The Processing of New Oilseed Crops—An Economic Evaluation

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ABSTRACT: The economics of pilot- to large-scale processing of the new oilseed crops *Crambe abyssinica, Euphorbia lagascae*, and *Dimorphotheca pluvialis* into oil, fatty acids, or esters were estimated. It was found that the processing costs for *Crambe* seed to oil is in the same range as that for rapeseed (~0.5 U.S. $/kg). Production of fatty acid esters from vernolic and dimorphecolic acids requires some special downstream processing operations that result in processing costs of about 1 U.S. $/kg ester. Good-quality *Dimorphotheca* oil is much more difficult to obtain and requires supercritical carbon dioxide extraction. Processing costs can be as high as 4 U.S. $/kg oil.
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KEY WORDS: *Crambe, Dimorphotheca*, economics, *Euphorbia*, new crops, processing of new oilseed crops, super critical extraction, vernolic.

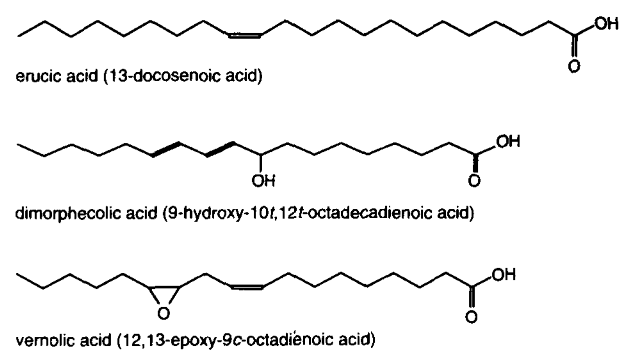

FIG. 1. Fatty acids in crambe oil (erucic acid), dimorphotheca oil (dimorphecolic acid), and euphorbia oil (vernolic acid).

Oils and fats are widely used in the nonfood industry, with a worldwide level of 20 million tons/year. The oleochemical industry produces and employs either the extracted oils or uses their intermediates, such as free fatty acids, fatty alcohols, and fatty acid methyl esters. These products are often derivatized into a wide range of end-products. For specialty products, fatty acids with naturally built-in functionalities can be interesting. Several oilseed crops that produce interesting fatty acids and derivatives have been identified (1–5).

In Europe, much research has been carried out in the last several years on new oilseed crops, such as *Crambe abyssinica, Dimorphotheca pluvialis*, and *Euphorbia lagascae*. These oils contain erucic acid, hydroxy fatty acids (dimorphecolic acid), and epoxy fatty acids (vernolic acid), respectively (Fig. 1). Except for erucic acid, derived also from high-erucic acid rapeseed and used for erucamide production, the other seed oils and fatty acids have not found wide applications so far.

Currently, investigations on new oilseeds include crop agronomics, breeding, and extraction and processing of their seed oils (2–5). Because information on the economics of processing new seed oils is virtually nonexistent, we estimated the costs of five different products, based on the three new seed oils mentioned above. These products are crambe oil, methyl vernolate, vernolic acid, dimorphecolic acid, and supercritically extracted dimorphotheca oil. Standard oleochemical processes are described at three capacity levels, and product costs for each were calculated.

GENERAL ASSUMPTIONS AND TECHNICAL INFORMATION

Capital investment and variable costs were based on the following assumptions: (i). Three oilseed processing capacities were examined, i.e., 10 tons, 60 tons, and 400 tons of seed/day. The benefits of scale-up can be of special importance during the introduction of a new crop. For reasons of clarity, the results for the 10 ton/day scale is not shown for all seeds.

(ii) Costs of solvent (hexane, 0.35 U.S. $/kg), electricity (0.07 U.S. $/kWh), gas (0.15 U.S. $/m^3), water (0.74 U.S. $/m^3), and steam (15 U.S. $/kg) are typical tariffs for industry in the Netherlands in 1994.

(iii) The heat of combustion for natural gas is assumed to be 30 MJ $\cdot$ m^{-3}.

(iv) In all calculations, 15% of the total capital costs was taken for interest and depreciation, and 10% of the total capital costs was taken for labor and maintenance (6,7).

(v) Calculation of operating costs is based on 300 operating days/year.

(vii) Hexane loss during the extraction process is estimated to be 3 kg per ton of cake (8).

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(vii) Costs and benefits from side products, such as glycerol and cake, were only included when the scale was such that data were available or could be extrapolated from current processes. For example, glycerol recovery was assumed to be only beneficial on a large scale, as is true in the processing of rapeseed (>400 ton/day capacity) (Kokke, M., personal communication, DeSmet, Belgium). For the seed hulls and seed cake, it has been shown that these cannot be used directly for cattle feed (9). Other possibilities for nonfood use are being investigated but are not yet at a stage to be incorporated in an industrial process.

Research on a broad range of new oilseed crops has resulted in insight in the optimal recovery routes for their oils and fatty acids. Some of the products can be recovered with conventional techniques, while others may require the use of modified or new technology (2–5).

Conventional oilseeds with high oil content, (e.g., rapeseed oil) may be economically pressed (full-pressure mill) on an intermediate scale (<100 tons seed/day). On a larger scale, hexane extraction is economically feasible because higher oil recovery offsets the extra investment in extraction equipment. Such considerations extend to the oil recovery from crambe and euphorbia seeds. In the present evaluation, we have combined our experimental bench-scale data on with conventional technology as much as possible. Based on these bench-scale experiments and existing knowledge on conventional oil processing, a conventional pressure mill is expected to be relevant for small-scale processing (10 and 40 tons seeds/day), whereas for higher production (100 tons/day), a combination of pre-pressing and hexane extraction is projected.

The application of a full-pressure mill to dimorphotheca seed is possible but is accompanied by a relatively high loss (up to 50%) of oil remaining in the seed. Therefore, oil recovery by solvent extraction (hexane or supercritical carbon dioxide) becomes essential. However, conventional processing (pressing, solvent extraction, and especially refining of dimorphotheca oil) can lead to extensive deterioration of the dimorphecolic acid, e.g., thermal and chemical dehydration and cross-linking (10). Pilot-scale supercritical CO_2 extraction experiments showed that oil with chemically intact dimorphecolic acid and low in pigments and gums can be produced (2–5).

Vernolate esters were synthesized from euphorbia oil by alcoholysis with methanol and purified by distillation. Because chemical hydrolysis is especially detrimental for dimorphecolic acid, a mild hydrolysis process is essential. Both vernolic acid and dimorphecolic acid were produced from their respective oils by an enzymatic hydrolysis procedure. Although enzymatic hydrolysis is not commonly used in the oleochemical processing industry, setting up such a process on an intermediate scale should not encounter technical difficulties.

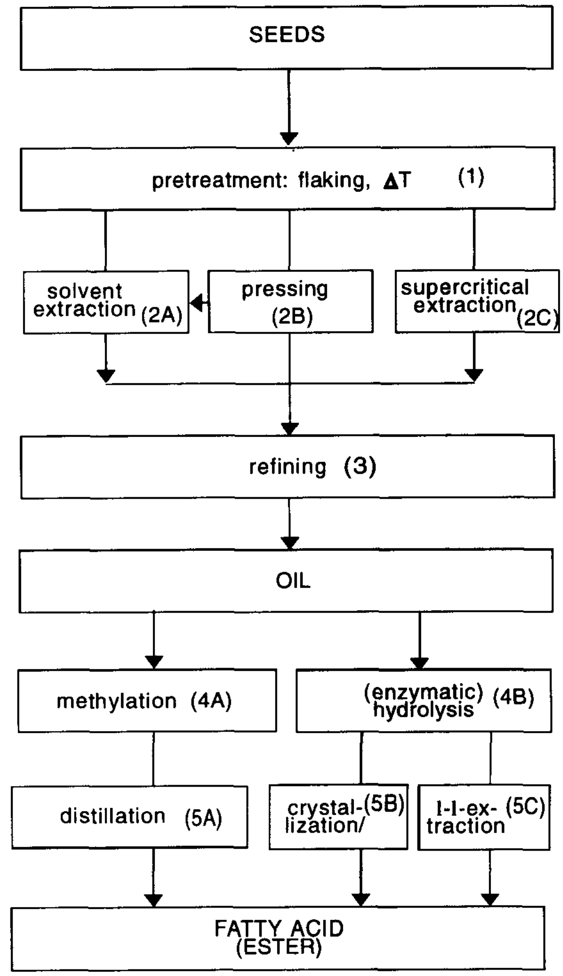

FIG. 2. Processing routes for crambe oil, dimorphotheca oil, and dimorphecolic acid as well as euphorbia oil, methyl vernolate, and vernolic acid as used in the cost calculations.

RESULTS AND DISCUSSION

Crambe seed can be efficiently extracted in a similar fashion as traditional oilseeds, such as rapeseed. Figure 2 shows the flow sheet for the recovery of crambe seed oil on a small and intermediate scale. Preliminary calculations show that only full-pressure expelling is economical for extracting 10 to 60 tons of seeds per day. The installed power of the 10-ton pressure mill is 50 kW, and for the 60- ton mill it is 350 kW. Oil content of the crambe seed is reduced from 42 to 9% in each mill.

Efficiency of the extraction on this scale is inherently poor and leaves 9% of oil in the seed. More efficient recovery of oil by solvent extraction requires too high investment costs to be economical, and co-products, such as proteins and phospholipids, cannot be economically recovered on this scale.

The procedure for extracting 400 tons/day of crambe seed is quite different from the processes for extraction of 10 and 60 tons per day. After flaking the seeds, the flakes are pre-pressed to decrease the oil content from 42 to 18%, and the residual cake oil is extracted with hexane (Fig. 2). The residual oil content of the extracted crambe cake is about 1%. Calculations show that the pre-press mill requires 1050 kW of electricity, and the solvent extraction plant uses 420 kW.

TABLE 1
Estimated Capital and Annual Costs (kU.S. $) for the Production of Crambe Oil and Methyl Vernolate

Product	Crambe oil			Methyl vernolate	
Seed capacity (tons/day)	10	60	400	60	400
Oil capacity (ktons/yr)	1	6	49	6	49
Full-press mill	457[a]	1464[a]	[–]	1464	[–]
Pre-press mill	[–]	[–]	3470[a]	[–]	3470
Solvent extraction	[–]	[–]	3040[a]	[–]	3040
Steam plant	24	36	130	36	130
Degumming and neutralization	60[b]	450[b]	900[b]	[–]	[–]
Methylation	[–]	[–]	[–]	1143	5393[b]
Distillation	[–]	[–]	[–]	1905	5952
Total capital costs	540	1950	7540	4548	17985
Interest and depreciation	81	293	1126	682	2698
Labor and maintenance	54	195	754	455	1799
Electricity	29	198	833	198	833
Steam	10	49	697	49	565
Water	7	7	[–]	7	[–]
Air	3	5	6	5	6
Hexane consumption	[–]	[–]	100	[–]	87
Methylation	[–]	[–]	[–]	1548	5908
Distillation	[–]	[–]	[–]	893	6012
Annual operating costs	184	747	3516	3837	17908
Costs (U.S. $/ton)	180	130	70	670	470

[a]Data directly given by De Smet Company (Edegem, Belgium).
[b]Budget prices given by Vogel & Noot Industrie und Anlagenbau (Graz, Austria).

Although the 400 ton/day unit is still relatively small, the costs are comparable to those for the extraction of soybean and rapeseed oil (11). At this time, no consideration is given to the value of crambe meal as a feed component.

The production of methyl vernolate is accomplished in three steps. First, the oil is extracted from the seeds *via* a 60 tons/day full-press process or by a 400 tons/day pre-press and solvent extraction approach. Subsequently, the crude oil is transesterified to yield fatty acid methyl esters. Finally, the methyl vernolate is collected by fractional distillation under vacuum. The process flowsheet is incorporated in Figure 2.

Lab-scale and pilot-scale experiments have shown that *E. lagascae* oil can be recovered by mechanical pressing and with hexane extraction (2–5). For higher capacities, pre-pressing and solvent extraction should be used. It was found that the residual oil content of euphorbia meal after full-pressure expelling is about 9%. Hence, about 25 tons of oil are expelled from 60 tons of seed. The free fatty acid content in the oil is low (<1%).

The costs for the small-scale process are summarized in Table 1. A study on the use of euphorbia meal as a component in animal feed resulted in the conclusion that the meal cannot be used for feed purposes due to the presence of poisonous compounds in the meal (9). These components are hard to remove from the meal by established unit operations. Decreasing the level of the toxic compounds in the seed meal may depend on plant breeding.

The processing scheme for the production of 128 tons/day methyl vernolate from 400 tons *E. lagascae* can be deduced from Figure 2. As with Crambe, the oil is extracted from the seeds by a pre-press mill, followed by hexane extraction. The residual oil content after solvent extraction is 0.9%, and hexane consumption is approximately 3 kg per ton of seed.

One of the important co-products in the methylation of oils is glycerol, which can be purified and sold. However, small-scale processing (60 tons/day) will most likely not economically justify the investment. The capacity of the large methylation plant is probably just large enough to generate an economic interest for the purification of glycerol from sweet water. Glycerol produced by a basic evaporative unit operation has a purity of 88% with an estimated market value of about U.S. $1 per kg (11).

The costs for producing methyl vernolate are of the same order of magnitude as production of rapeseed methyl esters (11). Table 1 shows that the process becomes more economical at larger scale. This is not only due to the benefits of scale but also to the additional revenues from glycerol.

One of the chemically most interesting new seed oils is that from *D. pluvialis*, which contains the chiral hydroxy-dienoic dimorphecolic acid. Because this moiety is reactive, conventional oleochemical techniques, such as Colgate Emery, cannot be used (3). Therefore, alternative hydrolysis processes have been developed (2–5). The oil is hydrolyzed enzymatically to liberate the fatty acids from the glycerol moiety to recover the unstable dimorphecolic acid. Because dimorphecolic acid thermally decomposes during vacuum distillation, it is best purified by crystallization from hexane (12).

Solvent-extracted oil contains large amounts of impurities, such as free fatty acids, phospholipids, and high levels of

TABLE 2
Capital and Annual Costs (kU.S. $) for the Production of Dimorphecolic Acid and Vernolic Acid

Product	Dimorphecolic acid			Vernolic acid	
Seed capacity (tons seed/day)	10	60	400	60	400
Oil capacity (ktons/yr)	0.4	2.2	14.7	5.4	36.6
Seed pretreatment	[–]	[–]	1143[a]	[–]	[–]
Full-pressure mill	457[a]	1464[a]	[–]	1464	[–]
Solvent extraction	[–]	[–]	3040[a]	[–]	3040
Steam plant	24	36	130	36	130
Degumming and neutralization	60[a]	450[a]	900[a]	450[a]	900
Equipment for oil hydrolysis	60	357	900	357	900
Scraper crystallizer	39[b]	99[b]	655[b]	[–]	[–]
L-L extraction	[–]	[–]	[–]	446	1340
Total capital costs	640	2406	6768	2753	9780
Interest and depreciation	96	361	1015	413	1467
Labor and maintenance	64	241	677	275	978
Electricity	29	198	340	198	833
Steam	10	49	482	49	565
Water	7	7	[–]	7	[–]
Air	3	5	6	5	5
Hexane consumption	[–]	[–]	137	[–]	87
Degumming and neutralization	7	48	286	86	512
Hydrolysis (incl. enzyme costs)	10	57	515	167	1130
Crystallization	Marginal	Marginal	Marginal	[–]	[–]
L-L extraction	[–]	[–]	[–]	89	298
Total annual costs	226	966	3458	1289	5875
Product costs (U.S. $/ton)	630	440	240	240	160

[a]Data directly given by De Smet Company (Edegem, Belgium).
[b]Budget prices given by Vogel & Noot Industrie und Anlagenbau (Graz, Austria).

carotene and other pigments. Refining with conventional techniques, such as neutralization and bleaching with earth or active coal (4), did not yield a clear oil with intact dimorphecolic acid-containing triglycerides. Even at the boiling point of hexane (69°C), dimorphecolic acid decomposes. A transparant clean, chemically intact oil can be produced by supercritical extraction. This process is described below. Unrefined oil was used for the production of fatty acids.

The oil is extracted from the dimorphotheca seed by high-pressure expelling, leaving a meal with a residual oil content of 9%. The oil is degummed by using only water to remove enzyme-inhibiting species. Then, the oil is hydrolyzed by enzymatic hydrolysis with *C. rugosa* lipase as a catalyst and water as the main reactant. The reaction is performed semicontinuously in batch and involves a series of tanks in which the enzymes, water, and oil are mixed and reacted. The oily phase is separated in a settler. The organic layer, containing mainly oleic and dimorphecolic acid, is diluted with hexane and fed to a crystallizer, where the dimorphecolic acid is separated from the reaction mixture. The process stream is shown in Figure 2. The estimated capital costs are shown in Table 2.

Larger quantities of dimorphotheca oil for dimorphecolic acid production are best obtained by solvent extraction. First, the seeds are prepared for extraction with a roller mill, flaker mill, or grinder. Then, the oil is extracted from the meal by direct hexane extraction, leaving meal with a residual oil content of only 0.5%. The oil is degummed, hydrolyzed and fed to a settler, and hexane is added. This hexane/free fatty acid mixture is fed to a scraped crystallizer, where the dimorphecolic acid (90 wt%) crystallizes from the reaction mixture.

The residual oil content in the seed meal after full-pressure extraction is relatively high. Moreover, in practice, the residual oil content depends on various as yet uncontrollable agricultural factors that lead to seed immaturity or high seed consistency, which makes it difficult to squeeze the oil from the seed. This can result in residual oil contents up to 12%. Together with the fact that dimorphotheca seed is relatively expensive, solvent extraction may be the method of choice for lower capacities than shown here.

One of the main constituents of *E. lagascae* seed oil is vernolic acid, an epoxy fatty acid, with potential uses in paints and lubricants and as a raw material for specialty chemicals (13). The extraction of euphorbia seed on small and intermediate scales is done with a full-pressure mill and leaves a meal with a residual oil content of 9%. The enzymatically catalyzed hydrolysis of the oil is performed in water. Hydrolysis of the oil yields a mixture with a variety of different fatty acids, which is further purified by standard liquid-liquid extraction. In this process, a hexane–methanol mixture is used.

To process 400 tons seed/day, the euphorbia seed is mechanically expelled first, reducing the oil content of the meal to about 18%, and then, the meal is fed to a solvent extraction unit to reduce the oil content in the meal to about 1% (Fig. 2). The total capital and operating costs are shown in Table 2.

For supercritical extraction of dimorphotheca seed, a semibatch type extractor was envisioned. The set-up should con-

TABLE 3
Capital and Annual Costs for Supercritical Extraction of Dimorphotheca Oil

Capital costs	(kU.S. $)
Seed pretreatment [3,8]	83
Supercritical unit [6]	3530
Total capital costs (kU.S. $)	3613
Interest and depreciation	542
Labor and maintenance	361
Electricity	
Seed pretreatment	8
Pumps and compressors	23
Heating	26
Cooling	30
Carbon dioxide	73
Total annual costs	1063
Costs/ton dimorphotheca oil (U.S. $/ton)	3750

sist of three 750-L extractor units in parallel. While the contents of two units are being extracted, the third unit is being unloaded and reloaded. The extraction is carried out at 300 bar and 45°C. In the first separator, the pressure is reduced to 80 bar, resulting in the separation of the bulk of the dissolved dimorphotheca oil. In the second separator, the pressure is decreased to 60 bar, which induces separation of the last traces of dimorphotheca oil plus the dissolved water. The required supercritical carbon dioxide flow for this equipment is estimated at 15,000 kg/h. The estimated costs for the extraction unit are shown in Table 3.

The extraction of vegetable oils and fractionation of fatty acids by supercritical CO_2 has been investigated extensively (14,15) but has never been put into a large-scale operation (extraction of, e.g., borage is a small-scale application). The main technical constraint of the process is the low solubility of triglycerides, which ranges from 0.1–3% (14) in supercritical CO_2. We found that dimorphotheca oil has a solubility of 0.1% in CO_2 at 45°C and 300 bar. Maximum solubility of evening primrose oil ranges from 0.1 to 5% when the pressure is increased above 600 bar (16). For castor oil, a higher solubility at increasing pressures has been reported (13–15). We expect that the saturation level for dimorphotheca oil can be increased about threefold (Henriksen, O., personal communication, FLS Miljo, Denmark), so the size of the apparatus can be reduced considerably. Still, two or three extractors are necessary to provide maximum operating flexibility.

The production costs for supercritical CO_2 extraction of dimorphotheca oil are almost six times higher than for the same oil produced by expelling. Although these calculated production costs are highly influenced by the solubility of the oil in CO_2, sufficient increases in solubility cannot be expected to reduce them to the costs of hexane extraction.

In this report, the production costs of vegetable oil and some intermediate products from new seed oils were estimated. Tables 1 and 2 review the calculated costs of the products studied, based on the rough but realistic assumptions made in this report. Estimates cover only the investment and operating costs. The installation costs for the equipment are not taken into account. Installation costs can be 1.5–3 times the calculated investment costs, depending on the production site, infrastructure, embedding in existing manufacturing processes, and the degree of integrated process control. These costs differ so much for different companies and locations that they have been excluded from our calculations.

Economy of scale is shown by the decreasing product costs per kg as production capacity increases. Because similar processes have been described for traditional oils, such as rape, sunflower and soybean, production costs for similar products from conventional and new seed oils may be compared. Production costs for methyl esters of rapeseed oil are well documented, because of their application as a biofuel. In Germany, the production costs for rapeseed methyl esters are U.S. $ 0.25/kg (11). This figure refers to a larger production facility, hence with inherently lower costs. Thus, rapeseed production costs are roughly one half of the U.S. $ 0.47/kg for production of 119 tons methyl vernolate/day as calculated in this report. Also, in the production of pure methyl vernolate, a purification step (distillation) is necessary, which is not required for biodiesel.

Except for crambe, production of new oilseed crops (*Euphorbia, Dimorphotheca*) has not yet reached a scale that is in the range of one of our processes. However, it is clear that, on the basis of current knowledge and data, processing costs for the new oils are somewhat higher than those of conventional oilseed crops. At the moment, agricultural production costs of the new crops are slightly to extensively higher than for conventional crops. Overall, the oils from new crops will be more expensive than conventional oils. This means that compounds from new seed oils can typically be used only in markets of high value-added products.

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