Available online at www.sciencedirect.com
ScienceDirect
Industrial Crops and Products 24 (2006) 300–306
INDUSTRIAL CROPS AND PRODUCTS
AN INTERNATIONAL JOURNAL
www.elsevier.com/locate/indcrop

Agricultural management of cuphea and potential for commercial production in the Northern Corn Belt

Russ Gesch[a,*], Frank Forcella[a], Alan Olness[a], Dave Archer[a], Andrew Hebard[b]

[a] USDA-ARS, North Central Soil Conservation Research Lab, 803 Iowa Avenue, Morris, MN 56267, USA
[b] Technology Crops International, Winston-Salem, NC 27116, USA

Abstract

Cuphea is a new oilseed crop that has undergone agricultural domestication for approximately the past 20 years. Its seed is rich in small- and medium-chain fatty acids, which are highly valued for manufacturing soaps, detergents, personal care products, and industrial lubricants. Since 1999, we have focused on developing an agricultural management strategy for cuphea production utilizing conventional technologies to minimize the need for specialized equipment. The semi-domesticated genotype, PSR23, developed through the interspecific hybridization of *Cuphea viscosissima* Jacq. (native to the US) with *C. lanceolata* W.T. Aiton (native to Mexico) performs well in temperate, short growing-season climates. PSR23 is an annual plant with a relatively shallow root system, a high water requirement for growth, and prefers mild temperatures for growth and development. Using best management practices we have developed, seed yields in excess of 1000 kg ha^{-1} have been achieved in research trials.

The summer of 2004 marked the first year for an experimental commercialization of cuphea. Technology Crops International, in cooperation with the USDA Agricultural Research Service, contracted six farmers within a 32 km radius of Morris, Minnesota (45.35°N, 95.53°W) to produce from 2 to 4 ha each of cuphea for a total of 18.6 ha. Some of the crop (about 2.6 ha) was lost to severe weather and herbicide drift from nearby crops, but the harvestable plantings produced seed yields ranging from approximately 78–744 kg ha^{-1} at 12% moisture. Valuable knowledge was learned through this experience that might not have been gained by plot-scale experiments alone. For instance, post-harvest management of seed on a large-scale (e.g., drying, cleaning, and storing) was problematic, indicating a further need for research and development in this area. Overall, the 2004 commercialization project made considerable progress in advancing cuphea towards large-scale production. This paper reviews some of our research results regarding best agronomic practices for cuphea production and reports on results obtained from the 2004 commercialization project.

Keywords: Cuphea; New crop; Medium chain fatty acid; Crop production

1. Introduction

The genus *Cuphea* (Lythraceae) contains about 265 species native to North, Central, and South America. Many of these species have the ability to synthesize and store medium-chain fatty acids (MCFA) in their seeds. Some of these MCFAs such as capric, lauric, and myristic acids are important feedstocks in manufacturing a wide range of chemical products (Thompson, 1984). Recent developments have also proven that MCFAs are a viable replacement for petroleum in uses such as motor oil (Cermak and Isbell, 2004) and diesel fuel (Geller et al., 1999).

Currently, coconut (*Cocus nucifera* L.) and palm (*Elaeis guineensis* Jacq.) are the only plant-derived sources of MCFAs used in chemical manufacturing, and

* Corresponding author. Tel.: +1 320 589 3411x132; fax: +1 320 589 3787.
E-mail address: gesch@morris.ars.usda.gov (R. Gesch).

0926-6690/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.indcrop.2006.06.007

developed countries import about 2.5 million Mt annually (UNFAO, 2003). Developing a MCFA-rich oilseed crop for temperate climates would be beneficial to industry and producers located in higher latitudes. Some species of *Cuphea* are known to flourish in temperate climates (Graham, 1989). Hirsinger (1985) was one of the first to show that several *Cuphea* species (henceforth referred to as "cuphea") have agronomic potential. Since then, advances have been made in domesticating cuphea for commercial use. As with most wild plant species, the largest barriers to domesticating cuphea have been indeterminate flowering, seed shattering, seed dormancy, and self-fertility. Additionally, most wild accessions of cuphea have a sticky coating on their stems, leaves, and flowers making harvesting more difficult (Hirsinger and Knowles, 1984). Recently, these barriers have been partially overcome through the development of genotypes arising from the interspecific hybridization of *Cuphea viscosissima* Jacq. with *C. lanceolata* W.T. Aiton. One selected genotype from this cross is PSR23 (Knapp and Crane, 2000), which produces non-dormant seed and has considerably improved seed retention and self-fertility over its wild relatives.

In 1999, our research group began working with just a few grams of PSR23 cuphea seed to determine its agronomic potential for the Midwestern US. Our primary objectives have been to develop best management practices for cuphea production and determine its response to environmental factors such as temperature, soil moisture, light, and soil type. Since the initiation of our work, substantial progress has been made, and the summer of 2004 marked the first year for on-farm commercial production of cuphea in the US. This was accomplished through close collaborative effort with industry (Technology Crops International, Winston-Salem, NC). Although the production scale in 2004 was small (approximately 17 ha), the results were encouraging and suggest that large-scale production is feasible in the near future. The focus of this paper is to review some our key research findings and give an overview of the 2004 commercialization project.

2. Cuphea agronomic management

2.1. Environmental limitations of domesticated cuphea

Cuphea (PSR23) grows well in west central Minnesota (45.6°N latitude) and when planted in mid May and harvested in mid to late September can produce seed yields that exceed 1000 kg ha^{-1} (Gesch et al., 2002a; Gesch et al., 2004b). Yield information for PSR23 in other areas is sparse, although Knapp and Crane (2000) reported 795 kg ha^{-1} from a site in Corvallis, Oregon (44.3°N) and seed yields around Peoria, Illinois (40.5°) tend to be less than those in Minnesota (Terry Isbell, personal communication). Forcella et al. (2005a) grew PSR23 at seven sites along a south-north transect from Iowa to Minnesota (latitudinal range of 41.3–48.9°N). As shown in Table 1, seed yield generally increased with latitude up to about 46°N in both years of the study. Seed yields in Crookston, MN (47.8°N) were lower than those in Morris, MN (45.6°N) in both years despite similar soil characteristics at each site and growing season

Table 1
Location description, seed yield, air temperature, and precipitation for seven sites in the Northwestern Corn Belt where PSR23 cuphea was grown in 2002 and 2003

	Location						
	Lewis, IA	Castana, IA	Calumet, IA	Lamberton, MN	Morris, MN	Crookston, MN	[a]Roseau, MN
Latitude (N°′)	41 31	42 07	42 94	44 23	45 59	47 77	48 85
Longitude (W°′)	95 08	95 91	95 55	95 26	95 91	96 61	95 76
[b]Soil class	Silty clay	Silty clay loam	Silty clay	Clay loam	Loam	Loam	Sandy clay loam
2002 Seed yield (kg ha^{-1})	53 d	190 c	342 b	301 b	431 a	96 d	–
2003 Seed yield (kg ha^{-1})	38 e	120 de	160 d	519 b	657 a	331 c	624 a
Temperature (°C)	19	18.5	17.4	16.8	16.4	15.4	14.6
Cumulative precipitation (mm)	383	408	408	434	521	522	489
Precipitation:temperature ratio (mm °C^{-1})	20.2	22.1	23.4	25.8	31.8	33.9	33.5

For seed yields, values within a row followed by the same letter are not different at the $P < 0.05$ level. Temperature and cumulative precipitation are averages over both years for the growing season (i.e. April–September). Adapted from Forcella et al. (2005a).
[a] In 2002 a flood destroyed the Roseau plots, so only the seed yield from 2003 could be used for comparison.
[b] Further description of soil classes is given in Forcella et al. (2005a,b).

temperature and precipitation (Table 1). Based on their findings, Forcella et al. (2005a) did not have a viable explanation for the lower yields at Crookston. Although many factors may have influenced yield differences in this study, likely temperature and available soil moisture variations were the most important. Along this transect, growing season temperature increased with decreasing latitude and for the Iowa sites where yields tended to be lower than those in Minnesota, cumulative precipitation was less (Table 1). We have previously shown that cuphea prefers mild temperatures for growth (Gesch et al., 2002b). The optimum mean daily growth temperature for PSR23 is approximately 24 °C (Gesch et al., 2002b), which is less than that for agronomic crops of sub-tropical origin such as corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.].

Cuphea PSR23 is not a highly efficient water user and requires a relatively large amount of water during its growth cycle for seed production. Its water use efficiency is about 1.5–2.0 kg ha^{-1} of seed mm^{-1} of water used (Sharratt and Gesch, 2004), which is less than half that of other oilseeds such as soybean and sunflower (*Helianthus annuus* L.) (Berglund, 1995). Furthermore, PSR23 lacks a deep, well structured root system, which may make it prone to drought stress. Field studies at Morris, Minnesota show, that in a dry year, the use of irrigation can more than double PSR23 cuphea seed yields (Gesch et al., 2004b). In the Forcella et al. (2005a) study, the ratio of growing season cumulative precipitation to temperature decreased with decreasing latitude (Table 1). At Lewis, Iowa where yield was lowest, the ratio was 36% lower than that at Morris, Minnesota where greatest yield occurred. A greater evapotranspiration demand, coupled with a tendency for precipitation to decline with decreasing latitude may further explain the lower yields reported for the more southerly sites (Table 1).

2.2. *Best management practices*

2.2.1. *Planting and weed control*

The seed of cuphea is small and disk shaped, with an average weight of about 3.0 g 1000 seed^{-1}. Germination can be quite variable and seedling vigor tends to be weak. Therefore, seeding depth is critical, and we have found that seeding deeper than 1 cm can lead to poor stand establishment. Thus the seedbed for cuphea must be well prepared with little excess crop residue on the surface. For planting cuphea, drill-seeding as shallow as possible works best. In west central Minnesota, the optimum time for planting is early to mid-May when soil moisture is relatively high and soil temperatures are above 10 °C (Gesch et al., 2002a). Recently, coating cuphea seed with a clay-based material (Germain's Technology Group, Fargo, ND) has facilitated more accurate planting by adding weight to the seed and making it more spherical.

A primary goal in developing cuphea production practices is to utilize equipment available to most farmers. Therefore, row-cropping equipment and techniques are being used. Plant spacing studies indicate that a population density in the range of 400,000–600,000 plants ha^{-1} with an interrow spacing of 40–60 cm (Gesch et al., 2003) is near optimum for seed yield. Because cuphea grows indeterminately, it has good yield compensation capacity. The more space allowed between plants, the more branching occurs and the greater the number of seed capsules and yield per plant (Gesch et al., 2003). Good cuphea stands are achieved by mechanically seeding at a rate of about 9 kg ha^{-1} (unpublished data).

Optimum soil fertility for cuphea growth and seed yield has not been well researched. Preliminary evidence indicates that cuphea seed yield does not respond greatly to nitrogen application, but may increase with added sulfur (unpublished data). Most of our studies have been conducted on heavy loam soils with relatively high levels of residual fertilizer from previous crops. This probably explains why we have not detected yield responses to added fertilizers. Nevertheless, in all other cuphea agronomic experiments we routinely incorporate N as urea, P as diammonium phosphate, and K as potassium oxide into the top 0.15 m of soil at rates of 112, 13, and 30 kg ha^{-1}, respectively, to guard against unexpected nutrient limitations.

The growth of cuphea tends to be slow during its vegetative development, but increases dramatically during anthesis, and canopy closure generally occurs soon after. For PSR23, flowering begins approximately 530–580 growing degree days (°C days; using a base temperature of 10 °C) after seeding (Gesch et al., 2002a). Because of its slow vegetative growth, early season weed control can be problematic. Because cuphea is a dicotyledonous plant, a number of graminicides can be used to control weedy monocots. We have successfully used sethoxydim at 0.3 kg ai ha^{-1} for this purpose. Our greatest challenge has been to identify broadleaf herbicides that cuphea tolerates. We have tested several potential broadleaf herbicides and found some to work well. Pre-plant incorporation of trifluralin or ethalfluralin at 0.84 kg ai ha^{-1}, pre-emergence application of isoxaflutole at 0.08 kg ai ha^{-1}, and post-emergence application of mesotrione up to 0.105 kg ai ha^{-1} controlled a wide range of broadleaf weeds without harming cuphea (Forcella et al., 2005b). However, for cuphea production to be successful over a wider geographical area, identification of additional herbicides is necessary.

2.2.2. Harvesting and seed drying

Because of cuphea's indeterminacy, once it begins flowering it can continue to flower up to 2 months. Additionally, even our most advanced line, PSR23, is prone to seed shattering. Therefore, the timing of harvesting to achieve maximum yields is critical. In a 2-year field study conducted in west central Minnesota, the best time to harvest was found to be in late September to early October (Gesch et al., 2005). When planted in the spring, cuphea continues to grow until it is killed by freezing temperatures. Because of this, seed moisture can be quite high at harvest unless plants are first killed and desiccated by a hard frost, swathing, or application of a chemical desiccant. However, desiccation of plants due to a hard frost or chemical treatment tends to hasten seed shattering, and when left in the field too long, seed yields can decline rapidly (Gesch et al., 2005). Thus far, combining directly has worked well for harvesting cuphea, although recent studies show that swathing has good potential (data submitted for publication). Paraquat and sodium chlorate, for desiccating plants, have also proven useful as harvest aids, but the crop should be harvested within approximately 7 days after treatment to avoid excessive shattering. Even with the use of swathing or chemical desiccation in the field, cuphea seed can contain as much as 30–40% water at harvesting, thus requiring further drying. To accomplish this, a commercial batch-dryer (Model 245XL, GT Manufacturing Inc., Clay Center, KS, USA) designed for small seeded crops (e.g. canola) has been successfully used. For long-term storage of cuphea seed, its water content should be less than 10% (personal observation).

Seed oil content, like seed yield, also appears to be influenced by harvest date. During a 2-year study, seed oil content responded sigmoidally, increasing substantially throughout early and mid September and reaching a plateau in late September at about day of the year 270 (Gesch et al., 2005). In the Northern Corn Belt region of the US, cuphea PSR23 typically begins flowering in late July and continues until inhibited by low temperatures in late September. However, the most extensive flower production tends to occur in mid August. Although no published data are available concerning the duration of seed development for domesticated cuphea (PSR23), preliminary evidence suggests that physiological maturity takes approximately 35 days (Berti et al., 2005). If this is so, then an extensive flowering event in mid-August might explain why the greatest seed yield and oil content occur in late September (Gesch et al., 2005).

3. Commercialization project of 2004

In terms of new crop development, we are discovering first-hand how difficult it is to make the leap from research to commercial production. However, with strong support from our industrial partners, Procter and Gamble Company and Technology Crops International (TCI), a small-scale, on-farm commercialization project was initiated in 2004. Since about 2001, producers in the upper Midwest obtained information about cuphea through university and USDA Agricultural Research Service (USDA-ARS) Field Day presentations and public media (i.e., radio, television, and popular press). Several producers expressing interest in growing cuphea contacted scientists at the USDA-ARS lab in Morris, Minnesota and with their approval, a list containing contact information for these farmers was kept for future reference. These farmers were contacted by the USDA-ARS 3–4 months prior to the 2004 growing season to confirm whether they were still interested in growing cuphea and TCI took the lead in contracting six farmers in west central Minnesota for the cuphea production. Because the farmers involved in this project had no prior experience with cuphea, TCI and the USDA-ARS took active roles in cooperating with farmers to manage the production. Prior to the 2004 growing season, a meeting was conducted with the farmers to inform them about cuphea and best management practices for its production. They were also provided a grower's guide compiled by the USDA-ARS based on prior research and field experience (Gesch et al., 2004a).

Each farmer grew 2–4 ha for an overall total of 18.6 ha (Table 2). The fields used to produce cuphea had similar loam soils (Table 2). Farms 1–5 were previously cropped in soybean, Farm 6 was cropped in corn the previous year. One of the farmers chose to do all of his own field work (Farm 1; Table 2), whereas the other five sub-contracted to have their planting, herbicide application, and harvesting done at a similar time by one person. Except for row spacing, timing of post-emergent application of mesotrione, and timing of harvest following defoliation and desiccant treatment, the guide lines provided to the farmers were followed relatively well. The seed used for planting was provided by the USDA-ARS lab in Morris, Minnesota and was coated with a clay-based material by Germain's Technology Group (Fargo, ND, USA), for ease of planting. Four of the farmers fertilized their fields with N, P, and K prior to planting at a rate of 56, 56, and 22 kg ha^{-1}, respectively, while Farms 1 and 3 were fertilized for corn, but the rate was not known. The farmer that chose to do his own field work

Table 2
Harvest results for the 2004 commercialization project conducted in west central Minnesota, USA

Farm	Soil type	Hectares planted	Hectares harvested	Harvest date	% Moisture at harvest	Total seed wt. (kg at 12% moisture)	Yield ($kg\,ha^{-1}$ at 12% moisture)
1	Barnes loam (Fine-loamy, mixed Udic Haploborolls)	4.05	4.05	5 october	42	1811	447
2	Forman clay loam (Fine-loamy, mixed Udic Argiborolls)	2.43	2.43	6 october	43	1007	415
3	Barnes loam (Fine-loamy, mixed Udic Haploborolls)	2.02	0.91	6 october	41	678	744
4	Barnes loam (Fine-loamy, mixed Udic Haploborolls)	4.05	3.44	6 october	37	1809	526
5	McIntosh silt loam (Fine-silty, mixed, frigid Aeric Calciaquolls)	4.05	3.84	11 october	30	297	78
6	Tonka loam (Fine, montmorillonitic, frigid Argiaquic Argialbolls)	2.02	2.02	6 october	NA	899	445
	Totals	18.62	16.69	–	–	6501	444[a]

[a] Mean.

seeded with a 7.6 m wide John Deere press-drill (Deere and Company, Moline, IL, USA) on 31 cm spaced rows by blocking every other drill opening. The press-drill, even when set as shallow as possible, tended to place the seed too deep (≥ 1.8 cm), resulting in a less than desirable stand of about 309,000 plants ha^{-1}. The other five fields were planted with a 4.6 m wide John Deere no-till drill on 38 cm spaced rows by blocking every other drill opening. The no-till drill seeded shallower than the press drill and resulted in better stands that ranged from 469,500 to 519,000 plants ha^{-1}.

Weather conditions during the 2004 growing season were cold and wet. The number of accumulated growing degree days (calculated with a 10 °C base temperature) from May through September was 1083 °C days, which is about 237 °C days below normal. Gesch et al. (2005) showed that the number of growing degree days from sowing to optimum harvest date of cuphea is approximately 1340 °C days, which typically occurs in late September to early October in west central Minnesota. On 21 August most areas within the study experienced frost. Despite these harsh conditions, cuphea PSR23 grew relatively well. For weed control, all fields were treated with ethalfluralin prior to planting and received a post-emergence application of mesotrione at recommended rates (see Section 2.2.1). The farmer that did his own field work applied mesotrione in early July, near the recommended time for application, and had slightly better weed control than the other farmers, who treated their fields in mid July. Generally, weed control was effective except for some fields where certain weed species escaped. Biennial wormwood (*Artemisia biennis* Willd.) escaped control and three of the six fields had substantial infestations.

On September 27, all fields were sprayed with a tank mix of paraquat (1.1 kg ai ha^{-1}) and sodium chlorate (8.3 kg ai ha^{-1}) to desiccate plants. The crop was relatively dry within 3 days after treatment, but because of a rain (43 mm) on the 4th day, harvesting was delayed an additional 5–10 days. Also, there were two hard frost events (i.e., <2 °C) that occurred between desiccation treatment and harvest. Consequently, this resulted in substantial seed shatter and yield-loss, although this was not measured. Five of the fields were harvested with a John Deere 9400 combine and the other with a John Deere 7200, both having 7.6 m-wide heads. Combining was done by straight cutting at a plant height of approximately 20 cm. Combine cylinder speed was kept at 1000 rpm or higher, while keeping the reel speed at approximately ground speed, and a narrow cylinder to concave spacing was used with little or no wind (i.e., blower fan). Seed yields ranged from 78 to 744 kg ha^{-1} (Table 2). The lowest yielding field was also the last to be harvested (Farm 5; Table 2). A severe infestation of *Sclerotinia sclerotiourum* (white mold) was identified in this field, which undoubtedly contributed to the low yield, as did seed shattering from the delayed harvest. Because of various unforeseen problems, not all of the land area of cuphea planted could be harvested (Table 2). Farm 3 suffered damage from herbicide drift from an adjacent corn crop and approximately 1.1 ha of damaged cuphea was cultivated and re-planted to soybean. Part of Farm 4 could not be harvested due to flooding and 0.21 ha of Farm 5 was not harvested because of severe biennial wormwood infestation (Table 2).

The moisture content of seed taken from the field averaged 39% (Table 2), and was therefore dried in a batch-style grain dryer designed for handling small-seeded crops. Because of limited dryer capacity and because all fields but one were harvested within 24 h, this stage of seed handling greatly restricted the timely processing of seed. Targeted moisture content was approximately 12%, but values after drying ranged from 9 to 15%. We later found that seed-lots stored above 10% experienced heating and mold growth and required re-drying to less than 10% moisture for proper storage.

Enterprise budgets for cuphea compared to budgets for other crops grown in the same area in 2004 are shown in Table 3. Operating costs for cuphea production were slightly higher than costs for spring wheat and soybeans, but substantially lower than for corn production. Total costs for cuphea production were comparable to the total costs for soybean production. The producers did not pay for cuphea seed in 2004, and no price for cuphea seed has been set, so this cost was omitted from the enterprise budgets. Although participants in the project did not pay drying costs, drying costs were estimated based on the harvest moistures observed. Net returns for cuphea exceeded net returns for the other three crops in 2004 given the \$370.50 ha^{-1} payment participants received and a price of \$330.69 Mg^{-1} of seed. These payments were set at a level sufficient to attract participants in the project, and do not reflect the market value of cuphea, as this market has not yet been established. A market price of \$1192 ha^{-1} would be necessary for cuphea income to cover production costs with a yield of 0.444 Mg ha^{-1} and in the absence of the \$370.50 ha^{-1} payment. The rather high market value based on the present data may be greatly reduced in the future by increasing seed yields through reducing seed shattering and selecting cuphea genotypes with other yield improvement characteristic. Developing more cost effective weed control options and harvest management practices to reduce seed moisture

Table 3
Budget summary for the cuphea commercialization project as compared to budgets for other crops grown in the same area in 2004

Budget	Crop			
	[a]Spring wheat	Corn grain	Soybeans	Cuphea
[b]Yield (Mg ha^{-1})	3.833	9.289	2.219	0.444
[c]Price (\$ Mg^{-1})	119.42	72.83	196.58	330.69
Other income				370.66
Total income	457.73	676.53	436.21	517.48
Operating costs				
Seed	57.82	112.09	93.95	0.00
Herbicides	36.37	46.90	23.45	97.29
Fungicides	0.00	0.00	0.00	0.00
Insecticides	0.00	0.00	21.65	0.00
Fertilizer	84.41	123.92	32.00	81.10
Crop insurance	11.94	20.04	10.16	0.00
Fuel	18.80	22.61	23.33	21.79
Repairs	29.60	35.31	35.01	33.14
Labor	16.36	20.16	19.69	18.90
Drying	0.00	52.51	0.00	15.22
Operating interest	7.49	9.86	6.18	5.96
Total operating cost	262.68	443.40	265.41	273.40
Ownership costs				
Machinery ownership	52.36	70.40	66.94	57.97
Land charge	197.68	197.68	197.68	197.68
Total ownership cost	250.04	268.08	264.62	255.65
Total cost	512.84	711.49	530.04	529.05
Net return	−55.12	−34.96	−93.83	−11.57
Breakeven price (\$ Mg^{-1})	133.80	76.59	238.86	1191.56

Costs and income are expressed in US \$ ha^{-1}.
[a] Production costs for wheat, corn, and soybean are based on research at the USDA-ARS Swan Lake Research Farm in Morris, MN.
[b] Stevens County, Minnesota average yields for 2004.
[c] Minnesota average prices received in 2004.

content in the field will also aid in this effort and are being researched.

4. Conclusions

The initial commercialization of cuphea in 2004 was generally successful and sufficient seed was generated to allow extensive seed and oil processing research and for on-farm production in subsequent years. For future large-scale production, need exists to identify additional broadleaf weed control options, and there is need to further study and characterize cuphea's soil nutrient requirements. Improved harvest management to reduce moisture content of seed before taken from the field is an important issue. Recent research shows that seed moisture content of cuphea can be reduced to about 20% following swathing and drying in the field for approximately 14 days (data submitted for publication). Also, until more shatter-resistant and determinate lines of cuphea are developed, equipment and techniques designed for shatter-prone plants will be necessary for harvesting.

Acknowledgment

The authors acknowledge Procter and Gamble Company for helping to fund cuphea research.

References

Berglund, D.R., 1995. Sunflower production. In: Ext. Bull. EB-25. North Dakota State Univ. Exp. Stn., Fargo, ND.

Berti, M.T., Johnson, B.L., Manthey, L.K., 2005. Cuphea seed oil content and fatty acid composition changes during seed development. Industrial crops and rural development. In: Pascual-Villalobos, M.J., Nakayama, F.S., Bailey, C.A., Correal, E., Schloman, W.W. (Eds.), Proceeding of the 2005 Meeting of the Association for the Advancement of Industrial Crops: International Conference on Industrial Crops and Rural Development, 17–21 September. Murcia, Spain, pp. 759–773.

Cermak, S.C., Isbell, T.A., 2004. Synthesis and physical properties of cuphea-oleic estolides and esters. J. Am. Oil Chem. Soc. 81, 297–303.

Forcella, F., Gesch, R.W., Isbell, T.A., 2005a. Seed yield, oil, and fatty acids of cuphea in the northwestern Corn Belt. Crop Sci. 45, 2195–2202.

Forcella, F., Amundson, G.B., Gesch, R.W., Papiernik, S.K., Davis, V.M., Phippen, W.B., 2005b. Herbicides tolerated by cuphea (*Cuphea viscosissima* x *lanceolata*). Weed Tech. 19, 861–865.

Geller, D.P., Goodrum, J.W., Knapp, S.J., 1999. Fuel properties of oil from genetically altered *Cuphea viscosissima* Ind. Crop Prod. 9, 85–91.

Gesch, R.W., Forcella, F., Barbour, N., Phillips, B., Voorhees, W.B., 2002a. Yield and growth response of Cuphea to sowing date. Crop Sci. 42, 1959–1965.

Gesch, R.W., Barbour, N., Forcella, F., Voorhees, W.B., 2001. Cuphea growth and development: responses to temperature. Trends in new crops and new uses. In: Janick, J., Whipkey, A. (Eds.), Proceedings of the 5th National Symposium of New Crops and New Uses Strength in Diversity, 10–13 November. Atlanta, GA. ASHS Press, Alexandria, VA, pp. 213–215.

Gesch, R.W., Forcella, F., Barbour, N., Phillips, B., Voorhees, W.B., 2003. Growth and yield response of Cuphea to row spacing. Field Crops Res. 81, 193–199.

Gesch, R.W., Forcella, F., Olness, A.E., 2004a. Cuphea grower's guide. Cuphea Production Contract 2004. Technology Crops International, Winston-Salem, NC, pp. 5–8.

Gesch, R.W., Sharratt, B.S., Cermak, S.C., 2004b. Cuphea seed yield, but not seed oil content is reduced by drought. Association for the Advancement of Industrial Crops Annual Meeting, Minneapolis, Minnesota. P. 38.

Gesch, R.W., Cermak, S.C., Isbell, T.A., Forcella, F., 2005. Seed yield and oil content of cuphea as affected by harvest date. Agron. J. 97, 817–822.

Graham, S.A., 1989. *Cuphea*: a new plant source of medium-chain fatty acids. Crit. Rev. Food Sci. Nutr. 28, 139–173.

Hirsinger, F., 1985. Agronomic potential and seed composition of Cuphea, an annual crop for lauric and capric seed oils. J. Am. Oil Chem. Soc. 62, 76–80.

Hirsinger, F., Knowles, P.F., 1984. Morphological and agronomic description of selected *Cuphea* germplasm. Econ. Bot. 38, 439–451.

Knapp, S.J., Crane, J.M., 2000. Registration of reduced seed shattering *Cuphea* germplasm PSR23. Crop Sci. 41, 299–300.

Sharratt, B.S., Gesch, R.W., 2004. Water use and root length density of *Cuphea* sp. Influenced by row spacing and sowing date. Agron. J. 96, 1475–1480.

Thompson, A.E., 1984. *Cuphea*—a potential new crop. HortScience 19, 352–354.

United Nations Food and Agricultural Organization. 2003. Statistical data bases. http:www.fao.org.