigments, heat, and light stabilizers.

The preparation of nylon-12 was first mentioned by Carothers (11). By trimerizing butadiene, Ziegler and Wilke (12) prepared cyclododecatriene, which was subsequently converted to nylon-12 through a series of reactions. The butadiene is produced mostly from petroleum gases by catalytic dehydrogenation of butene or butene–butane mixture, or alternatively by cracking naphtha (C_6H_{14}–C_7H_{18}) or light oil.

Several other methods for synthesizing 12-aminododecanoic acid have been reported in the literature. For example, 11-formyl-4,8-undecadienoic acid was reacted with aqueous ammonia and 30% sodium hydroxide, with subsequent reduction of the imine (13). Hawkins and coworkers (14) reduced 11-cyanoundecanoic acid, obtained by vapor-phase pyrolysis of 11-peroxydicyclohexylamine at 300–1000°C, to yield 12-aminododecanoic acid. Also, Tsyskovskii and Razumovskii (15) treated the monoozonide of a cycloolefin or cyclopolyolefin with hydroxylamine and reduced the resulting oxime. Bacterial conversion of dodecamethylenediamine to 12-aminododecanoic acid was cited by Matsumoto (16).

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Nylon-11 (tradename Rilsan) is an engineering resin that is used in various engineering plastics because of its excellent dimensional stability, abrasion, and vibration resistance. Other uses include electrical (cable extrusion), mechanical (molding intricate components), and sports equipment and industrial fabrics, powder coatings and synthetic fibers. Currently, castor oil is the only source of this versatile polymeric resin. The synthesis of nylon-11 from castor oil involves at least six reaction steps, one of which is the energy-intensive pyrolysis (450–500°C) reaction.

In this communication, we present experimental results that demonstrate the potential use of vernonia oil in the production of both nylon-12 and nylon-11 monomers. For both monomers, the key intermediate was 12-oxododecanoic acid oxime. For the nylon-11 monomer, the acid oxime was converted to the amide (11-carbamoylundecanoic acid), which subsequently underwent Hofmann degradation to give the 11-aminododecanoic acid. Earlier synthesis of 11-carbamoylundecanoic acid had been reported in a British patent by Durston (17). In his work, 1,1-peroxydicyclohexylamine was thermally decomposed below 450°C to give decane-1,10-dicarbonimide, which was subsequently hydrolyzed to obtain the amide. Also, Kataoka and Ohno (18) synthesized 11-carbamoylundecanoic acid from a cyclic hydroxyimino ketone by treatment with concentrated sulfuric acid. Thus, our investigation represents the first reported syntheses of both 12-aminododecanoic acid and 11-aminoundecanoic acid from a single source, vernolic acid, *via* the intermediacy of 12-oxododecanoic acid oxime.

EXPERIMENTAL PROCEDURES

The crude VO that was used in this project was obtained from IXTT Corporation (Culver, IN). Reactions and products were monitored with a Finnigan gas chromatograph (model 9611), equipped with a splitless injector and interfaced with a Finnigan MAT 4500 automated mass spectrometer with a SUPERINCOS data system (San Jose, CA). The interface oven and transfer line were maintained at 300°C, the ionizer temperature setting was at 150°C, with electron impact (EI) mode, with emission current 0.39 mA, electron multiplier 1500 V and electron energy at 70 eV. High-resolution capillary gas chromatography was conducted with a Supelco fused-silica SPB-1 (30 m, 0.32 mm i.d., 0.25 μm film) column (Bellefonte, PA), oven temperature was programmed from 50 to 300°C, and helium was used as the carrier gas with a head pressure of 10 psi. Characterization of the acids by gas chromatography/mass spectrometry (GC/MS) was performed with methylated samples, prepared by adding 1 mL ethereal solution of diazomethane to *ca.* 10-mg sample of acids. The infrared (IR) spectra were obtained on a Perkin-Elmer model 983G spectrophotometer (Palo Alto, CA). Solid samples were run with KBr, while liquid samples were run neat. The ^{13}C nuclear magnetic resonance (CNMR) and proton nuclear magnetic resonance (PNMR) spectra were recorded on a GE-NMR QE-300 model spectrometer (Fremont, CA), with chloroform-d ($CDCl_3$) and methanol-d$_4$ (CD_3OD) as solvents and sources of internal standards. Melting points (m.p.) were determined on a mel-temp II capillary m.p. apparatus.

Saponification of VO. To a 250-mL distilling flask, equipped with a magnetic stir bar, was transferred 50 mL methanol and 4.97 g (0.124 mol) sodium hydroxide. The flask was then fitted with a condenser, and the mixture was heated to reflux until complete dissolution of the sodium hydroxide. To the hot alkaline solution was added, in one portion, 5.12 g (5.5×10^{-3} mol) VO. The resulting brownish solution was refluxed with continuous stirring for 10 min, after which it was immediately transferred into a beaker and allowed to form a semisolid on cooling. About 100 g ice was added, mixed thoroughly, followed by addition of 100 mL water with mixing. The cold mixture was vacuum-filtered to afford an off-white solid soap in the filter bed.

The soap was transferred into a beaker and mixed with *ca.* 100 g ice and 100 mL water, then acidified with *ca*. 4 mL acetic acid. The acidified mixture was immediately vacuum-filtered to afford a white solid (containing a mixture of acids). The cold white solid was transferred into a beaker, containing 100 mL hexane, with mixing to dissolve the acid, and the resulting mixture was transferred into a separatory funnel to allow separation of the organic and aqueous phases. The hexane layer was stripped to afford crude vernolic acid (4.5 g).

Gas-chromatographic analysis of the methylated crude product indicated palmitic, oleic, linoleic, stearic, and vernolic acids. Mass spectral data of the methyl vernolate were consistent with previously reported data (19).

Purification of vernolic acid. The vernolic acid isolated above was 76% pure, based on the oxirane value of 4.1%. Purification of the acid was accomplished by low-temperature recrystallizations. Hexane (50 mL) was added to a 150-mL beaker containing 4.5 g of the crude vernolic acid, and the beaker was then placed in a –20°C freezer for 24 h. The resulting solid was vacuum-filtered and rinsed with an additional 50 mL ice-cold hexane to give 2.77 g (56.72% yield) vernolic acid (m.p. 23–25°C, lit. m.p. 25–28°C, oxirane % 5.22, 96.0% purity).

Preparation of cis-*12,13-epoxystearic acid.* A 2.6-g (8.8×10^{-3} mol) sample of vernolic acid was placed in a Parr hydrogenation bottle, followed by 0.03 g (1.3×10^{-4} mol) platinum oxide (Adam's catalyst) and 15 mL methanol. The bottle and its contents were fitted to a Parr high-pressure system (Moline, IL). The air in the bottle was evacuated with a water aspirator, after which the bottle was filled with hydrogen gas to maintain a pressure of 3 atm for 45 min with continuous shaking. After hydrogenation, methanol (15 mL) was added to the reaction mixture, then heated to gentle boiling to dissolve the product. The hot mixture was quickly filtered to remove the suspension of black platinum, and the filtrate was evaporated to give 2.42 g (93% yield) of white solid, consisting of 99% (GC purity) *cis*-12,13-epoxystearic acid after recrystallization from hexane (m.p. 52–54°C, lit. m.p. 52–53.5°C).

Oxidation of cis-*12,13-epoxystearic acid.* A 2.40-g (0.008

mol) sample of *cis*-12,13-epoxystearic acid was placed in a 250-mL Erlenmeyer flask and dissolved with 18 mL water and 9 mL tertiary butyl alcohol. The mixture was stirred continuously for homogeneity, followed by addition of 1.95 g (0.0086 mol) periodic acid in one portion. The reaction mixture was then stirred for 5 h, after which 150 mL ice-cold water was added. The mixture was stirred for another 30 min, and the resulting solid was vacuum-filtered to give crude 12-oxododecanoic acid. The acid was washed, then recrystallized with light petroleum (b.p. 35–60°C) to give 1.22 g 12-oxododecanoic acid (73% yield, m.p. 53–54°C).

Preparation of 12-oxododecanoic acid oxime. A 2.75-g (0.04 mol) sample of hydroxylamine hydrochloride was placed in a 250-mL Erlenmeyer flask, followed by 16.5 mL water and gentle warming of the contents of the flask. To the flask was added 11 mL 10% sodium hydroxide and 1.1 g (0.005 mol) 12-oxododecanoic acid. Ethanol (15 mL) was added to give a clear solution. The mixture was warmed in a water bath for 10 min after which it was cooled in an ice-bath. The resulting solid was filtered and dried to give 1.05 g of aldoxime acid. Recrystallization was carried out in water/ethanol mixture (4:1) to give 0.92 g aldoxime acid (m.p. 104–106°C). Elemental analysis found: C, 62.65; H, 9.92; N, 5.72%. Calculated for $C_{12}H_{23}NO_3$: C, 62.85; H, 10.11; N, 6.11%.

Preparation of 12-aminododecanoic acid. In a Parr hydrogenation bottle was placed 0.92 g of 12-oxododecanoic acid oxime (4×10^{-3} mol), 10 mL methanol, and then 0.005 g (2.2×10^{-5} mol) platinum oxide (Adam's catalyst). The bottle was fitted to a Paar high-pressure system, deaerated, then filled with hydrogen gas to maintain a pressure of about 3 atm for 1.5 h with continuous shaking. After hydrogenation, 10 mL methanol was added to the reaction mixture, then heated to gentle boiling to dissolve the product. The hot mixture was quickly filtered to remove the suspended black platinum, after which the filtrate on evaporation gave 0.85 g (92% yield) 12-aminododecanoic acid. Recrystallization was effected in ethanol/water mixture (1:1) to give 0.80 g (87% yield) 12-aminododecanoic acid (m.p. 184–186°C, lit. 185–187°C).

Isomerization of 12-oxododecanoic acid oxime to 11-carbamoylundecanoic acid. A 100-mL round-bottomed flask, equipped with a magnetic stirring bar, was charged with 5.00 g (2.18×10^{-2} mol) 12-oxododecanoic acid oxime, followed by the addition of 0.11 g (4.41×10^{-5} mol) finely ground nickel acetate tetrahydrate, 0.5 mL piperidine, and 25 mL *p*-xylene. The resulting mixture was stirred continuously and heated (110–115°C) for 24 h. The flask and its contents were allowed to cool to room temperature with occasional stirring to facilitate crystallization of the solid product, which was filtered and rinsed with 15 mL of ice-cold hexane. The crude amide weighed 3.0 g (60% yield, m.p. 124–126°C). Recrystallization from 20 mL ethanol/water mixture (4:1) gave 2.25 g of 11-carbamoylundecanoic acid (45% yield, m.p. 129–131°C, lit. m.p. 129–130°C).

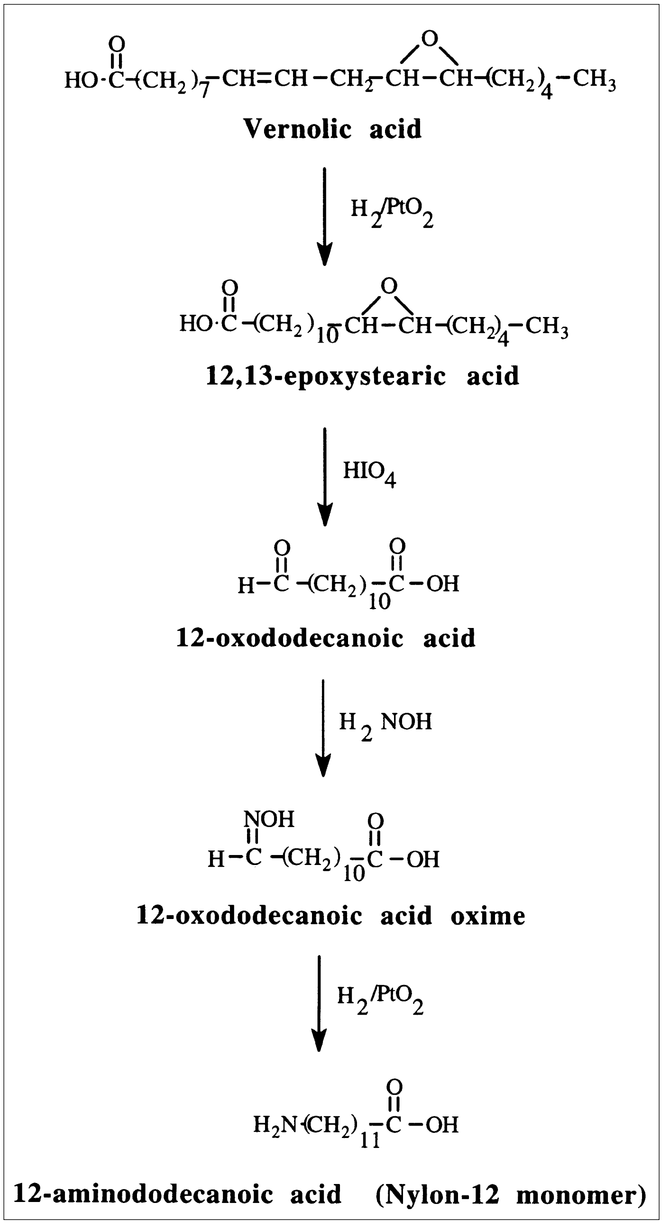
Preparation of 11-(methoxycarbonylamino)undecanoic acid (methyl carbamate). Sodium methoxide in methanol was prepared by adding 0.6 g (2.6×10^{-2} mol) of sodium to 25 mL methanol in a 100-mL flask, equipped with magnetic stirrer, condenser, and addition funnel. Alternatively, 11 mL 25 wt% sodium methoxide/methanol (Aldrich Chemical Company, Inc., Milwaukee, WI) was transferred into the 100-mL flask. The solution was cooled with ice to *ca.* 5°C. Then, a solution of 2.0 g (8.7×10^{-3} mol) amide in 10 mL methanol was added to the cooled sodium methoxide solution. To this mixture was added, with thorough mixing, 0.6 g (8.7×10^{-3} mol) bromine. The resulting solution was heated to 70–80°C in a water bath for 15 min. The flask was cooled to 25°C, and the solution was made acidic (litmus paper) with acetic acid. The solvent was evaporated, and the resulting solid was rinsed with 50 mL water to remove sodium bromide. The crude product weighed 2.03 g (89.8% yield) and was recrystallized from 30 mL ethanol/water mixture (1:1) to give 1.7 g methyl carbamate (75% yield, m.p. 84–86°C). Elemental analysis: calculated for $C_{13}H_{25}NO_4$: C, 60.19: H, 9.73; N, 5.40; O, 24.68%. Found C, 60.02; H, 9.81; N, 5.26; O, 24.91%.

Hydrolysis of 11-(methoxycarbonylamino)undecanoic acid to 11-aminoundecanoic acid. A 1.0-g (3.9×10^{-3} mol) sample of 11-(methoxycarbonylamino)undecanoic acid was dissolved in 20 mL ethanol, which was then added to a solution of 2.0 g (5.0×10^{-2} mol) sodium hydroxide in 2 mL water. The mixture was refluxed for 17 h. The resulting gold-colored solution was cooled and neutralized with acetic acid to pH 7, then filtered to remove any salt. The filtrate was stripped to give crude amino acid, which was dissolved in 50 mL water, then cooled in ice before filtering to give 0.41 g (53%) of the amino acid. Recrystallization from 16 mL ethanol/water (3:1) gave 0.26 g (34% yield) 11-aminoundecanoic acid (m.p. 189–192°C, lit. m.p. 190–192°C).

RESULTS AND DISCUSSION

Upon saponification and acidification, crude *V. galamensis* oil usually contains about 75–80% vernolic acid. Thus, the first step in the present investigation was the isolation and purification of the epoxy acid. We investigated several isolation techniques (i.e., extraction, chromatography, low-temperature crystallization) and found that low-temperature crystallization was most efficient and cost-effective because it utilizes the least amount of solvent.

Scheme 1 depicts the synthetic transformation of vernolic acid to 12-aminododecanoic acid. The hydrogenation step was generally quantitative; however, reaction time should not exceed 1 h to avoid formation of hydroxy acids, presumably due to catalytic opening of the epoxy functionality. The resulting 12,13-epoxystearic acid was easily oxidized with periodic acid to give 12-oxododecanoic acid and hexanal. In many instances, when the reaction was allowed to proceed for more than 5 h, some dodecanoic acid and hexanoic acid were produced as a result of overoxidation of the aldehyde functionalities. On the other hand, efforts to keep the reaction time below 5 h resulted in incomplete reaction, in which case there was unreacted vernolic acid. Thus, it is important to maintain a 5-h reaction time. There was no attempt to isolate the hexanal.



SCHEME 1

Conversion of the 12-oxododecanoic acid to its oxime was undertaken in an acidic medium (pH 4–5) with hydroxylamine hydrochloride as the nucleophilic agent. Lower pH value reduces the nucleophilicity of the hydroxylamine, thereby preventing the formation of the oxime. The reaction usually resulted in more than 85% isolated yield of the product. Subsequent hydrogenation of the aldoxime afforded, in all cases, more than 90% yield of the 12-aminododecanoic acid. The GC characterization of the 12-aminododecanoic acid was performed after methylation with ethereal solution of diazomethane, and we noted that the amino group was methylated to form methyl *N,N*-dimethylaminododecanoate, thus confirming the presence of the amino functionality.

The IR spectrum of both 12,13-epoxystearic acid and vernolic acid shows strong absorptions at 1700 cm^{-1} (carbonyl), 824 cm^{-1}, and 846 cm^{-1} (epoxy group). The absorption at 1600 cm^{-1} in the spectrum of vernolic acid corresponds to the olefinic carbons. The PNMR of vernolic acid and 12,13-epoxystearic acid were closely related, except that the absorption due to the olefinic protons at 5.5 ppm was absent in the spectrum of 12,13-epoxystearic acid. The epoxy protons at 2.9 ppm were present in both spectra. ^{13}C NMR (proton-decoupled) of vernolic acid (Fig. 1) indicated the presence of carbonyl carbon at 180 ppm and olefinic carbons at 124 ppm and 133 ppm, and the carbons attached to the epoxy functionality appeared at 56 and 57 ppm. On the other hand, a comparison of the ^{13}C spectrum of 12,13-epoxystearic acid (Fig. 2) revealed the absence of olefinic carbon. Another significant difference in the spectrum is the single peak at 57 ppm (epoxy carbons), suggesting that the two carbons on the epoxy functionality of the 12,13-epoxystearic acid have an identical electronic environment. Figure 3 shows the ^{13}C NMR of the 12-oxododecanoic acid. Two distinct peaks were observed at 180 ppm (carbonyl carbon of the carboxylic acid) and 203 ppm (carbonyl carbon of the aldehyde). The mass spectral data of the 12-oxododecanoic acid indicated extensive fragmentations with a base peak at *m/z* 74, due to McLafferty rearrangement. The peak at *m/z* 229 represents (M + 1) ion. Other diagnostic ions are *m/z* 210 (M – H_2O), *m/z* 200 (M – CO), *m/z* 179 (M – OCH_3) and *m/z* 185 (M – CH_2OH). The 12-oxododecanoic acid shows an IR absorption at 3500 cm^{-1} that is characteristic of the O-H of carboxylic acids. The PNMR data indicated the presence of a proton attached to the aldehyde functional group at 9.3 ppm. The multiplets at 0.8–1.8 and 2.2–2.5 ppm were due to the methylene protons.

The IR spectrum of the aldoxime acid showed a carbon–nitrogen double bond (C=N) stretch at 1690 cm^{-1} and carbonyl (C=O) absorption at 1700 cm^{-1}. The O-H stretching vibrations of both functional groups were observed at the 2950–3300 cm^{-1} region. Delineation of the *syn*/*anti* isomeric composition of the aldoxime group was accomplished with ^{13}C NMR studies. The quantitative ^{13}C NMR spectrum (Fig. 4) showed three absorp-

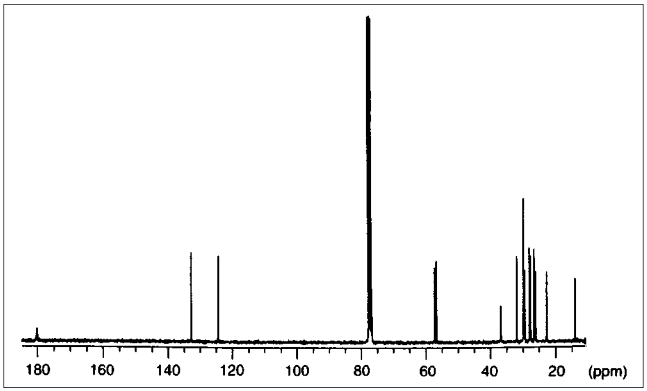


FIG. 1. Proton-decoupled ^{13}C nuclear magnetic resonance spectrum of vernolic acid. Peaks are referenced to $CHCl_3$ at 77 ppm. Samples were made to 10 wt% in $CDCl_3$. Operating frequency was at 75.6 MHz. Chemical shifts (δ = ppm): carbonyl carbon, 180; olefinic carbons, 124 and 133; epoxy carbons, 56 and 57.

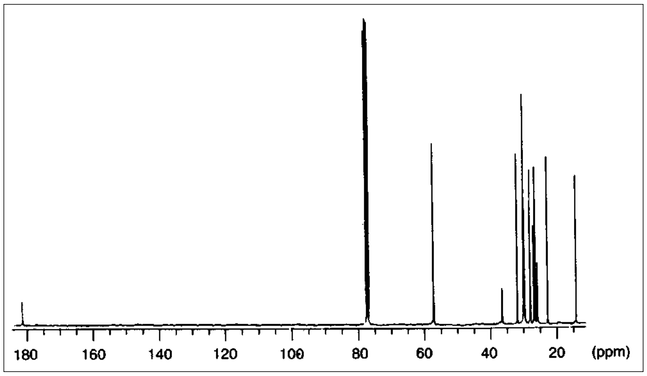


FIG. 2. Proton-decoupled ^{13}C nuclear magnetic resonance spectrum of 12,13-epoxystearic acid. Peaks are referenced to $CHCl_3$ at 77 ppm. Samples were made to 10 wt% in $CDCl_3$. Operating frequency at 75.6 MHz. Chemical shifts (δ = ppm): carbonyl carbon, 182; epoxy carbons, 58.

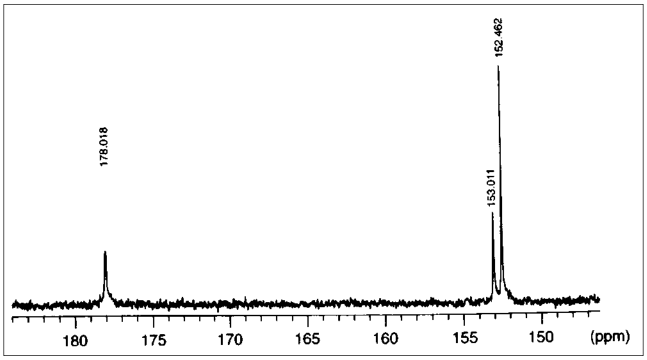


FIG. 4. Proton-decoupled ^{13}C nuclear magnetic resonance spectrum of 12-oxododecanoic acid oxime. Peaks are referenced to CD_3OD at 49.0 ppm. Samples were made to 10 wt% in CD_3OD. Operating frequency at 75.6 MHz. Chemical shifts (δ = ppm): carbonyl carbon, 178.018; *anti*-oxime carbon, 153.011; and *syn*-oxime carbon, 152.462.

tion peaks due to sp^2-hybridized carbons. The signal at 178.018 ppm was attributed to the carbon of the carbonyl group, while the signals at 153.011 and 152.462 ppm were assigned to the carbons of the *anti*- and *syn*-aldoxime groups, respectively, based on a previous report (20) on the ^{13}C NMR spectra of aldoximes, which demonstrated that the resonances due to the *anti* isomers are slightly higher than the corresponding resonances from the *syn* isomer. Thus, the ^{13}C NMR spectrum (Fig. 4) indicated the ratio of *syn*/*anti* isomers was about 7:3, a ratio that was further supported by gas chromatographic data.

The MS of both *syn* and *anti* isomers gave similar fragmentation patterns except that the *syn* isomer showed a base peak at *m*/*z* 74, and no molecular ion peak was observed owing to loss of OH to give the ion at *m*/*z* 226. On the other hand, the *anti* isomer showed a base peak at *m*/*z* 59, which may be attributed to a McLafferty-type rearrangement that involves the oxime part of the molecule. An (M + 1) peak was apparent at *m*/*z* 244 for the *anti* isomer.

The GC of the 12-aminododecanoic acid showed two peaks when methylated with diazomethane. These peaks correspond to primary amino ester $H_2N(CH_2)_{11}CO_2CH_3$ and tertiary amino ester $(CH_3)_2N(CH_2)_{11}CO_2CH_3$. The diagnostic ions observed in the mass spectral data of the primary amino ester are (M + 1) ion at *m*/*z* 230, a base peak at *m*/*z* 30 (H_2NCH_2), and *m*/*z* 156 (M – $[(CH_2)_6CO_2CH_3]$). The tertiary amino ester gave a molecular ion peak at *m*/*z* 257 and a base peak at *m*/*z* 44 $[(CH_3)_2N]$. Other fragmentation ions were *m*/*z* 58 $[(CH_3)_2\text{ - N-}CH_2]^+$, *m*/*z* 170 (M – 87) and *m*/*z* 212 (M – 45).

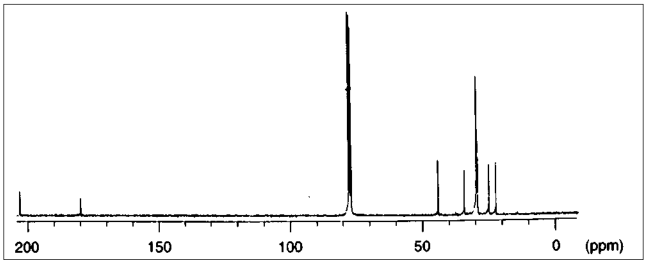
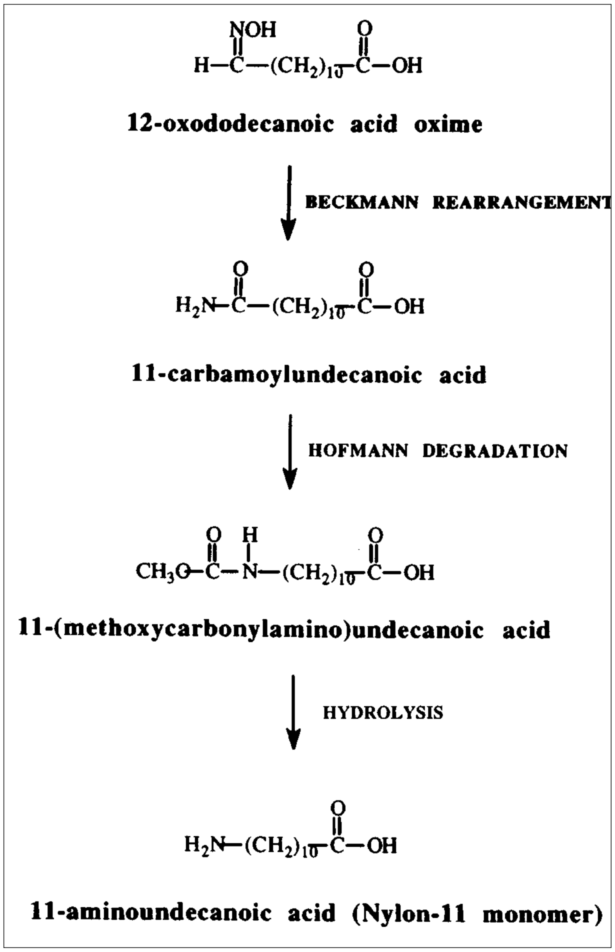


FIG. 3. Proton-decoupled ^{13}C nuclear magnetic resonance spectrum of 12-oxododecanoic acid. Peaks are referenced to $CHCl_3$ at 77 ppm. Samples were made to 10 wt% in $CDCl_3$. Operating frequency at 75.6 MHz. Chemical shifts (δ = ppm): carbonyl carbon of the aldehyde group, 203; carbonyl carbon of the acid group, 180.

The IR of the 12-aminododecanoic acid exhibited an absorption at 1646 cm^{-1} attributable to the C=O and at 2900–3200 cm^{-1} owing to the O-H group. The usual $-NH_2$ group absorption was weak at 3300 cm^{-1} owing to the strong O-H absorption of the carboxylic acid group at this region. However, the $-NH_2$ bending frequency was observed at 1508 cm^{-1}, and the C-N stretching frequency produced a strong peak at 1400 cm^{-1}.

The synthetic sequence for the transformation of 12-oxododecanoic acid oxime to 11-aminoundecanoic acid is outlined in Scheme 2. Isomerization (or hydrolysis) of the oxime to the amide was performed under neutral conditions because it has been demonstrated that mineral acid catalysis of aldoximes results in the regeneration of the starting aldehyde (21). We first investigated the rearrangement of the aldoxime to amide under conditions similar to those of Leusink and coworkers (22), in which the aldoxime was treated with a catalytic amount of nickel acetate and refluxed in *p*-xylene for 5 h. We found that the reaction did not go to completion under these conditions, and that only traces of the product were isolated. Moreover, a tar-like reaction mixture was obtained, suggesting the possibility of some polymerization. Hence, the temperature for subsequent reactions was maintained at 110–115°C, and the reaction time was increased to 24 h to give 48% yield of 11-carbamoylundecanoic acid (m.p. 129–131°C, lit. m.p. 129–130°C). This relatively low yield was attributed to the fact that the aldoxime was a mixture of *syn*- and *anti*-isomers (ratio 7:3). GC/MS analysis of the reaction mixture indicated that the *anti*-isomer was mostly unreacted, a finding that is consistent with reported studies indicating that Beckmann rearrangement reactions generally favor the isomerization of the *syn*-isomer. However, there are



SCHEME 2

studies that have shown that boron trifluoride in acetic acid would convert both *syn-* and *anti-*isomers to amide in excellent yield (23). It is important to maintain the reaction temperature between 110–115°C, because the product yield is much reduced at reflux temperature, probably owing to other side reactions that lead to polymer formation. Similarly, a lower reaction temperature resulted in incomplete reaction.

For the Hofmann degradation, the 11-carbamoylundecanoic acid was transformed to the 11-(methoxycarbonylamino)undecanoic acid (methyl carbamate) by treating a solution of the amide in methanol with sodium methoxide and bromine. Several attempts at direct conversion of the amide to 11-aminoundecanoic acid by using concentrated sodium hydroxide solution and bromine resulted in the hydrolysis of the amide to give dodecanedioic acid in addition to some methyl carbamate. The methyl carbamate (m.p. 84–86°C; elemental analysis: calculated for $C_{13}H_{25}NO_4$: C, 60.19; H, 9.73; N, 5.40; O, 24.68%. Found: C, 60.02; H, 9.81; N, 5.26; O, 24.91%) was obtained in 75% yield.

Hydrolysis of the methyl carbamate surprisingly required prolonged refluxing for 17 h, to give a 53% yield of crude 11-aminoundecanoic acid, which was recrystallized in 16 mL of ethanol/water (3:1) to obtain 34% yield (m.p. 189–192°C, lit. m.p. 190–192°C).

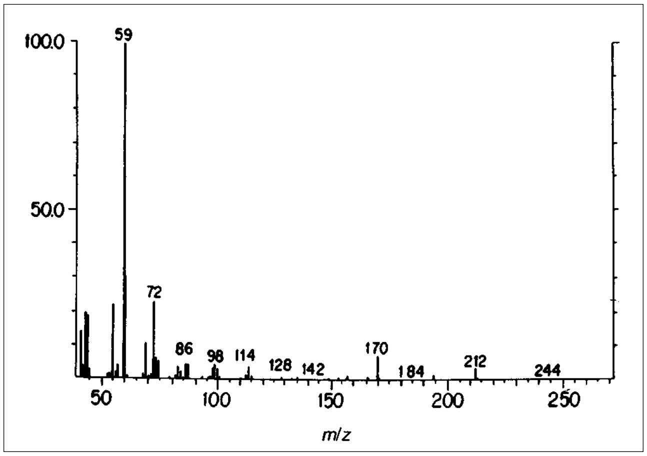


FIG. 5. Mass spectrum of methyl 11-carbamoylundecanoate: *m/z* 244 (M + 1), *m/z* 59 ($[H_2NC - CH_2]H^+$), *m/z* 212 (M – OCH_3), *m/z* 184 (M – CO_2CH_3) and *m/z* 170 (M – $CH_2CO_2CH_3$).

Spectroscopic characterization of 11-carbamoylundecanoic acid. The mass spectrum of methyl 11-carbamoylundecanoate is shown in Figure 5. The fragmentation pattern is that of a typical long-chain aliphatic molecule. A weak (M + 1) ion is observed at *m/z* 244. Other diagnostic ions include: *m/z* 212 (M – OCH_3), 170 (M – $CH_2CO_2CH_3$), and 59 (McLafferty-type rearrangement involving the carbamoyl group).

The IR spectrum showed two fairly sharp peaks at 3450 and 3220 cm^{-1} (N-H stretching bands). The O-H group stretching exhibits characteristic absorption at the 3200–2500 cm^{-1} region. There are two C=O peaks, at 1730 cm^{-1} due to the carboxylic acid C=O and at 1650 cm^{-1} due to the amide C=O. Other characteristic absorptions include N-H bending at 1600 cm^{-1} and C-O stretching at 1460 cm^{-1}. The ^{13}C NMR (Fig. 6) indicated two carbonyl carbon absorptions at 178.0 ppm (carbonyl carbon of amide) and at 179.5 ppm (carbonyl carbon of carboxylic acid).

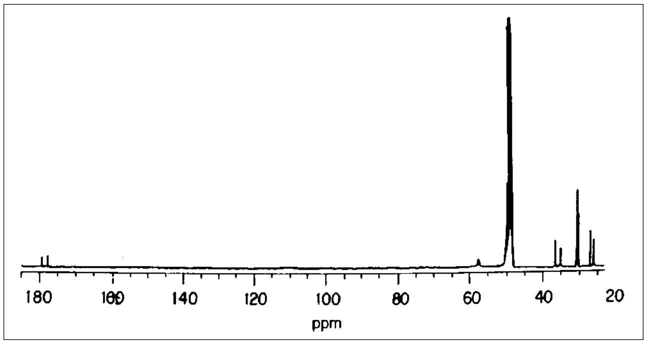


FIG. 6. Proton-decoupled ^{13}C nuclear magnetic resonance spectrum of 11-carbamoylundecanoic acid. Peaks are referenced to CH_3OD at 49.0 ppm. Sample was made to about 10 wt% in CD_3OD. Operation frequency at 76.6 MHz. Chemical shift (δ = ppm): carbonyl carbon of the carboxylic acid 179.5 ppm, carbonyl carbon of the amide 178.0 ppm, carbon alpha to the carboxylic acid 37.0 ppm, and carbon alpha to the amide 35 ppm.

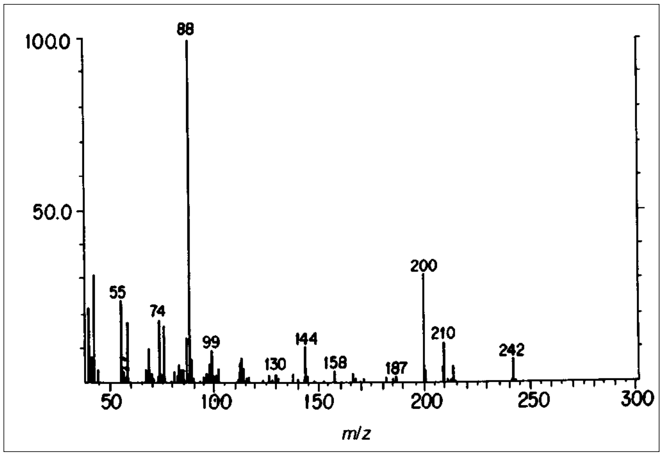


FIG. 7. Mass spectrum of methyl 11-(methoxycarbonylamino)undecanoate: *m/z* 88 base peak, *m/z* 242 (M – OCH_3), *m/z* 214 (M – 59), *m/z* 200 (M – 73), and *m/z* 144 $[CH_3O_2CNH(CH_2)_5]^+$.

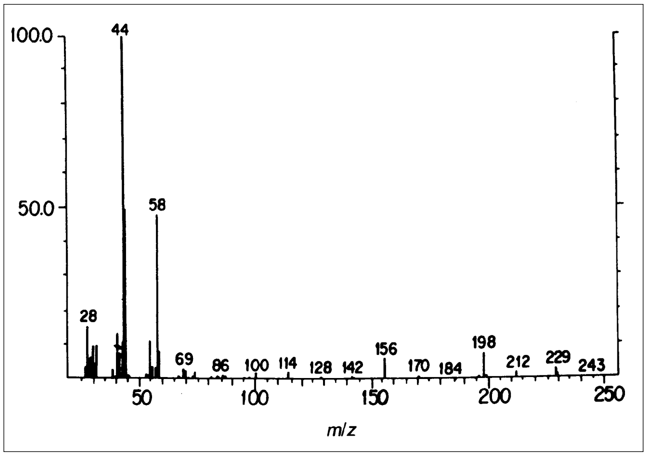


FIG. 9. Mass spectrum of methyl *N,N*-dimethylaminoundecanoate: *m/z* 243 (M + 1), *m/z* 44 $[CH_3NCH_3]^+$, *m/z* 212 (M – OCH_3), *m/z* 58 $[(CH_3)_2NCH_2]^+$, and *m/z* 156 (M – $CH_2CH_2CO_2CH_3$).

Spectroscopic characterization of 11-(methoxycarbonylamino)undecanoic acid. The mass spectral data of methyl 11-(methoxycarbonylamino)undecanoate are shown in Figure 7. The base peak at *m/z* 88 is attributed to cleavage of the C_{10}-C_{11} bond. Other prominent diagnostic ions include: *m/z* 242 (M – OCH_3), 214 (M – carbomethoxy), and 144 $[CH_3O_2CNH(CH_2)_5]^+$. The IR spectrum (cm^{-1}) showed a broad OH absorption at 3500–2500, which overlaps with a sharp absorption at 3370 due to the N-H stretching vibration. A carbonyl absorption is shown at 1695, probably owing to overlapping absorptions by the two carbonyl groups. C-N bending vibration gave an absorption at 1515, while C-N stretching appeared at 1240 and 1280, and C-O stretching was observed at 1475.

The PNMR spectrum showed absorptions at 4.9 ppm (N*H*), 4.1 ppm (OCH_3), 3.56 ppm (2H), 2.9 ppm (2H), 2.2 ppm (2H), 2.1 ppm (2H), 1.9 ppm (12H). The ^{13}C NMR spectrum showed two carbonyl signals, one at 179.37 ppm (attributed to carbonyl carbon of the carboxylic acid) and the other at 157.12 ppm (assigned to the carbonyl carbon of the carbamate). Other significant signals include the chemical shift at 55 ppm due to methyl carbon, at 42 ppm due to methylene carbon alpha to the nitrogen, and at 35 ppm for methylene carbon alpha to the carboxylic acid group.

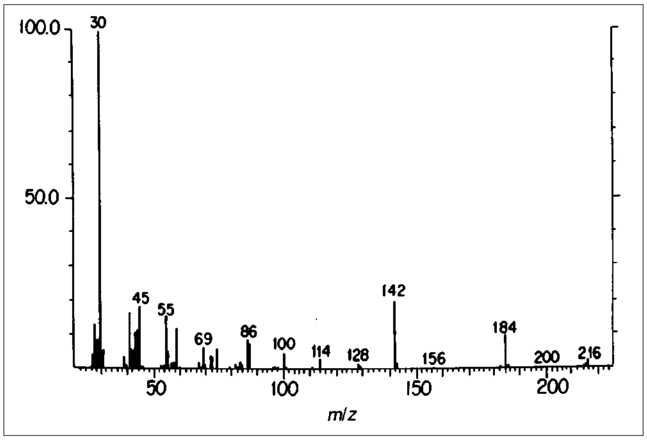


FIG. 8. Mass spectrum of methyl 11-aminoundecanoate: *m/z* 216 (M + 1), *m/z* 30 (base peak, $[CH_2{=}NH_2]^+$), *m/z* 184 (M – OCH_3) and *m/z* 142 (M – $CH_2CO_2CH_3$).

Spectroscopic characterization of 11-aminoundecanoic acid (nylon-11 monomer). The gas chromatogram of the methylated sample of 11-aminoundecanoic acid showed two peaks. One peak corresponds to a primary amino ester $H_2N(CH_2)_{10}CO_2CH_3$, and the second peak corresponds to the tertiary amino ester $(CH_3)_2N(CH_2)_{10}CO_2CH_3$. Apparently, the amino group was methylated by diazomethane. Figure 8 shows the mass spectrum of the primary amino ester with a protonated molecular ion (M + 1) at *m/z* 216. Other fragmentation ions were *m/z* 184 (M – OCH_3), *m/z* 142 (M – $CH_2CO_2CH_3$) and *m/z* 30 (base peak). The mass spectral data of the tertiary amino ester (Fig. 9) gave a molecular ion (M+) peak at *m/z* 243. Other prominent fragmentations include: *m/z* 212 (M – 31), 58 $[(CH_3)_2NCH_2]^+$, 86 $[(CH_2)_2NCH_2CH_2CH_2]^+$, and 156 (M – $CH_2CH_2CO_2CH_3$).

The IR of 11-aminoundecanoic acid exhibited an asymmetrical N-H stretching absorption that appeared at 3400 cm^{-1}, while that of symmetrical N-H stretching was observed at 3200 cm^{-1}. Almost overlapping these two bands was the strong OH absorption at 3300–2500 cm^{-1}. The C=O absorption was at 1640 cm^{-1}. The -NH_2 bending and C-N stretching were at 1540 and 1400 cm^{-1}, respectively.

The potential commercial application of the syntheses outlined in these studies is enhanced by the fact that VO, the source of vernolic acid, is a renewable raw material. These studies represent the first reported production of both nylon-12 and nylon-11 monomers from a single source. Furthermore, the three-step reaction sequence from 12-oxododecanoic acid oxime to 11-aminoundecanoic acid consists of relatively simple reactions, thus offering an advantage over the current use of castor oil, in which several more steps are involved, one of which is the energy-intensive pyrolysis reaction. Additionally, the intermediate 11-carbamoylundecanoic acid produced in the present investigation could be a potential source of dodecane-1,12-diamine, one of the monomers of nylon-12,12.

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