Winter Camelina

SUPPLY CHAIN DEVELOPMENT IN MINNESOTA

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Introduction

The Agricultural Utilization Research Institute (AURI) partnered on a project led by researchers at Central Lakes College (CLC) aimed at integrating winter camelina into crop rotations in Minnesota. The Minnesota Environment and Natural Resources Trust Fund, as recommended by the Legislative-Citizen Commission on Minnesota Resources (LCCMR), provided funding for this project. The Trust Fund is a permanent fund constitutionally established by the citizens of Minnesota to assist in the protection, conservation, preservation, and enhancement of the state's air, water, land, fish, wildlife, and other natural resources.

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND

The project focuses on protecting water quality and supporting economically viable agriculture that is fundamentally important to Minnesota. CLC is leading a farm-based effort to adopt kura clover and camelina cover crops into corn-soybean rotations to protect vulnerable wellhead areas from nitrate contamination, working in partnership with the University of Minnesota and the U.S. Department of Agriculture's Agricultural Research Service (USDA-ARS).

AURI's role in the overall project included the following activities:

1. Determine costs for farm operations and winter camelina yields.
2. Assess costs, rates and options for winter camelina seed processing (e.g., seed cleaning, pressing, packaging).
3. Evaluate market demand and opportunities.
4. Identify equipment and infrastructure needs specific to processing winter camelina.

AURI's goal is to highlight opportunities to strengthen the value chain, identify market opportunities and address gaps in the value chain. Using input gathered from key stakeholders, AURI aims to strategically support the adoption of winter camelina by engaging private businesses in developing pilot-scale projects demonstrating the pressing, processing, and marketing of winter camelina-based products.

For more information on the project and Central Lakes College's work on LCCMR-funded research, visit: http://clcagandenergy.org/lccmr/.

Figure 1. Winter Camelina (Photo: UMN Forever Green).

Executive Summary

This report identifies possible markets, potential demand and processing infrastructure requirements, and potential commercialization pathways for winter camelina meal and oil markets.

Market Opportunity

Based on its chemical and nutritional profile, production characteristics and potential uses identified by key industry stakeholders, AURI and its project partners identified several market opportunities of varying size and scope which are worthy of continued review. These include:

- Industrial – sustainable aviation fuels (SAF), biofuels, biobased products
- Livestock and Aquaculture Nutrition
- Companion Animal Dietary Supplements
- Human Food – vegetable/cooking oil, supplements, food ingredients, alternative protein

Barriers

While winter camelina holds great potential for market development in several different use classes, creating economically sustainable markets for this new oilseed involves multiple notable barriers, including:

- Limited options for crop insurance and risk management
- Limited seed availability
- Regulatory limitations on inclusion in animal diets
- Unclear U.S. Food and Drug Administration (FDA) status for Generally Regarded as Safe (GRAS)
- Anti-nutritional/glucosinolates in meal and oil
- Reduced economies of scale

Next Steps

Successful commercialization of winter camelina will require continued effort by key supply chain stakeholders. While there are multiple areas requiring action, important steps will likely need to include the following activities:

- Obtain FDA GRAS status for use of winter camelina in products intended for human consumption
- Conduct additional feed trials to provide data for development of animal nutrition products and meet regulatory standards– dairy, swine, poultry, aquaculture, etc.
- Scale up seed production and ensure supply is available to potential growers
- Engage processors and key supply chain stakeholders
- Recruit and provide information to crop producers
- Reduce risk for initial producers – develop risk management pilot programs, ensure producer access to crop insurance programs, explore alternative financing options during early stages of commercialization
- Investigate and develop higher value uses
    - Human Nutrition

    - Cosmetics
    - Industrial – Sustainable Aviation Fuel, biodiesel, industrial chemicals
    - Pharmaceutical/Nutraceutical Uses

Commercializing Winter Camelina in Minnesota

AURI began its supply chain analysis by assessing commercialization factors to determine the potential to establish winter camelina as a profitable crop. To establish a viable market, winter camelina needs to be profitable for each supply chain segment from the farm to end user. Working with project partners, AURI examined the following components of supply chain development:

- Crop Production
- Product Characterization
- Seed Production, Cleaning, and Processing
    - Oil pressing, meal defatting
- Distribution
- Potential End Markets
    - Seed Production
    - Feed/Animal Nutrition
        - Ingredient in animal diets, including aquaculture
        - Dietary supplement- animal nutrition
    - Industrial+
        - Renewable Fuels
        - High Value Chemicals
        - Biobased Materials
    - Human Food Products
    - Cosmetics, Pharmaceuticals, and Nutraceuticals

Considerations for each component were identified during discussions with stakeholders and outside experts. While other partners in Minnesota's broader winter camelina development initiative are currently involved in efforts to bring winter camelina to market, AURI's efforts focused on the commercialization pathway for use in livestock feeds and supplements. Developing these types of uses for winter camelina meal will be critical to successfully tapping winter camelina's strong potential as a high-quality feedstock for biofuels. Based on the opportunities available and the barriers to opening higher value uses, the animal nutrition market has the potential to launch commercially in the near term, serving as an outlet for meal produced during processing, with the oil destined for biofuel production. If successful, the development of animal nutrition markets for winter camelina can provide a foundation for further market development.

This report also addresses the key factors crop farmers and processors may consider when making investments in winter camelina commercialization. Information for this report was collected through discussions with crop producers, animal nutritionists, camelina marketers (Smart Earth Camelina), the University of Minnesota Forever Green Initiative, Nutrien, Yield 10 Bioscience, Cargill, the Regenerative Agriculture Alliance, and the Ag Innovation Campus. Finally, this report identifies key next steps, including areas needing additional research to evaluate investment in further commercialization efforts for winter camelina.

MBOLD
MINNESOTA: LEADING THE WAY TO THE FUTURE OF FOOD

MBOLD is a coalition consisting of major food and agriculturally related Minnesota companies including Cargill, Schwans, Target, Compeer and General Mills. MBOLD has identified winter camelina as one of its two focus initiatives to identify crops with commercial potential that can improve soil health.

In addition to the partners and industry stakeholders mentioned above, AURI and the University of Minnesota have engaged with the Greater MSP's MBOLD initiative as it examines potential commercialization pathways for winter camelina.

MBOLD members are currently conducting research and taking part in discussions about how its members may incorporate winter camelina into various product lines.

Winter camelina holds the potential to fit into Minnesota's cropping rotations and processing infrastructure and could provide opportunities throughout the supply chain for Minnesota agriculture. However, as with any new product, barriers to commercialization exist and key questions need answering. This report encourages continued efforts to engage stakeholders and build on current momentum to develop winter camelina as an economic and ecosystem-enhancement opportunity for Minnesota agriculture.

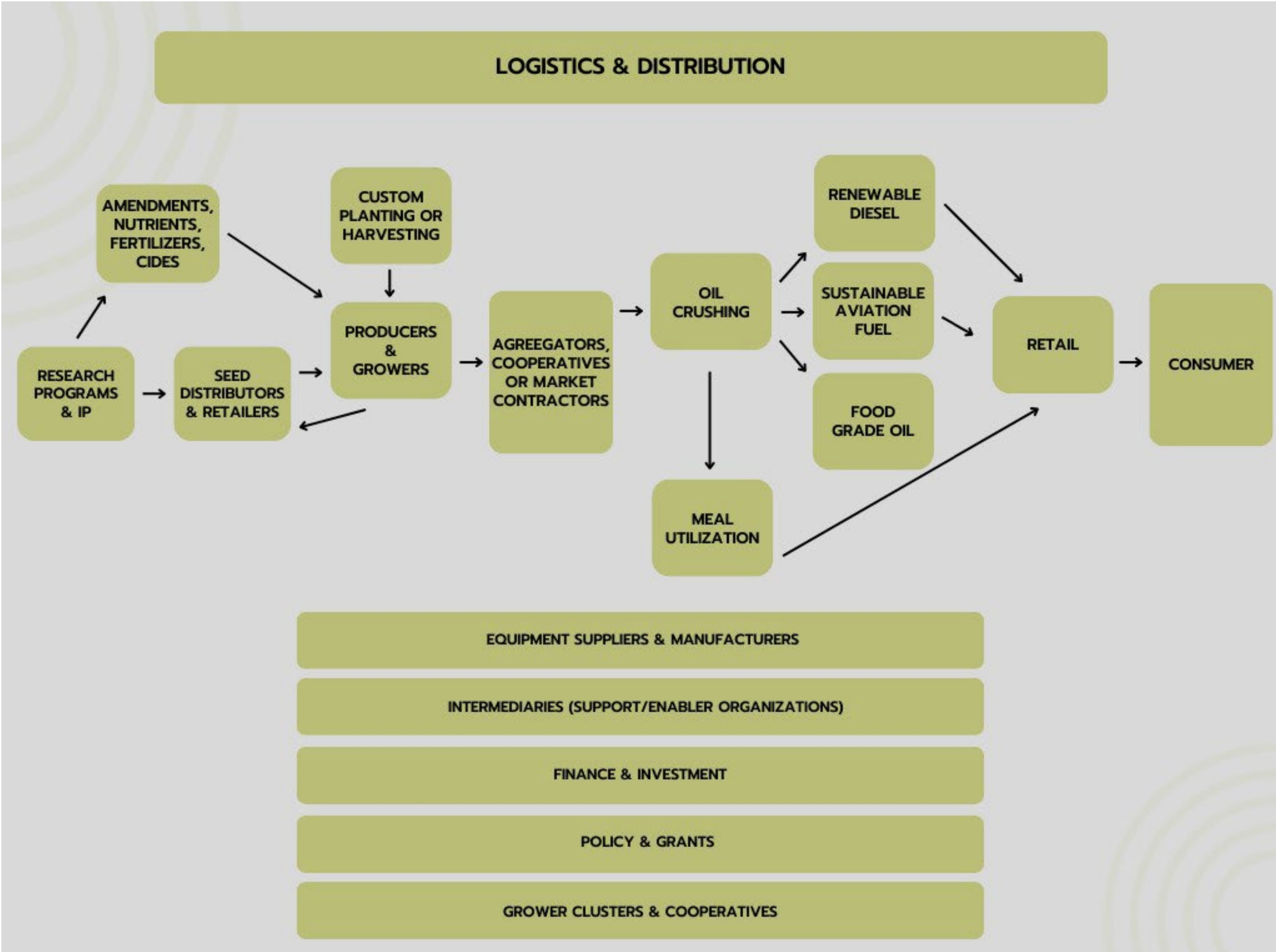

Figure 2: Value-Chain Map of Winter Camelina in the Upper Midwest.

Winter Camelina Product Attributes

AURI scientists researched analytical characteristics of winter camelina seed and meal to help guide the commercialization process and inform discussions with potential end users. This ongoing work focuses on developing additional data to meet industry needs and open new supply chain opportunities. The work also focuses on the nutrient analysis of winter camelina seed and meal, and an assessment of winter camelina's amino acid profile. Table 1 illustrates a replicate analysis comparison of soybean and winter camelina seed and meal (n=5).

Table 1: Nutrient Analysis- winter camelina vs soybean meal and seed (AURI 2020)

Analysis		Winter Camelina Seed[1]	Soybean Seed[2]	Winter Camelina Meal	44% Soybean Meal
Moisture	%	9.1	7.6	11.2	10.0
Dry matter	%	90.9	92.4	88.8	90.0
Crude Protein	% DM	25.7	40.6	39.7	53.0
Fat	% DM	40.0	21.8	14.6	1.7
Ash	% DM	4.0	5.3	6.0	7.0
Calcium	% DM	0.3	0.3	0.4	0.4
Phosphorus	% DM	0.8	0.6	1.2	0.8
Potassium	% DM	1.0	1.8	1.4	2.5
Sulfur	% DM	0.6	0.3	0.9	0.4
Magnesium	% DM	0.3	0.3	0.5	0.3
Sodium	%DM	ND	0.0	ND	0.1
Iron	ppm (DM)	119.4	86.6	169.6	109.1
Manganese	ppm (DM)	27.8	32.5	42.7	39.4
Copper	ppm (DM)	6.7	17.3	8.9	16.8
Zinc	ppm (DM)	65.9	42.2	95.7	54.2
Net Energy (Lactation)	Mcal/lbs	1.3	1.4	0.9	1.1
Metabolizable Energy	Mcal/lbs	2.2	1.9	1.6	1.7
Digestible Energy	Mcal/lbs	2.4	2.1	1.8	1.8

Table 2: Amino acid profile, winter camelina (AURI 2020)

Amino Acid	Winter Camelina Meal W/W%	44% Soybean Meal W/W% (DM)[a]
Aspartic Acid	2.56	5.59
Threonine	1.31	1.93
Serine	1.34	2.38
Glutamic Acid	5.38	8.81
Proline	1.65	2.48
Glycine	1.94	2.08
Alanine	1.54	2.18
Cysteine	0.80	0.74
Valine	1.71	2.38
Methionine	0.54	0.69
Isoleucine	1.21	2.28
Leucine	2.09	3.76
Tyrosine	1.04	1.73
Phenylalanine	1.45	2.52
Lysine	1.68	3.07
Histidine	0.77	1.34
Arginine	2.80	3.61
Tryptophan	0.36	0.69
Total	30.67	48.26
Crude protein*	34.42	49.5
NDF	33.45	14.8
Crude Fat	9.31	1.9

W/W%= grams per 100 grams of sample. Crude protein= %N x6.25. §Non-proteinogenic amino acids.*
Results are expressed on an "as is" basis unless otherwise indicated.

a) https://www.feedipedia.org/node/11682

Of note is the high fat content in winter camelina seed compared to soybean seed, which is used in multiple value-added roles that may offer market opportunities for winter camelina. This reflects winter camelina's relatively high oil content, an attribute that may prove useful for end users in the biofuel industry. The disparity in fat content measured in winter camelina meal and soybean meal reflects the methods of processing. AURI's processing tests on winter camelina made use of cold pressing methods, which extracts less oil from the seed, leaving higher residual amounts in the meal.

Crude fiber content in winter camelina meal is higher than soybean meal. Investigation into dietary fiber will be important for animal feed applications and requires future work. The soybean meal sample used in this example results from hexane extraction, enabling higher levels of oil extraction, and accounting for the lower fat level and higher crude protein percentage. Again, this area needs additional study.

Notable Winter Camelina Attributes

Omega 3/6

Winter camelina's omega oil profile (Table 3) offers potential for use in feed rations aimed at increasing omega levels in the end products. One potential use is inclusion of winter camelina in layer hen diets to increase omega 3's and 6's in table eggs. According to one poultry producer, winter camelina is a preferred potential omega oil source to fish meal, which can cause a "fishy" taste in the eggs. Table eggs containing elevated omega oils fit the specialty egg product definition and command a premium price for the nutrient-enhanced feature.

According to the Association of American Feed Control Officers (AAFCO), camelina is approved for up to 10% inclusion in poultry (12% in broiler chickens) and cattle (in feedlot) diets. The Minnesota-based Regenerative Agriculture Alliance has been feeding unprocessed camelina to laying hens and broiler chickens. Their trials show unprocessed camelina seed supplies a higher nutrient level to the hens than crushed seed. Additionally, research indicates that use of poultry feeds with 10 percent camelina meal lead to an increase in health-promoting omega-3 fatty acids of over 3-fold in chicken meat and 8-fold in eggs.[1] Lastly, Obour et al., states that winter camelina appears to be safe for consumption in meal diets and may provide a benefit to humans as well.[2]

Table 3: Comparison of winter camelina fatty acids to other oilseeds.

Fatty Acid (g/100g)	Soybean	Canola	Pennycress	Winter Camelina
Myristic (C14:0)	0.07	0.05	0.06	0.07
Pentadecanoic (C15:0)	-	-	0.02	0.02
Palmitic (C16:0)	9.89	3.61	2.09	4.91
Palmitelaidic (C16:1 Trans)	-	-	0.21	0.03
Palmitoleic (C16:1 Cis)	0.07	0.18	0.09	0.09
Heptadecanoic (C17:0)	-	-	0.02	0.04
10-Heptadecanoic (C17:1)	-	-	0.04	0.04
Stearic (C18:0)	3.52	1.56	0.33	2.40
Eliadic (C18:1 Trans)	-	-	-	0.02
Oleic (C18:1 Cis)	19.37	56.64	11.97	15.46
Linoleic (C18:2 Cis)	49.72	16.41	18.77	15.94
Nonadecanoic (C19:0)	-	-	-	0.02
alpha-Linolenic (C18:3 alpha)	6.24	7.18	10.57	36.96
Arachidic (C20:0)	-	-	0.22	1.56
11-Eicosenoic (C20:1)	-	1.96	8.64	14.06
11-14 Eicosadienoic (C20:2)	-	-	1.42	1.76
11-14-17 Eicosatrienoic (C20:3)	0.27	-	0.33	1.52
Arachidonic (C20:4)	-	-	-	0.01
Behenic (C22:0)	-	0.27	0.18	0.33
Erucic (C22:1)	-	-	37.07	2.68
Docosadienoic (C22:2)	-	-	0.59	0.13
Tricosanoic (C23:0)	-	-	0.02	0.03
Lignoceric (C24:0)	-	0.13	0.09	0.23
Nervonic (C24:1)	-	0.12	2.71	0.62

Digestibility

AURI scientists analyzed in vitro digestibility methods in ruminants and found winter camelina meal (processed via cold press) had neutral detergent fiber (NDF) levels similar to roughage, rather than shell corn which is a starch source. (See Appendix B). When compared to alfalfa hay, fiber in camelina meal had a greater NDF digestibility rate through the rumen than average alfalfa hay. Further analysis of the meal led to an estimated feed value for the cold-pressed winter camelina meal. (See Appendix C)

Results indicate that winter camelina meal provides a significant source of protein and energy as a single feed ingredient when focusing on ingredient value. Winter camelina meal evaluated by AURI scientists had a crude protein of 38%, fat content of 17.6%, and total digestible nutrient value of 81% on an “as-is” basis. Additional extraction of oil from the meal when using hexane oil extraction would significantly increase the ingredient value for protein content, while decreasing energy values.

Ecological/Carbon Footprint/Life Cycle Assessment

Winter camelina's most notable distinguishing factors are its potential ecological and rotational benefits. Winter camelina has the potential to fit in Minnesota's crop production system as a "relay" crop. In this system, winter camelina is planted in late summer-early fall (late August-mid October) after removing the previous crop (e.g., wheat, corn silage, sunflowers, or other early-harvest crops). It can be harvested in mid-June to early July after a second crop (e.g., soybeans) has been inter-seeded between camelina rows. Winter camelina may also "work extremely well in rotation with winter cereals," such as winter wheat and winter rye in non-relay cropping systems, providing a crop with an early harvest date that allows for timely planting of subsequent winter cereal crops in regions with shorter growing seasons.[3]

During the months when fields would otherwise be bare in conventional cropping systems, winter camelina's established root system and above ground leafing can prevent soil erosion from wind and water, nutrient and sediment runoff, and nitrate leaching while also improving soil health by increasing organic matter, microorganism habitat, and water holding and drainage capacity. These ecological benefits are becoming more important to consumers. Companies are seeking attributes to distinguish their consumer facing products. For example, Mike Karst of Sustainable Oils claims, "...camelina has a low carbon intensity score compared to other plant feedstocks and because it's grown [in tandem with other crops or] when food crops aren't in the fields, it can be produced on existing agricultural lands without diminishing food production."[4] These attributes may motivate consumers seeking products with a more environmentally friendly profile.

Similarly, winter camelina has the potential to add revenue to farm businesses. While a yield drag may occur for soybeans (or another second crop) in the relay rotation, value obtained from winter camelina production should result in increased economic return to the cropping enterprise overall.[5] University of Minnesota researchers, through the Forever Green Initiative, are working to reduce yield drag and improve the economic competitiveness of winter camelina as a rotation option. Even with reduced soybean yields, the relay system of camelina and soybean holds the potential to produce over 100 gallons of oil per acre, compared to 60 gallons/acre for a single full-season soybean crop without winter camelina.[6] With current germplasm, winter camelina is projected to produce average yields of 1,000 lbs/acre, which would also allow production of approximately 600 to 650 pounds of winter camelina meal per acre after hexane oil extraction.

Other potential ecosystem benefits

Winter camelina offers strong potential to improve pollinator health by diversifying the state's crop landscape. According to University of Minnesota researchers examining pennycress, winter canola, and winter camelina, "winter camelina provided the highest combined agroecosystem value through pollinator resources, green cover, and seed yields."[7] Their research established winter camelina:

- Can "(1) provide early forage resources for pollinators, (2) function as traditional cover crops, and (3) provide a seed yield to farmers with value as bio-oil feedstock."
- "consistently flowered in all sites and years, making it a reliable forage resource for pollinators as well as a more dependable crop for farmers. "

University of Minnesota researchers noted that "winter camelina showed the most potential as a reliable seed crop and was readily used by pollinating insects as a forage resource."[8] USDA-funded production trials in South Dakota reported that "one of the more-immediate observations…was the value of this early crop to pollinators. The camelina was in full flower by mid-May, and large numbers of honeybees were present in the crop, while almost none were found in adjacent crops".[9]

Additional studies reported that "double- or relay-cropping winter camelina (Camelina sativa L. Crantz.) with forage or food crops, can increase yield per area, improve energy balance, and provide several ecosystem services. Double-cropping can help balance food and energy production"[10] and researchers also noted that "camelina has been reported to reduce soybean cyst nematode."[11] Pilot growers also reported the crop performed well, despite challenging drought conditions.[12]

> *"In addition to its role in crop rotations, [Camelina] may be used to provide a range of ecosystem services… to promote atmospheric carbon sequestration, suppress weeds, provide erosion control, protect ground water quality, promote organic matter carbon and nitrogen accumulation in soils, and suppress the accumulation of fungal pathogens"*[13]

Integration into Existing Cropping Systems

University of Minnesota researchers noted that a "crop rotation that has shown particular promise is winter camelina, following spring wheat and preceding soy."[14] Adoption of winter camelina rotations with wheat could provide ecological benefits to producers. Wheat production benefits soil health and disrupts plant disease cycles when incorporated into corn-soybean rotations. Winter camelina may also fit particularly "well in dryland winter wheat-based cropping systems in regions where warmer summer temperatures may limit camelina production."[15]

Increased global wheat production has negatively impacted Minnesota wheat producers' profitability and led to a reduction in acres planted in the state. Integrating winter camelina production into the crop rotation can increase profitability when viewed as part of a larger cropping system. Further economic analysis is necessary to quantify this opportunity.

Market Opportunities

Animal Nutrition – Food Producing Animals

The AURI commercialization staff met with academic and industry-affiliated swine, poultry, and beef nutritionists to gather expert feedback on the potential for camelina meal and oil as a feedstuff. The team also met with an egg producer to identify key factors in adding a new ingredient to laying hen diets. Based on information gathered through this engagement with key stakeholders, animal nutrition appears to be the quickest path to market as either an ingredient for food-producing animal diets and/or as a supplement for non-food producing animals such as horses and companion animals.

Use of winter camelina in rations is dependent on several factors including, but not limited to, nutrient content (e.g., fat, protein, minerals, etc.), availability, price, fit with ration, and desired end-product characteristics.

According to a 2016 Western Poultry Conference presentation, camelina offers an alternative to canola, sunflower, flax, and soybean in livestock, poultry, equine, and aquaculture diets.[16],[17]

Factors Food Animal Customers Consider

Livestock and poultry producers' top priority is raising healthy animals from both an economic and market perspective. One key to animal health is access to high quality, consistently available feedstuffs at a reasonable price. Livestock and poultry producers are interested in additional feed ingredients that are safe for animals, available, and accessible. To successfully commercialize winter camelina for animal nutrition markets, these concerns must be adequately addressed.

Safety

Several regulatory hurdles must be cleared before nutritionists and livestock and poultry producers will consider incorporating winter camelina meal and oil into rations beyond current allowable levels. More work will be needed to address regulatory requirements for uses at higher inclusion rates and if new varietals of winter camelina offer different nutritional profiles. Camelina-based products have received approval for use in some product classifications, and work is ongoing to develop data to support use in other products and at other inclusion rates. A few examples follow:

- 2021 AAFCO guidelines state that "camelina meal, extracted," may be "used in in the diets of broiler chickens, cattle fed in confinement for slaughter, and laying hen chickens as an inclusion of no more than 10% of the diet."[18]
- Camelina has approval from feed regulatory agencies in both the United States and Canada for inclusion in layer diets at 10% and in broiler diets at 10% in the United States and 12% in Canada. Camelina has also received FDA approval for a 2% inclusion rate in swine diets.[19]

- In Canada, "mechanically extracted camelina oil has… been approved for use in feeds for juvenile salmonid fish in an amount not to exceed 13% of the total diet."[20],[21], [22]
- Canadian researchers have conducted dairy research,[23] and more studies are reportedly underway or in planning.

Availability

A consistent supply and verified quality of winter camelina meal is crucial for the animal nutrition market. Successful incorporation of camelina as a feed source is dependent on availability. Market adoption will also rely on participation by key partners in the animal nutrition supply chain. These will include feed processors, nutritionists, and logistics providers. Established feed crops already have supply chains with production capacity and expert knowledge available to connect new products to farmers. Winter camelina lacks these established supply chains, and development of these ties and product awareness will be needed to provide interested livestock producers with a reliable, predictable supply of winter camelina-based products.

Market Access

- Research is necessary to develop more information about the characteristics of specific winter camelina varietals to determine the best utilization options for food-producing animal nutrition products.
- Selling camelina as a supplement may provide accelerated access to some markets because it can require fewer regulatory approvals.
    - Equine and companion animals are two market examples where camelina-based products are currently sold as a high-value dietary supplement by Canadian-based company Smart Earth Camelina.

Niche Markets

- Current available winter camelina varieties fit non-GMO status.
- A herbicide-tolerant camelina variety launched in 2021 was intentionally developed "with traditional mutagenesis and plant-breeding techniques"[24] to maintain non-GMO status.

Animal Nutrition Market Segments

To assess specific animal nutrition market segment opportunities, AURI and its research partners hosted multiple meetings and discussions with key stakeholders and nutritionists. AURI reviewed existing publications and research for additional context. During this process, the team gathered information on the opportunities and barriers facing winter camelina market development in several different sectors.

Swine

Nutritionists recommended looking at younger pigs as the initial potential market for winter camelina in the swine sector. Recommended swine diet inclusion is 10% or less because of winter camelina's anti-nutritional attributes.

- "In summary, it appears that camelina meal can be a replacement for soybean meal in diets for growing-finishing pigs when used at levels of 10% or less. Farmers need to evaluate the economics of using camelina meal in swine diets, as well as the anti-nutritional content of camelina meal and balance this against the other value considerations realized by planting winter camelina over the long term".[25]

Poultry

Winter camelina holds potential as a feed source for the poultry industry, in both meal and whole seed form. Researchers noted that the fatty acid profile of winter camelina was a potential positive attribute for use in the industry.

- The layer hen (table eggs) market segment is looking for high omega 3 & 6 eggs and camelina offers 8-fold increase in omega 3 & 6 in eggs.[26]
- Camelina is preferred over fish oil because it does not result in a "fishy" taste.
- It may provide a more "sustainable" source of feed compared to fish oil.
- U.S. regulators allow camelina inclusion up to 10% in layer diets and broiler diets.

Aquaculture Market

Aquaculture represents a strong potential market for winter camelina. The industry is growing, creating increased demand for feed products.

- Aquaculture has seen a compound annual growth rate of 6% over two decades. The industry is not only aware of camelina oil, but also favors its utilization.
- Camelina is making considerable inroads in Canadian aquaculture markets.
- Opportunities may exist to explore new feed markets such as juvenile salmon and trout.
- Camelina oil is currently used to replace fish oil in salmon feed.[27]
- In October 2023, Yield10 Bioscience announced a new partnership with BioMar Group, a Denmark-based global aquafeed producer, to develop and commercialize camelina "engineered to produce omega-3 oil for use as a high-quality supplement" for use in aquafeed products.[28]

Beef Cattle

Discussions with animal nutritionists highlighted a couple potential uses and market product comparisons for its use in cattle feed rations.

- Range Cubes: nutrient packages fed to cattle on pasture. While a low value market, winter camelina fits the desired range cube nutritional profile.
- Dried distillers grains may be a comparable market segment for meal in cattle uses based on nutrient analysis.

Dairy

While limited research exists regarding winter camelina use in dairy rations, much of the existing work appears to focus on the use of spring varietals. More research is necessary to assess the use of winter camelina feeds, assess its impacts on milk production, and assure food safety.[29]

Animal Nutrition – Non-Food Producing Animals

Supplements to non-food producing animals are not regulated by the FDA, thereby providing fewer barriers to access the equine and companion animal markets. This segment may provide market opportunities for winter camelina-based products while the industry addresses regulatory approvals in other animal nutrition markets.

Equine

The equine nutrient supplement market may provide quicker market access due to less stringent regulatory requirements associated with nutritional products for non-food producing animals. As of 2021, Canadian-based Smart Earth Camelina held a notable market share selling camelina oil as an equine supplement.

- Smart Earth Camelina reports that it plans to do further studies on the use of camelina-based ingredients in nutritional products for companion animals.
- Winter camelina's omega 3 & 6 levels are attractive attributes for horse owners seeking nutritional benefits for their animals.

Companion Animals/Pets

The companion animal supplement market segment offers a great opportunity in both the United States and Canada, in part due to fewer regulatory barriers. Pet and companion animal owners may be willing to pay a premium for preferred pet foods.

- Camelina-based products are under development for the canine market.
- These markets do not need regulatory approval for use as a nutritional supplement but do require regulatory approvals for use as a feed and food ingredients.

Fuel and Industrial Uses

Winter camelina holds strong potential for use as a feedstock in the production of biofuels and falls under the approved pathway by the Environmental Protection Agency for renewable fuels.[30] The high oil content of camelina seeds has drawn the attention of major, multinational energy producers, including ExxonMobil. The company announced it will purchase up to 5 million barrels per year of renewable diesel made from camelina. According to ExxonMobil, camelina "has a number of attributes that make it attractive from both an environmental and cost perspective," including a "high oil content," providing a "high oil yield from the extraction process," and allowing "camelina oil to be produced at a lower cost, which is important as the feed oil is the highest-cost component in renewable diesel production."[31]

Other research shows that camelina oil has good potential for use as a sustainable aviation fuel and "could become an economically feasible alternative to conventional jet fuel under certain market conditions."[32] In August 2023, the Greater MSP Partnership, Delta Airlines, and other government and industry partners announced the launch of the "Minnesota SAF Hub," the nation's "first large-scale SAF Hub" focused on "scaling SAF production to replace conventional jet fuel."[33] The coalition's strategy includes a focus on developing "commercially viable production of ultra-low carbon SAF from regenerative agricultural inputs,"[34] which may open new market opportunities for crops including winter camelina. According to a 2023 analysis released by a working group that included the Forever Green Partnership and Friends of the Mississippi, the use of winter camelina and other winter oilseeds as a "drop-in replacement for conventional jet fuel" may represent a "significant market opportunity," providing a pathway to SAF production that "can be expanded beyond the limitations of traditional summer oilseed crops."[35]

Biofuels

Made from an increasingly diverse mix of resources such as recycled cooking oil, soybean oil, and animal fats, biodiesel and renewable diesel are renewable replacements used in existing diesel engines without modification. They are the nation's first domestically produced, commercially available advanced biofuels. Oliver Peoples, CEO of Yield 10 Bioscience, notes that "with the U.S. Energy Information Agency projecting renewable diesel production capacity could reach 5 billion gallons by 2024, and existing feedstock only capable of providing about 1 billion gallons, "we've got to find another 4 billion gallons of feedstock." Peoples believes camelina can help fill that gap while also offering additional revenue for the grower.[36]

According to the Clean Fuels Alliance America, an industry association for biofuels producers, the classes and technical definition of biodiesel include the following[37]:

- Biodiesel - a fuel comprised of mono-alkyl esters of long chain fatty acids derived from vegetable oils or animal fats, designated B100, and meeting the requirements of ASTM D 6751.
- Biodiesel Blend - a blend of biodiesel fuel meeting ASTM D 6751 with petroleum-based diesel fuel, designated BXX, where XX represents the volume percentage of biodiesel fuel in the blend.

Creation of fuels in these classifications are derived "through a chemical process called transesterification, whereby the glycerin is separated from the fat or vegetable oil. The process produces methyl esters. Methyl esters is the chemical name for biodiesel." Its coproduct, glycerin, can be used to create a variety of products, including soap.[38]

Stamenković et al., (2021) investigated camelina biodiesel properties for use as a B100 and identified areas that meet and do not meet qualifications. For commercial use as fuel in diesel engines, winter camelina biodiesel must satisfy the biodiesel standards like ASTM D6751 or EN 14214 (Table 4). In order to meet industry standards, winter camelina-based biodiesel will likely need to be used in blends (e.g., BXX). According to Stamenković, et al.:

> *"Generally, many properties of camelina biodiesel meet the biodiesel quality standards, with exceptions of iodine value, linolenic acid and polyunsaturated methyl ester, viscosity, cetane number, and cold filter plugging point.*
>
> *Iodine value measures the unsaturation degree of biodiesel and influences its stability during storage and use. As a rule, the iodine value of all camelina biodiesel exceeds the limited value of the EN14214 standard (120 g I2/g) due to a large content of polyunsaturated fatty acid esters and ranges from 142 to 166.2. Exceptionally, it was reported a significantly lower iodine value (81.7) with no explanation. Iodine value can be reduced below the standard limit by blending the camelina methyl esters with the pork lard, beef tallow, or waste frying oil esters.*

The polyunsaturated methyl esters are closely related to the camelina oil fatty acid profile. The former property of camelina biodiesel exceeds the EN14214 standard limit of 12% for almost three times and ranges between 32.7% and 38.09%.

Cetane number points out the ignition delay of a fuel after its injection into the combustion cylinder. Significantly lower cetane numbers than the limit of both standards has been reported for camelina biodiesels. In most of the studies, the cetane number of camelina biodiesel satisfies or is close (up to 6% less) to the standard limit due to the fatty acid composition and high unsaturation degree of the used camelina oil.

The kinematic viscosity is of importance for the fuel atomization and combustion in the diesel engine. Camelina biodiesel, generally, fulfills the standard requirements regarding the kinematic viscosity. A higher viscosity is observed for the camelina methyl-butyl and ethyl-butyl ester mixtures, which increases with increasing the butanol proportion in the alcoholic mixture during the esters' synthesis. The increase in the butyl esters amount leads to a higher content of the esters with twenty or more carbons that contributes to a higher kinematic viscosity.

The most important parameter for evaluating the fuel flow operability at low temperatures is the cold filter plugging point, the lowest temperature at which fuel begins to gush through a standard filter. Camelina biodiesel does not satisfy the EN14214 standard specification. Its cold flow operability can be improved by blending it with fossil diesel. A decrease in the biodiesel proportion in the biodiesel/diesel blend from 80% to 20% reduces the cold filter plugging point from −7°C to −13°C. The cold filter plugging point of camelina biodiesel decreases more than twice in the B5 and B10 blends. Another method for reducing the cold filter plugging point of camelina biodiesel is to use suitable additives like CP7134 and Lubrizol (Fröhlich and Rice, 2005). The cold filter plugging point of a camelina and used frying oil esters mixture was reduced below the standard limit by the addition of Wintron XC-30 or Infineum R-442 depressant. Oxidation stability or oil stability index (OSI) of a biodiesel is measure of its degradation by atmospheric oxygen. Oxidation causes the formation of corrosive acids and polymers that block jets and impede the normal engine operation. The oxidation stability of "pure" camelina biodiesel (0.6–2.9h) is below the standard limit because of its high unsaturation degree and high linolenic acid ester content, with an exception where the oxidation stability is 12.36 h. The camelina biodiesel stability can be improved by its blending with the methyl esters obtained from other feedstocks or by adding antioxidants." [39]

Table 4: Biodiesel standards in Europe and United States compared to petroleum diesel. Modified from https://www.biofuelsystems.com/specification.htm

Biodiesel Standards	Units	Europe	USA	Petroleum Diesel
Specfication		EN 14214:2003	ASTM D 6751-07b	EN 590:1999
Applies to		FAME	FAAE	Diesel
Density 15°C	g/cm³	0.86-0.90		0.82-0.845
Viscosity 40°C	mm²/s	3.5-5.0	1.9-6.0	2.0-4.5
Distillation	% @ °C		90%, 360°C	85%,350°C - 95%, 360°C
Flashpoint (Fp)	°C	120 min	93 min	55 min
CFPP	°C	* country specific		* country specific
Cloud point	°C		* report	
Sulphur	mg/kg	10 max	15 max	350 max
CCR 100%	%mass		0.05 max	
Carbon residue (10%dist.residue)	%mass	0.3 max		0.3 max
Sulphated ash	%mass	0.02 max	0.02 max	
Oxid ash	%mass			0.1 max
Water	mg/kg	500 max	500 max	200 max
Total contamination	mg/kg	24 max		24 max
Cu corrosion max	3h/50°C	1	3	1
Oxidation stability	hrs;110°C	6 hours min	3 hours min	N/A (25 g/m3)
Cetane number		51 min	47 min	51 min
Acid value	mgKOH /g	0.5 max	0.5 max	
Methanol	%mass	0.20 max	0.2 max or Fp <130°C	
Ester content	%mass	96.5 min		
Monoglyceride	%mass	0.8 max		
Diglyceride	%mass	0.2 max		
Triglyceride	%mass	0.2 max		
Free glycerol	%mass	0.02 max	0.02 max	
Total glycerol	%mass	0.25 max	0.24 max	
Iodine value		120 max		
Linolenic acid ME	%mass	12 max		
C(x:4) & greater unsaturated esters	%mass	1 max		
Phosphorus	mg/kg	10 max	10 max	
Alkalinity	mg/kg			
Gp I metals (Na,K)	mg/kg	5 max	5 max	
GpII metals (Ca,Mg)	mg/kg	5 max	5 max	
PAHs	%mass			11 max
Lubricity / wear	µm at 60°C			460 max

Life cycle analysis showed that camelina-based jet fuel and biodiesels reduce carbon emissions by 75% and 80%, respectively, compared to petroleum products.[40] However, due to the high amounts of n-3-fatty acids in camelina oil, biodiesel prepared from camelina oil exhibited poor oxidative stability and showed the highest potential to form coke (solid carbonaceous materials) during combustion.[41,42] The sustainable aviation fuel shows lower greenhouse gas emissions that benefit airlines working to reduce their carbon footprint. In addition to its potential uses in biofuels, winter camelina oil may also be suitable for use in a wide variety of biobased products.

Bioplastics – Converting Oil into Plastics

A major source of bioplastic, polylactic acid (PLA), is made by fermenting starch and sugars from crops such as corn, beets, and/or sugar cane that can be reconfigured as PLA and used in a wide variety of products. Yield10 Bioscience is working to create polyhydroxyalkanoates (PHA) that are both marine and soil biodegradable. Yield10 developed a camelina variety featuring an extractable polymer inside the seed. This product could help continue the shift toward more biodegradable plastics in the near future.[43] Additionally, "The high amounts of unsaturated fatty acids (about 90%) make camelina oil fast drying which can be used for making polymers, varnishes, paints, cosmetics, and dermatological products."[44]

Biobased Products

Finding outlets for winter camelina in the bioproducts industry could present a high value opportunity. Researchers have noted that "using oilseed derived oils to produce polymers is far more profitable… than when used as feed meal," and that "the ability to make use of camelina by-products for bio-products after oil extraction would be a major breakthrough" in market development.[45] Regulatory and technical limitations on winter camelina inclusion rates in food and feed products may necessitate development of other market outlets for byproduct produced during bioenergy production. Besides bioplastics, winter camelina's bioindustrial applications could include soaps, cosmetics, lubricants, paints, and biofilms.[46]

Human Food Products

Camelina oil may have human health benefits when consumed. Researchers identified "camelina sativa-derived oil" as a potentially "good source of alpha-linolenic acid" and examined the oil's potential impact on low-density lipoprotein (LDL) cholesterol concentrations. According to one study, LDL cholesterol concentrations in human subjects "decreased significantly by 12.2% in the camelina oil group, 5.4% in the rapeseed oil group, and 7.7% in the olive oil group" and noted that "[c]amelina oil's serum cholesterol-lowering effect was comparable to that of rapeseed and olive oils."[47] In addition to potential health benefits, camelina oil has a high smoke point[48] making it desirable for cooking and has high Vitamin E levels providing additional antioxidant benefits.[49]

Winter Camelina Production-Farm Operations

As a cash cover crop, winter camelina production may offer multiple attractive characteristics for Minnesota's crop farmers. These include:

- Potential for increased land productivity

- Potential for additional revenue
    - University of Minnesota research projects winter camelina relay rotations could "add an additional $40 net revenue per acre for growers."[50]
- Ability to integrate into existing rotations, including soybeans and small grains
- Ecosystem benefits

Unlocking the crop's market potential will be based on consistent winter camelina meal and oil production. Consistent production is based, in part, on reliable winter camelina seed availability. University of Minnesota breeders and other partners are developing strategies to ramp up seed production to match growth in market demand and allow for scaling of production. Additional factors and activities associated with increased production that were identified while preparing this report include the following:

- Nutrien is working with growers in Minnesota and two other states on field scale production and looking to expand.
- Smart Earth Camelina is interested in expanding into the U.S. market. It currently contracts with growers on both sides of the border - Montana and Saskatchewan for spring camelina production. Given the potential scale of the market, Smart Earth feels there is enough opportunity for expansion and noted that all things being equal, it would be beneficial for product grown in the United States to be processed in the U.S., and product grown in Canada to be processed in Canada. Smart Earth is interested in contracting with Minnesota based growers.
- There is a need to grow production and processing infrastructure capacity in tandem with growth in market demand.
- Yield10 Bioscience is working with Minnesota and North Dakota farmers to increase acreage by taking on risk, in the absence of crop insurance, by providing seed, covering logistics, and ensuring payment regardless of yield.[51] Yield10 is also executing a program to develop and commercialize winter camelina with stacked herbicide tolerance traits to scale adoption in North America.[52]
- The University of Minnesota Forever Green Initiative Environmental and Economic Clusters of Opportunity (EECO) Implementation Program includes four crops, winter camelina among them. The EECO provides technical assistance to growers, ecosystem payments ranging from $20-$50 per acre, and covers risk at half the cost of production in the event of a crop or market failure.[53]
- Cargill conducted a 2023 pilot achieving 2,000+ acres across Minnesota and North Dakota.[54]
- Minnesota wheat production is contracting due to competition from row crops, specifically corn. Winter camelina may offer a new way to support Minnesota's wheat farmers and enhance overall farm profitability.
- A USDA-ARS study published in January 2021 reported positive environmental effects from winter oilseed relay cropping systems, while also noting that the economics of such systems still present challenges.
    - *"On an area per year basis, when winter oilseed cover crops were used in the cropping system and not given any nitrogen fertilizer, the system had lower water pollution potential and soil erosion, and lower global warming potential (GWP) than a business-as-usual corn-soybean rotation. However, on an economic basis, camelina and pennycress did not work as well in the*

inter-seeding system. The two primary reasons for this were: 1) the added costs for establishing the oilseed covers including nitrogen fertilization, and 2) relatively poor yields of both the winter oilseeds and relayed soybean associated with the inter-seeding system and methodology used. This information is valuable to researchers and agricultural extension specialists who are focused on developing better management practices for establishing cover crops in the traditional corn-soybean rotation used in the US Corn Belt."[55]

While potential yields will depend on multiple factors, Yield10 Bioscience reported "expected average dry land yields around 1400 lbs/ac" for their contracted producers growing camelina as a winter crop.[56] Research from the University of Minnesota and USDA-ARS released in 2023 reported that yields of 1000 pounds per acre could be expected when relay and double cropping with soybeans.[57] Other research in the upper Midwest has reported "consistent yields of 1000 – 1,150 lbs/acre" with "yields as high as 1,900 lbs/acre" being observed in some relay-cropping systems.[58]

Processing

Like seed availability for growers, processors need consistent winter camelina supply to economically justify incorporating camelina into their processing and product lines. "The capture of maximum value is only achievable for an oilseed processor when established market channels exist for sale of both oil and meal for a given production run."[59] Processor business decisions will be based on access to consistent and profitable outlets for winter camelina oil and meal.

Potential end users have shown interest in winter camelina and may be key players in the development of processing capacity in Minnesota. For example, the MBOLD initiative is prioritizing winter camelina as a priority crop in its soil health and water quality initiative. As part of this focus, MBOLD member companies are testing winter camelina for use in products. This market exploration may open new opportunities for local processors to provide meal, oil, and other winter camelina-based ingredients to meet emerging demand. However, development of new opportunities will take time and support. According to Forever Green Initiative staff, 18 months is the typical timeline for scale up and product inclusion, highlighting the need for continued collaboration with key commercialization stakeholders to provide support and assistance as these initial market opportunities are pursued.[60]

Barriers to Adoption

Several notable barriers to winter camelina adoption were identified during discussions with key stakeholders.

Farm and Production Barriers

Risk to Winter Camelina Producers

One significant factor to successful production is the ability to reduce risk to farmers who are "early adopters" of the crop. This will be particularly true over the next few years as production ramps up to meet growing demand. Until production and processing reach enough equilibrium to be economically sustainable, production of winter camelina will carry higher risk than that faced by producers who choose to grow more established crops. Strategies need to be developed to provide assurance to growers who take part in the early stages of commercialization. The University of Minnesota Forever Green Initiative has partnered with MBOLD and other industry partners to support pilot production and de-risk production for producers in an attempt to address some of these issues.[61] While this will be helpful in reducing risk to early producers, development of permanent risk management tools will be a priority to support a larger scale of production.

- USDA Risk Management Agency (RMA) involvement is necessary to have winter camelina listed as an insurable crop. While the RMA updated its camelina pilot crop insurance policies in November 2021, only "spring-planted camelina grown under contract with a processor is eligible for coverage."[62]
- To meet the scale needed to support processor demand, those seeking to commercialize winter camelina will need to secure enough producers and acres. Similarly, a concern to crop farmers is having a reliable and profitable market for the crop. Growing in a balanced, sustainable way that addresses producer concerns while meeting demand levels that remain fluid will be an ongoing challenge in the early stages of commercialization.
- Outside support may be key to ease the process. Stakeholders interviewed by AURI reported that Agriculture Canada has been a great partner in camelina development efforts, launching multiple projects and providing a potential model for expanded efforts in the United States.
    - Support could be focused on multiple areas including agronomic and technical support to producers and support for equipment upgrades.

Yield Drag

According to University of Minnesota Forever Green Initiative research, "…the relay system of camelina + soybean can produce around 130 gallons of oil per acre, compared to about 60 gallons/acre for a sole full-season soybean crop."[63] There is a yield loss for soybean per acre, however, which may be of concern to some producers. While early research by the University of Minnesota "observed a yield drag of up to 30% on soybeans," more recent work has shown that "yield drag of 10% or less may be feasible with improving germplasm and agronomic best management."[64] In a 2022 assessment of winter camelina farmgate economics, the University of Minnesota noted that a 15% yield drag represented a "reasonable near-term" scenario for soybeans in winter camelina relay-cropping systems.[65]

Seed Supply

Seed supply and availability is important to allow consistent production of winter camelina. Progress has been made on this front over the past two years, as the Forever Green Initiative developed and strengthened partnerships with seed companies, such as Millborn Seeds based in Brookings, SD and Albert Lea Seed based in Albert Lea, MN to expand access and availability. In the near term, however, seed supply may continue to be a limiting factor in the ability to rapidly scale up production.

Processing

A 2020 study conducted by University of Minnesota Extension Regional Sustainable Development Partnerships (RSDP) researchers, and supported by AURI, found limited interest in winter camelina among small-scale oil processors. According to the study, "risks associated with capital investment purchases for processing equipment were too high to warrant expenditures until supply chains and market channels were more developed."[66] As a result, midscale and large processors will likely be the point of entry for winter camelina processing in Minnesota and surrounding states. This, however, will require more significant production to meet the volumes needed.

- Smart Earth Camelina notes that one major hurdle to expansion in the United States is finding the right partner for crush operations.
- Processors may see limited practicality in adoption of winter camelina if limited to the current low inclusion rates in feed products.
- The Ag Innovation Campus (AIC) in Crookston, MN opened in 2023 and aims to develop process techniques suited to winter annuals. This is a 240 MT/day cold-press crush facility.
- Cargill has conducted some initial crushing at its West Fargo, ND oilseed processing facility.

Market Barriers

Food

While an application for the Food and Drug Administration's GRAS status for "refined camelina oil" was submitted in 2016, and the FDA responded that "the agency has no questions at this time regarding [the] conclusion that camelina oil is GRAS under the intended conditions of use,"[67] the supporting data focused on products made using oil from spring camelina. As a result, this GRAS application may be of limited utility for products made from winter camelina oil, and for food products other than refined oil.

One processing/marketing company reported that it currently considers inclusion of winter camelina in food a niche market due to large barriers to entry. With whole aisles dedicated to olive, canola, soy, and so forth, bringing a new oil product to market is expected to be a challenge.[68]

Winter camelina's oil profile may provide a more limited shelf life than other comparable oils. Emerging varietals may produce more stable fatty acid profiles, but for now, the relatively low oxidative stability of winter camelina oil is a potential hurdle to its adoption by food processors.

Functionalization of practical, effective means of protein extraction will need to be developed to allow winter camelina to provide useful, viable ingredients for the booming plant protein market. The University of Minnesota's Plant Protein Innovation Center (PPIC) is working to optimize extraction and functionalization, which holds potential to transform winter camelina protein into a viable plant protein ingredient for the marketplace.

Animal Nutrition

Winter camelina seed, oil, and meal all offer potential utility for use in animal nutrition products. Potential barriers to market development do exist, however.

- Low inclusion rates present a disincentive for feed mills to use in rations. FDA restrictions on inclusion in poultry and cattle diets is ~10%.

- Anti-nutritional characteristics of existing varieties may limit inclusion rates.
- Livestock producers consider several factors when considering changes to their nutritional programs: cost, availability, digestibility, nutrient density, and safety.
- Price:
    - If viewed as a commodity, nutritionists compare winter camelina against other established ingredients (soybean, canola, sunflower) and price becomes more important in the purchasing decision.
    - Winter camelina competes more favorably when ecological attributes are desired by the purchaser and/or end market.
- Glucosinolates limit feed consumption and inhibit growth performance, and the breakdown of glucosinolates can affect gut microflora.[69,70]
    - Continued varietal research is necessary to reduce glucosinolates and other anti-nutritive traits.
- Finding industry partners willing to commit to a lengthy commercialization window to build the market will be key to successful market development.
- Continued feed trials are needed to prove its use and effectiveness in diets.

Next Steps

As commercialization efforts move forward, there will be a need for continued partnership building and collaboration to develop new uses and build sustainable supply chains for winter camelina. Some areas of focus for collaboration may include the following:

Product Safety

- Securing funding and conducting research to gather data to establish Generally Regarded As Safe (GRAS) status for key use classes, which assures product safety to the end user.
- Support ongoing research and data collection needed to support new and expanded AAFCO certifications for winter camelina-based animal nutrition products.

Production-Farm Operations

Ecosystem Economics

- Establishing reliable ecosystem benefit payments to enhance the return on investment to crop farmers.
- Determine crop enterprise profitability for crop farmers integrating winter camelina into various cropping systems.
    - e.g., look at 3–4-year profitability/soil health to add winter camelina into rotation
    - Quantify potential longer-term financial benefits to crop farmers integrating winter camelina into various crop rotations
- Assess winter camelina's Life Cycle Assessment to animal protein buyers to meet the needs of customers demanding lower carbon intensity inputs and associated premiums.
- Determine market premium or value consumers would be willing to pay for products associated with ecosystem benefits provided by winter camelina.

Farm Operation Economics:

- Conduct economic analyses for producer return on investment (per acre)
    - Quantify the oil yield/acre or meal yield/acre as crop genetics and agronomic practices are improved
    - How does it compare to current practices - planting only an acre of soybeans or other crops?
- Explore specialty markets. Look at enhanced quality characteristics of camelina such as digestible amino acids and value-add markets for these characteristics.

Seed Availability

- Develop seed sources for interested producers.
    - Millborn Seeds (Brookings, SD) and Albert Lea Seedhouse (Albert Lea, MN) are now retailers for winter camelina seed and may offer a good foundation for future market development.
    - Programs through Yield10 Bioscience, Cargill and the University of Minnesota Forever Green Initiative (FGI) EECO Implementation Program are providing seed at reduced or no cost to enable larger-acreage production.

Production Volume

- Establish more data on yields to provide interested producers with useful guidance.
- Identify, assist, and educate potential growers.
    - The FGI EECO Implementation Program identifies and provides technical assistance to support growers.

Risk Management

- Address risk management issues for growers, especially early adopters. Winter camelina presents a developing market with immature processing, distribution, and market infrastructure. FGI is working with the Minnesota Department of Agriculture and other partners on pilot programs.
- Work to obtain recognition of winter camelina as an eligible crop through USDA Risk Management Agency (RMA) insurance programs.

Markets

- Identify and support development of highest value markets such as:
    - Renewable Fuels
    - Animal Nutrition
    - Biobased Products
    - Food Ingredients

Areas for Additional Research

- Further Animal Nutrition Research
    - Study digestibility and performance compared to other oilseed meals
    - Conduct feed trials for empirical data to show potential end uses
    - Explore what other co-product(s) can be bundled with winter camelina
    - Identify opportunities for feed mills to include winter camelina at higher inclusion levels

    - Limited research exists for dairy and beef nutrition, and more may be useful to assess safe inclusion rates
    - Study the glucosinolates throughout the feeding system
    - Assess ways to reduce glucosinolates (and balance desired traits, e.g., Omega 3 & 6 availability)
    - Study polyunsaturated oil content due to its impact on shelf-life and potential for oxidation. Higher oil oxidation may create barriers for some market sectors, particularly food, animal nutrition, and biodiesel. Renewable diesel and sustainable aviation fuel may provide less challenging commercialization pathways.
    - Consider aquaculture trials which are less expensive than other feed trials. Work was done in Canada with spring camelina, but more research will need to be done to establish use in the U.S. market.[71]
        - According to Canadian researchers, salmon producers spend up to 70% of their budgets on fish feed and are in search of more ecologically and economically sustainable alternatives to wild-sourced feeds. Canadian aquaculture researchers feel that camelina could provide a viable alternative because the "oil is high-quality," for aquaculture uses, and "can be purchased at a lower price, which will provide cost savings and produce a high-quality fish."[72]
- Identify specialty markets
    - While winter camelina competes well with the nutrient profile of more common commodity feedstuffs (soybeans, canola, and sunflowers) it may have other ecological benefits that have market value.
- Find strategic industry partners to develop commercial market outlets for winter camelina products.

Summary: Pathways to Commercialization

In examining potential commercialization options for winter camelina, AURI and its project partners identified several market opportunities for the crop. These include biofuels, animal nutrition and supplements, bio-industrial applications, and to a more limited extent, human food and nutritional products.

Currently, the primary commercialization opportunity for winter camelina appears to be as a feedstock in the biofuels industry- particularly for use in renewable diesel and sustainable aviation fuels. Policy and regulatory developments at the federal and state level are likely to expand demand for plant-based oils to develop new, lower-carbon fuels. With its potential ecosystem benefits, winter camelina holds potential to meet the rapidly emerging demand for lipids used in renewable hydrocarbon fuel production.

Markets for oil will require development of associated opportunities for winter camelina in the animal nutrition sector. Meal remaining after oil extraction contains protein that will provide utility for animal feed and nutritional products. Identification and development of key sectors of the market where winter camelina's profile fits industry needs will be vital to successful commercialization. While winter camelina holds potential for multiple classes of animal feed, interesting opportunities may be found in the poultry and aquaculture industries. Blending in feed rations with other plant-based proteins may also offer market opportunities for the crop. One aspect of winter camelina that will need to be addressed to allow greater use in animal nutrition is the crop's notable levels of glucosinolates that may impact taste and limit inclusion rates in feed mixes.

While winter camelina may hold some potential for human food uses, its current fatty acid profile may limit its attractiveness to this market. Development of the crop for these markets will be a long-term process, with new opportunities dependent on the release of new germplasm lines with oil and meal characteristics better suited for use in food production. Opportunities for development of winter camelina protein isolates are also worthy of continued research and development, which may offer new market opportunities in the future.

Despite this promise, barriers to successful commercialization must be addressed. Matching demand to supply will be challenging as the crop continues its path to wider, farm-scale production. Continued development of agronomic practices will also be key to providing producers with the tools needed to grow the crop with minimal impact on their current rotational practices. Regulatory issues for human and animal nutrition will also remain an ongoing point of focus to ensure the crop can enter promising markets.

While the winter camelina market is still nascent, the spring camelina market is global, potentially easing barriers of entry for winter camelina into the marketplace. AURI's goal is to highlight opportunities to strengthen the value-chain, identify market opportunities, and highlight and address gaps in the value-chain. Using input gathered from key stakeholders, AURI worked to strategically support the adoption of winter camelina by engaging private businesses and demonstrating the pressing, processing, and marketing of winter camelina-based products. This work continues, guided by ongoing input from industry, academia, and beyond. Moving forward, the information developed will be leveraged to build awareness, identify and develop promising market opportunities, build partnerships, and identify a path toward economically sustainable value-chains for winter camelina in Minnesota.

Appendices

APPENDIX A

NUTRIENT ANALYSIS:
WINTER CAMELINA

Winter Camelina

Nutrient Analysis
November 2020

		Winter Camelina-Seed[1]	Soybean-Seed[2]	Winter Camelina Meal	44% Soybean Meal
Moisture	%	9.4	7.6	10.8	10.0
Dry matter	%	90.6	92.4	89.2	90.0
Crude Protein	% DM	26.0	40.6	38.2	49.9
Fat	% DM	36.4	21.8	17.6	1.5
Fiber	% DM	16.1	32.2	12.0	7.0
Ash	% DM	3.4	5.3	5.8	7.3
Calcium	% DM	0.3	0.3	0.4	0.3
Phosphorus	% DM	0.8	0.6	1.1	0.7
Potassium	% DM	1.0	1.8	1.3	2.0
Sulfur	% DM	0.6	0.3	0.9	0.4
Magnesium	% DM	0.3	0.3	0.5	0.3
Sodium	%DM	ND	0.0	ND	0.3
Iron	ppm (DM)	116.0	86.6	159.0	175.0
Manganese	ppm (DM)	25.9	32.5	39.6	35.0
Copper	ppm (DM)	7.3	17.3	8.3	24.0
Zinc	ppm (DM)	64.4	42.2	91.8	66.0
Net Energy (Lactation)	Mcal/lbs	1.3	1.4	1.0	0.9
Metabolizable Energy	Mcal/lbs	2.1	1.9	1.7	1.8
Digestible Energy	Mcal/lbs	2.4	2.1	1.9	1.7

[1] Winter Camelina data- AURI research, 2020. Funding for this project was provided by the Minnesota Environment and Natural Resources Trust Fund as recommended by the Legislative-Citizen Commission on Minnesota Resources (LCCMR).
[2] Source for Soybean seed and meal data- Format Solutions, Feed Ration Balancer; Feed Management Systems, Inc. 2008

APPENDIX B

INVITRO DIGESTIBILITY OF WINTER CAMELINA MEAL

Invitro Digestibility of Camelina Meal

LCCMR – Camelina
Project #FS033 IN
November 18, 2020

Purpose

To evaluate the potential feed value of cold-press Camelina meal, also referred to as cake. All estimates are based on an 'as-is' basis with a current moisture content of 10%.

Results:

Meal samples were produced by AURI and submitted to Dairyland Labs in Arcadia, Wisconsin for In Vitro Analysis of a 12- and 30-hour digestibility focus. 30-hour digestibility is a recommended timeline for digestibility analysis in ruminants. In Vitro digestibility analysis utilizes acids and enzymes to simulate rumen fluid for digestion estimates. Below are definitions for the acronyms to help aid in understanding meal digestibility performance.

- aNDFom (available NDF focused on organic matter) is the measurement of aNDF (available NDF) without the presence of ash (soil contaminants, mineral, etc.), aNDFom is the measurement used for this comparison.
- (undigestible NDF focused on organic matter) is the percent of total NDF that is not digested at 12 hours or 30 hours in the presence of rumen fluid.
- NDFD is the percent of NDFom fiber digested. NDFD is calculated as: total available NDFom - undigestible NDFom / total available NDFom
- Starch % is the total amount of starch available in the feedstuffs
- IVSD7-o is similar to NDFD but is the percent of starch digested based on an 8%/hr. rumen digestibility rate.

*Shell corn and alfalfa hay data obtained from Dairyland Labs, Arcadia, Wisconsin based on the median results of 600 samples and >10,000 samples respectively.

Nutrient	Basis	Camelina Meal	Shell Corn*	Alfalfa Hay*
Moisture	% As Is	9.3	14.8	11.9
Dry Matter	% As Is	90.7	85.2	88.1
aNDF	%DM	43.61	7.02	38.17
aNDFom	%DM	34.67	7.64	35.82
NDFD12	%NDFDom	53.74	Unavailable	36.23
NDFD30	%NDFDom	56.04	Unavailable	43.92
uNDFom12	%DM	16.04	Unavailable	23.05
uNDFom30	%DM	15.24	Unavailable	20.13
Starch	%DM	2.09	71.26	1.7
IVSD7-o	%Starch	64.85	48.05	Unavailable

Conclusion:

- The level of Neutral Detergent Fiber (NDF) in Camelina meal is more similar to roughage values than to an energy source such as shell corn, which contains much greater levels of starch.
- The Camelina meal had a significant reduction in available aNDFom (vs. aNDF) due to greater levels of ash or possibly contaminants.
- Camelina meal has less undigestible NDF than typical alfalfa hay.
- Camelina meal has greater NDF digestibility through the rumen than average alfalfa hay.

Disclaimer: All AURI technical results generated are for development use only.

APPENDIX C

MEAL FEED VALUE ANALYSIS

Winter Camelina and Yellow Pennycress Meal Estimated Feed Value Comparison

Agricultural Utilization Research Institute (AURI)
June 2023

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Purpose

To evaluate the potential feed value of Winter Camelina and Yellow Pennycress meals post oil extraction. Estimates are based on a standardized 10% moisture 'as-is' or 'as-fed' basis (90% dry matter).

Evaluation

A Feed Value Calculator tool (South Dakota State University Beef Extension Service) was utilized for the comparison. The feed value calculator focuses primarily on a commodities dry matter content, crude protein, total digestible nutrients, net energy for maintenance and net energy for gain. These values are then based on #2 shell corn price and *48%* soybean meal price, both primary energy and protein ingredients for most livestock and poultry diets. ***Values estimated are based on either crude protein or energy and should not be combined for a total value per ton estimate.***

Products in this comparison include Winter Camelina meal and Yellow Pennycress meals, which we cold-pressed and hexane extracted to identify value differences against solvent-extracted 48% crude protein soybean meal using 2017 NRC values. Nutrient values utilized for the comparison can be viewed in Table 1 below.

Table 1 – Ingredient Nutrient Values – Dry Matter Basis

Product	Dry Matter (%)	Crude Protein (%)	Total Digestible Nutrients (%)	Net Energy – Maint. (Mcal/kg)	Net Energy – Gain (Mcal/kg)
Winter Camelina Meal – Cold Pressed	88.7	39.9	78.8	2.16	1.43
Winter Camelina Meal – Hexane	92.8	43.5	72.4	1.67	1.12
Yellow Pennycress Meal – Cold Pressed	89.4	33.7	88.5	2.13	1.41
Yellow Pennycress Meal – Hexane	92.6	40.2	69.6	1.61	1.03
48% Soybean Meal – Solvent	89.5	53.8	81.4	2.09	2.37

Based on the nutrient values stated, below are estimated feed values at various commodity prices on an 'As-Fed' basis (Table 2).

Table 2 - Potential Feed Value Based on Protein and Energy (As-Fed basis)

	$4.00/bu. corn ($143/ton) & $320/ton 48%SBM	**$5.00/bu. corn ($179/ton) & $380/ton 48%SBM**	**$6.00/bu. corn ($214/ton) & $440/ton 48%SBM**
Product	**Value per ton based on *protein/value* per ton based on *energy***	**Value per ton based on *protein/value* per ton based on *energy***	**Value per ton based on *protein/value* per ton based on *energy***
Winter Camelina Meal – Cold Pressed	**$234 / $130 per ton**	**$278 / $163 per ton**	**$322 / $196 per ton**
Winter Camelina Meal – Hexane	**$267 / $125 per ton**	**$317 / $157 per ton**	**$366 / $188 per ton**
Yellow Pennycress Meal – Cold Pressed	**$198 / $147 per ton**	**$235 / $184 per ton**	**$273 / $220 per ton**
Yellow Pennycress Meal – Hexane	**$246 / $120 per ton**	**$292 / $150 per ton**	**$338 / $180 per ton**
48% Soybean Meal – Solvent	**$320 / $137 per ton**	**$380 / $171 per ton**	**$440 / $205 per ton**

Secondly, AURI utilized an additional feed value calculator, which also considers shell corn value as well as 48% soybean meal and 17% alfalfa hay values on a per-ton basis for price estimates. The data from this calculator provides one value per ton rather than a value based solely on crude protein or energy. Following are the results (Table 3).

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Table 3 - Potential Feed Value (As-Fed basis)

Product	$4.00/bu. corn ($143/ton) & $320/ton 48%SBM	$5.00/bu. corn ($179/ton) & $380/ton 48%SBM	$6.00/bu. corn ($214/ton) & $440/ton 48%SBM
Winter Camelina Meal – Cold Pressed	**$261 per ton**	**$310 per ton**	**$360 per ton**
Winter Camelina Meal – Hexane	**$278 per ton**	**$328 per ton**	**$380 per ton**
Yellow Pennycress Meal – Cold Pressed	**$251 per ton**	**$299 per ton**	**$349 per ton**
Yellow Pennycress Meal – Hexane	**$262 per ton**	**$309 per ton**	**$359 per ton**

Based on the above results, Winter Camelina meal, which has been solvent extracted, has a theoretical 6% premium over cold-pressed meal. Likewise, solvent extracted Yellow Pennycress meal has a 4% premium over cold-pressed meal.

Comments

- The feed value calculators used focus only on total crude protein and energy values. Calculators do not determine potential feed value based on amino acid content/profile.
- Table 2 indicates the fiscal gain observed in feed value at various commodity pricing is due to protein increases in the meal rather than the effect solvent extraction has on energy content.
- Solvent-extracted Winter Camelina meal and Yellow Pennycress meal have a 14% and 19% value discount to 48% soybean meal, respectively.
- Projected feed values provided can serve as a tool to evaluate economics associated with oil extraction of oil seed meals.
- Residual plant-based oils in meals can be a limiting factor for poultry and livestock diet inclusion levels.
- Note: Cold-pressed oilseed meals have not undergone proper heat treatment to prevent trypsin inhibitors from reducing digestive performance.

Disclaimer: *All AURI technical results generated are for development use only.*

APPENDIX D

CLEANING AND DEHULLING WINTER CAMELINA

Winter Camelina: Cleaning & Dehulling Process

Agricultural Utilization Research Institute

Dirty Camelina Grain From Combine

Test Grain for Molds, Yeasts, APC, Coliforms, Etc.

Before Entering Cleaning Facility

Size Separation of Large Dockage

Shaker Table OR Circular Sieve OR Rotary Cleaner with *2mm or 5/64" Screen*

Air Separation of Fines

Aspiration - ~1000CFM Air Draw

These 2 steps could be done in conjunction with an air screen cleaner, fanning mill or similar equipment which combine air and size separation principles

Color Sorting

Optional step to remove any further impurities not removed in previous cleaning steps. To be determined on case-by-case basis depending on end-user purity desires

Cleaned Winter Camelina

In recent years, AURI has gained a significant amount of experience in cleaning Winter Camelina.

We've learned that when compared to other crops, the seed cleans up relatively easily by using air and sizing/screening separation techniques. Thus, AURI recommends the use of either a shaker table or a rotary screener in conjunction with an aspirator to clean the seed. Alternatively, the cleaning is achievable in one step with an air screen cleaner or fanning mill. As always, a color sorter is a good idea to have on hand (but not necessary in many instances), in case of weed seeds similar in size or density to camelina, or to remove any disease affected grain.

The amount of removed dockage appears to vary significantly and depends on a number of factors, including but not limited to combine settings, growing conditions and variety. The lots received by AURI saw anywhere from 10%-30% dockage or foreign material removed through cleaning to achieve a marketable grain. This document provides recommendations on screen size, but these are subject to change with new genetics, or even crop to crop, given the current novelty of this crop. Having several replacement screens on-hand at the cleaning or processing facility is highly recommended to remain flexible between various grain lots.

The size of a Camelina seed is around 1mm (half the size of a Canola seed), and so AURI recommends the bottom screens or any bin gaps are at most 700 micron in order to avoid a significant loss of seed while processing, handling or storing. This can be accomplished by either caulking or welding any larger gaps on cleaning or storage equipment.

	Estimated Throughput	Estimated Cost (As of 2022)
Bench Air Screener	1500 lb/hr	$15,000
	3000 lb/hr	$30,000
GCS air screen cleaner	10,000 lb/hr	$42,000
	20,000 lb/hr	$66,000

APPENDIX E

DENSIFICATION STUDY

Winter Camelina and Yellow Pennycress Densification Summary

Project Summary
Projects: FS033 and FS045

November 15, 2023

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Purpose:

Identify the potential feed inclusion rate of Yellow Pennycress and Winter Camelina in a traditional 16% crude protein (targeted 0.75% lysine) swine diet. Secondly, to evaluate the effect using whole seed Yellow Pennycress and Winter Camelina has on pelleting and pellet quality if utilized in a swine nursery diet.

Feed Inclusion Calculations:

AURI utilized the *Feed Ration Balancer* ™ software from Format Solutions to develop three swine diets. The swine diets included a 'control' diet consisting of shell corn as the primary energy source and 44% soybean meal which is the major protein source for most poultry and livestock diets. The two additional diets allowed for the inclusion of Yellow Pennycress or Winter Camelina based on the energy and protein value the seeds contain.

Feed Ration Balancer ™ is a least-cost formulating ration that looks at the most efficient blend to meet nutrient parameters first, while also considering ingredient price. Parameters for the diets were:

- Crude Protein – 16%
- Lysine – 0.75%
- Digestible Energy (Mcal/lb.) – 1.5
- Metabolizable Energy (Mcal/lb.) – 1.33
- Crude Fat (ether extract) – 5.8% - 7%
- Crude Fiber – 3.0% - 6.0%

Crude fiber showed the greatest variability when utilizing Yellow Pennycress and Winter Camelina. Traditional corn and soybean meal diets are generally around 3% fiber; however, when Yellow Pennycress or Winter Camelina were incorporated into the diets, the maximum fiber limit had to be increased to 7%.

The following are the swine diets developed and utilized for the pelleting trials for demonstration purposes only.

Ingredient	Control Diet	Y. Pennycress Diet	W. Camelina Diet
Corn - #2 shell	77.6%	75.2%	75.9%
44% Soybean Meal	21.4%	18.8%	15.6%
Yellow Pennycress Seed		5.0%	
Winter Camelina Seed			7.5%
Mineral	1%	1%	1%

Milling and Pelleting Trial:

Optimum pellet production and diet uniformity of nutrients require the feed ingredients to be milled and blended before pelleting. The average particle size of feedstock must be less than 5/32” in length when producing a 5/32” diameter pellet to improve pelleting efficiency, reduce pellet die wear, and prevent poor pellet durability due to fractures and breaking of the final pellet. Swine diets were blended utilizing a ribbon mixer and then milled on a 25-horsepower, 22-inch Champion brand hammer mill rotating at 3,400 r.p.m. using a tear-drop style 3/16” diameter hole screen to achieve proper particle size.

Picture 1: AURI’s Champion Hammer Mill

Following milling, pelleting for the trial was conducted on a 60-hp California Pellet Mill. The pellet mill operates using 220V/3 phase electricity. The operating idle amperage is 16A and the maximum load amperage is 70A. Generally, it is ideal to operate at or less than 80% of full load which is 56 amps. The pellet die utilized for the trial was a 5/32” hole die with a 9:1 compression ratio (1.41” effective depth). The compression ratio is calculated by dividing the effective length of the die by the hole diameter (compression ratio = die length /hole diameter).

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AURI’s 60-hp California Pellet Mill

Control panel

Steam addition to conditioner

The initial starting moisture of all three diets evaluated were very similar, ranging from 8.3% to 8.8% moisture. Ideal pelleting moisture ranges vary based on the feedstuffs and pellet die utilized but most often is 10% to 14% moisture before entering the pellet die. High-pressure steam was utilized during the pelleting trials to obtain proper pelleting moisture and aid with improved pellet quality. Steam pressure is controlled at the pellet mill conditioner based on product throughput and temperature. Test diets showed optimum pelleting moisture based on the pelleting results. Pelleting parameters and pellet characteristics from the trials are listed in Tables 1 and 2.

Table 1 – Pelleting Results

Product	Starting Temp (F)	% Amp Load Utilized	Control Moisture (%)	Pelleting Moisture (%)	Pellet Exit Temp (F)
Swine Complete Feed - Control	75	20 Amps (31% of load)	8.3	12.9	129
Swine Complete Feed - W. Camelina	75	19 Amps (29% of load)	8.8	11.1	130
Swine Complete Feed - Y. Pennycress	75	20 Amps (31% of load)	8.7	12.0	130

Table 2 – Pellet Quality Results

Product	Final Pellet Moisture (%)	Pellet Durability (%)	Pellet Density (Lbs./cubic food)	Pellet die utilized
Swine Complete Feed - Control	10.1	87.3	40.8	5/32" X 9:1
Swine Complete Feed - W. Camelina	9.5	83.2	40.0	5/32" X 9:1
Swine Complete Feed - Y. Pennycress	9.3	80.8	40.0	5/32" X 9:1

Pellets produced had below-average to fair pellet quality and durability. Pellet durability is based on the Kansas State Pellet Durability Index score (PDI) which focuses on tumbling 500 grams of cooled pellets in a durability tumbler for 10 minutes at 50 r.p.m. Pellets are then sieved according to their starting diameter, allowing fines to pass through, and retained pellets are weighed to determine percent durability. As a guideline, good pellet durability ranges from 92% to 98% and fair pellet durability ranges from 86% to 92%.

Both diets containing the ground Yellow Pennycress and Winter Camelina seed indicated a reduced pellet durability of 4.1 to 6.5% below the standard control diet with corn and soybean meal only. This could be primarily due to the increased oil content in those diets containing ground whole seed. Generally, blends containing more than 3% to 4% fat/oil show reduced pellet durability because oil cannot be compressed and acts as a lubricating agent in the pellet die. To offset this issue, a thicker pellet die could be used to generate additional friction heat for improved gelatinization of starch in the pelleting process.

Densification through pelleting diets containing Yellow Pennycress and Winter Camelina indicated very similar bulk densities to the control diet of corn and soybean meal only.

Below is a view of the three pelleted blends side-by-side and as individual diet photos.

Oat hull pellets produced. Note the fracturing of the pellet which could be reduced with a smaller grind size and/or increased pellet die compression.

Pelleted 16% Crude Protein Feed Samples

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Swine Feed Complete – Control (Corn/Soy only)

Swine Feed Complete with Yellow Pennycress

Swine Feed Complete with Winter Camelina

Conclusion:

- Whole seed Yellow Pennycress and Winter Camelina meal can be added to standard 16% crude protein swine diets. However, due to the nutrient profile of the seed, initial indications show a limited 5% to 7.5% inclusion into the diets.
- Yellow Pennycress and Winter Camelina seeds displace some corn and soybean meal in swine diets because of the seed's high oil content, which equates to energy, along with limited protein concentration, which displaces some soybean meal.
- High oil and fiber content in the Yellow Pennycress and Winter Camelina seeds are the limiting inclusion factors compared to traditional meals.
- Pellet durability was reduced in the swine diets containing Yellow Pennycress and Winter Camelina due to the slightly elevated oil content in the blended diets.
- When pelleting diets containing Yellow Pennycress and Winter Camelina seeds, a pellet die with a compression ratio greater than 10:1 is recommended, along with limiting the final fat content in the diet to 6% or less.

APPENDIX F

SOLVENT EXTRACTION OF WINTER CAMELINA OIL (NCI)

Solvent Extraction of Winter Camelina Oil

Northern Crops Institute

As part of its process development activities, the Agricultural Utilization Research Institute (AURI) contracted with the Northern Crops Institute (NCI) at North Dakota State University in Fargo, North Dakota to perform lab testing of solvent extraction of Winter Camelina oil. These tests focused on developing data to determine the effectiveness of solvent extraction of oil from Winter Camelina seeds. Industrial processors use such processes to improve efficiency in oil extraction and meal production, making such data potentially useful for future Winter Camelina supply chain development.

As part of its mission to support value-added processing in North Dakota, South Dakota, Minnesota and Montana, NCI conducts pilot-scale oilseed extraction using equipment and processes that “approximate full-scale hexane-based extraction systems.”[i]

NCI conducted solvent extraction tests and data collection for this analysis in February 2023.

WINTER CAMELINA

PROJECT DETAILS:

Study Plan:

- AURI will provide seed and current oil content level
- Defatting Process:
    - NCI will expeller press seed at ~8% seed moisture
    - Oil and meal stored in air-tight containers in cold room
    - NCI will test residual oil level

    -Solvent extraction to produce defatted meal.
        - Full 20# sample will receive 2 washes with hexane at 57C at 40 minutes
            - Meal will be vacuum dried using 15-20 in. Hg vacuum and <65C
            - Sample pulled and tested for residual oil
        - Split sample in half with remaining 10# and process repeated with one additional hexane wash

        - Raw oil collected, desolventize oil
        - Oil purged with N2 in sealed container and stored in cooler

    - All samples stored in cooler and shipped to AURI

Figure 1. Plan of Study for Winter Camelina Solvent Extraction Trials.

AURI provided NCI with approximately 20 pounds of Winter Camelina seed for its tests. The results were as follows:

	Oil % (As Is)	Moisture Content (%)	Oil % (Dry Basis)	Cumulative Oil Extracted (% Dry Basis)
Seed Before Extraction Process	32.73	7.89	35.53	NA
Pressed Cake (After Expeller Pressing)	13.04	10.22	14.53	21.0
After Two Hexane Washes	0.76	8.43	0.83	34.7
After Three Hexane Washes	0.75	6.95	0.80	34.73

NCI Technical Notes:

- Oil tests were run on the "original seeds, after expeller pressing, 2 hexane washes and 3 hexane washes."
- NCI technical staff noted how the oil extraction with two washes worked well, and that a third wash was "definitely not necessary" given the limited amount of oil extracted from the meal between washes 2 and 3.
- Given the unexpectedly high efficiency of two washes, NCI noted that it may be worth further study to see if they are necessary for effective processing.

[i] Northern Crops Institute, Oilseed Extraction. Online at https://www.northern-crops.com/whats-new/oilseed-extraction. Accessed December 2023.

APPENDIX G

WINTER CAMELINA
SEED STORAGE STABILITY

Winter Camelina

Seed Storage Stability Trial (2020-2021)

As part of its process development and technical assessment activities, the Agricultural Utilization Research Institute (AURI) monitored camelina seed storage stability over twelve months, measuring yeast and mold on the seed and oil quality after the seed was cold-pressed. These tests focused on developing data to determine the effectiveness of storage conditions for Winter Camelina seeds, making such data potentially useful for future Winter Camelina supply chain development. The seed for these trials was obtained from test plots harvested in 2020, with the twelve-month trial conducted in the second half of 2020 and the first half of 2021.

The results of the trials indicate that the Winter Camelina initially had high mold content on the grain, but over the following 12 months, there was little to no yeast or mold found on the remaining seed. This indicates that the mold may result from seed coat and foreign material present during harvest and/or initial cleaning. Additionally, the oil in the seed over 12 months is relatively stable as peroxide values decrease over time (rather than increase), and the p-ansidine values are negligible, too, indicating oil stability in the stored seed.

Table 1. Winter Camelina seed quality for yeast and mold over 12 months.

	Month 0	Month 3	Month 6	Month 9	Month 12
Yeast (cfu/g)	1000	140	20	10	<10
Mold (cfu/g)	133000	120	30	40	<10

Table 2. Peroxide and p-ansidine values of Winter Camelina oil from cold-pressed seed.[1]

	Month 0	Month 3	Month 6	Month 9	Month 12
Peroxide (meq/kg fat)	N.D.	7.3	4.8	3.6	2.8
p-anisidine value	N.D.	N.D	N.D.	< 2	<2

[1] N.D.= Not Detected

APPENDIX H

BIODIESEL PRODUCTION FROM WINTER CAMELINA OIL (SASYA)

Report for FS045IN and FS035IN

Background

Biodiesel (methyl esters of fatty acid), an alternative diesel fuel, is made from renewable biological sources such as vegetable oils and animal fats. It is biodegradable and nontoxic, has a low emission profile and is environmentally beneficial. The conversion of vegetable oil into biodiesel is very well documented and is practiced at large scale across the globe. This report describes the conversion of oil from camelina and pennycress, as documented in the agreements FS045IN and FS035IN with AURI. First, we evaluated the alkali-catalyzed transesterification reaction of camelina seed oil and identified the conditions that resulted in the highest yield Next, we used these conditions to convert camelina oil and pennycress oil into biodiesel.

Optimization with Camelina Oil

Transesterification is an equilibrium-driven reaction. Therefore, the amount of excess methanol used and the nature of alkali and its loading are important factors that determine the reaction completion. Previous biodiesel conversions using camelina oil identified that 1% basic catalyst (KOH or NaOH), an 8-to-1 molar ratio of methanol to oil, and a reaction temperature of 50°C resulted in the highest yield[1] [1]. Using this condition as the baseline, we performed the conversion of camelina oil to biodiesel. Time samples were taken at 1 hour and 3 hours.

Baseline

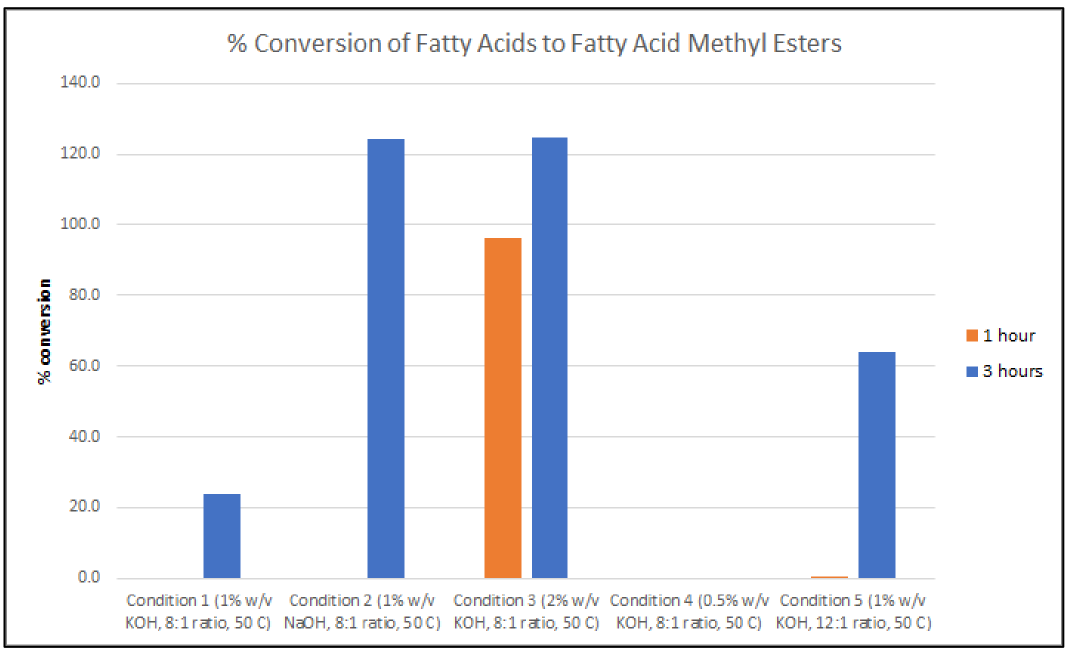
1 g of KOH was added to 30 mL of methanol in a 150 mL glass beaker and stirred until it was fully dissolved. Alkalized methanol was added to 58.87 g (70 mL) of camelina oil and stirred vigorously at 50°C for 1 hour.

A 15 mL sample of the reaction mixture was collected in a 15 mL tube and allowed to cool on ice for 10 minutes, while the reaction continued. After 10 minutes, the chilled sample was poured into a separating funnel and allowed to phase-separate for 3 to 5 hours. After the phases were separated, the biodiesel phase was collected and separated from methanol and glycerol. After 3 hours the remaining mixture was poured into a 150 mL separating funnel and the two phases separated and stored for subsequent analysis.
To evaluate the impact of the catalyst, its loading and excess methanol on the biodiesel conversion efficiency, the three parameters were varied. The conditions are summarized in the table below. All conversions were performed in the same manner as for the baseline. Samples from 1 h and 3 h from all the conditions studied were sent to AURI for analysis.

[1] Wu, X., & Leung, D. Y. C. (2011). Optimization of biodiesel production from camelina oil using orthogonal experiment. *Applied Energy*, *88*(11), 3615–3624. https://doi.org/10.1016/j.apenergy.2011.04.041

Condition	Catalyst	MeOH to Oil (mol)	Temp
Condition 1 (baseline)	1% w/v KOH	8:1	50 C
Condition 2	1% w/v NaOH	8:1	50 C
Condition 3	2% w/v KOH	8:1	50 C
Condition 4	0.5% w/v KOH	8:1	50 C
Condition 5	1% w/v KOH	12:1	50 C

The data we received listed the individual fatty acid methyl esters in the biodiesel samples as a fraction of the total mass of fatty acid methyl esters (g/100g). The analysis was performed such that only the fatty acid methyl esters in the biodiesel samples were detected, not any free unreacted fatty acids. This means that any fatty acid methyl esters detected were converted from fatty acids in the oil. The sum of all fatty acids in the oil as a mass fraction (g/100g) should equal 100. By adding up the individual fatty acid methyl esters in the biodiesel samples, this will show the percent conversion from fatty acids in the oil. The results are summarized below. (Units are % conversion from triglycerides to fatty acid methyl esters)



The theoretical maximum for conversion of triglycerides to biodiesel would be 100%. The numbers produced for the analysis were based on the use of an internal standard in each sample, the inaccurate measuring of which could lead to values over 100%. This was seen in our analysis.

However, given that the goal of the analysis is a relative comparison of the different conversion conditions, so long as the error is consistent, we can still get a reliable answer. 1% NaOH, an 8-to-1 molar ratio of methanol to oil, and a reaction temperature of 50°C for 3 hours was the set of conditions with the most effective condition conversion of triglycerides to fatty acid methyl esters. 2% KOH, an 8-to-1 molar ratio of methanol to oil, and a reaction temperature of 50°C for 3 hours was not considered because although the % yield was high, the glycerol and biodiesel phases did not separate after the reaction.

Conversion with Camelina and Pennycress Oil

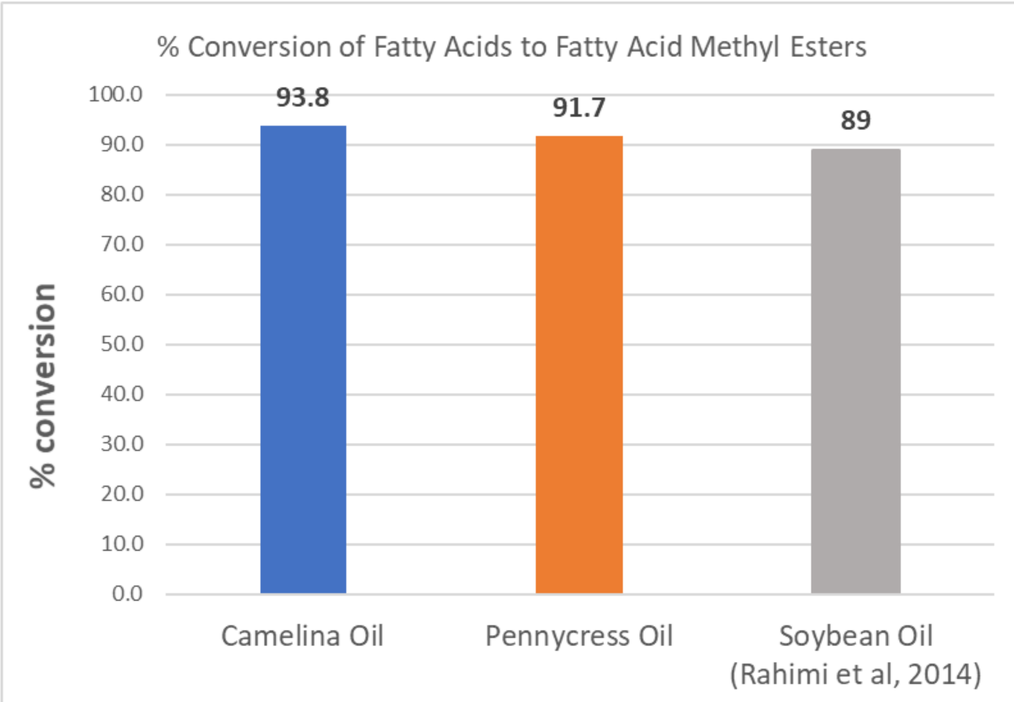
Based on the optimization data from the first set of experiments, it was determined that using NaOH instead of KOH to alkalize the methanol for the baseline condition resulted in at least three-fold increased conversion. The conversion reaction was repeated using 700 mL of camelina oil and 290 mL of pennycress oil using this condition to increase the total volume of biodiesel.

The processing of camelina oil was repeated with a goal of producing around 200-250 mL of biodiesel. 555.04g (700 mL) of camelina oil was measured into a 1 L beaker and heated to 50°C. While it was heating, 10 g of NaOH (1% of the total volume) was dissolved in 232.51g (300 mL) of methanol. After the oil reached the reaction temperature, the methanol/NaOH was added and the mixture was stirred for 3 hours. After three hours, the mixture was allowed to cool and then it was poured into a 1 L separating funnel and allowed to separate overnight. The biodiesel phase was collected and separated from the glycerol phase and sent to AURI for analysis.

The conditions found to be conducive to the transesterification of camelina oil were used with pennycress oil, without any changes.

The biodiesel and the glycerol phases were analyzed for the percent mass of fatty acid methyl esters. Using the known mass of each phase, the total mass of fatty acid methyl esters was calculated. The total mass of fatty acid methyl esters divided by the calculated mass of fatty acids in the unprocessed oil that was added to the reaction which showed the percent conversion of fatty acids to fatty acid methyl esters. The camelina oil process achieved a conversion of 93.8%, and the pennycress oil process achieved a conversion of 92.1%.
For the sake of comparison, under similarly optimized conditions, the corresponding transesterification of soybean oil was 89%[2].

[2] Masoud Rahimi, Babak Aghel, Mohammad Alitabar, Arash Sepahvand, Hamid Reza Ghasempour, Optimization of biodiesel production from soybean oil in a microreactor, Energy Conversion and Management, Volume 79, 2014, Pages 599-605



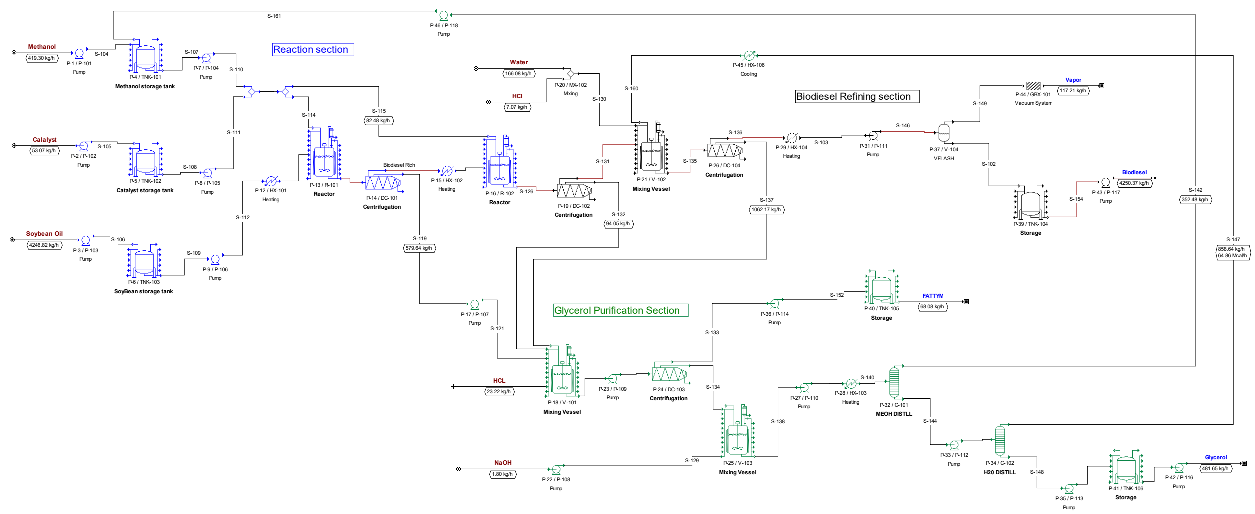
Economics of biodiesel from camelina oil

A mass/energy balanced model to produce biodiesel from cold-pressed degummed camelina oil was adapted from a baseline model for soybean oil-based conversion[3]. The paper provides a detailed description of the model.

One hundred pounds of fat or oil (such as camelina oil) are reacted with 10 pounds of a short chain alcohol in the presence of a catalyst to produce 10 pounds of glycerol and 100 pounds of biodiesel. This is a reversible reaction, the progress of which is largely determined by equilibrium. So, methanol is charged in excess to ensure quick conversion. The sections below correspond to the flow diagram below.

[3] Michael J.Haas, Andrew J. McAloon, Winnie C.Yee, Thomas A. Foglia, "A process model to estimate biodiesel production costs", Bioresource Technology 97 (2006), pages 671-678

Biodiesel Production from Camelina Oil



Reaction Section

The reaction section consists of[4]:

- The raw material storage tanks for the methanol (TNK-101), the catalyst (TNK-102) and the camelina oil (TNK-103)
- The two reactors (R-101 and R-102)
- A decanter centrifugal separator (DC-101)

At the front of the reaction section, the camelina oil is directly fed from the camelina storage tank (TNK-103) to the first reactor (R-101). In addition, methanol and the catalyst are mixed and 90% of this mixture is fed to the first reactor. The rest (10%) is fed to the second reactor. Methanol reacts with camelina oil and yields biodiesel and glycerol. Product is removed at a rate equal to the rate of charging the reactants and catalyst. The average residence time of materials in the reaction is 1 h. Glycerol, a co-product of the acylglycerol transesterification, separates from the oil phase as the reaction proceeds. The reaction extent is approximately 90%[5]. The material is then fed to a centrifugal separator (DC-101) where the biodiesel and the camelina oil that has not reacted are separated from the glycerol-rich co-product phase. The latter is sent to the glycerol recovery unit.

The biodiesel stream, which also contains unreacted methanol, camelina oil and catalyst, is fed into a second stirred tank reactor (R-102) along with the addition of the methanol-catalyst stream

[4] Smaller pieces of equipment such as pumps and heat exchangers are not included on the flowsheet, although they could be added (if desired). Note that the approximate cost of these auxiliary equipment items is already accounted for in this model due to the use of a capital cost factor related to "unlisted equipment".

[5] The conversion percentage can be increased by increasing methanol ratio, but also increases the production costs.

from the splitter (FSP-101). The reaction conditions are the same as the conditions in the first reactor. The reaction extent in the second reactor is 90%, which yields a combined conversion efficiency of 99%.

The mixture of methyl esters (biodiesel), glycerol, unreacted substrates and catalyst exiting the second reactor is then fed to a second centrifugal separator (DC-102).

Biodiesel Refining Section

This section consists of:

- Two continuous centrifugal separators (DC-102 & DC-104)
- A mixing vessel (V-102)
- A vacuum dryer system (V-104 & GBX-101)
- The Biodiesel storage tank (TNK-104)

The crude biodiesel stream is washed with acidified water at a pH of 4.5 in a mixing tank (V-102) to neutralize the catalyst and turn any soaps into free fatty acids. The material is then fed to a continuous centrifugal separator (DC-104) to separate the biodiesel from the aqueous phase, which is fed to the glycerol recovery section. The crude biodiesel product must contain a maximum of 0.1% w/w water. This is achieved by using a vacuum dryer system (V-104 & GBX-101) which lowers the water content from 2.2% to 0.1%.

Glycerol Purification Section

This section consists of:

- Two mixing vessels (V-101 & V-103)
- A centrifugal separator (DC-103)
- Two distillation columns (C-101 & C-102)
- Two storage tanks (TNK-105 & TNK-106)

Glycerol produced during trans-esterification requires purification before it can be sold. The equipment in this section is sized to remove methanol, the fatty acids, and most of the product in order to yield 80% pure glycerol which is then sold to industrial glycerol refiners at a price of $0.33/kg.

Both glycerol streams (S-119 & S-132) and fatty acid contaminants (S-137) exiting the reactors are pooled and treated with acid (HCl) in V-101 to convert soaps into free fatty acids which are subsequently removed by centrifugation (DC-103). The fatty acid stream is disposed of.
The glycerol stream is then neutralized with caustic soda (in V-103). The methanol contained in the glycerol stream is recovered by distillation (C-101) and recycled back to the first reactor (R-101). Finally, the glycerol stream is concentrated to 80% purity by another distillation step (C-

102). The distillate from this unit, which is mainly water, is recycled back to the mixing vessel (V-102).

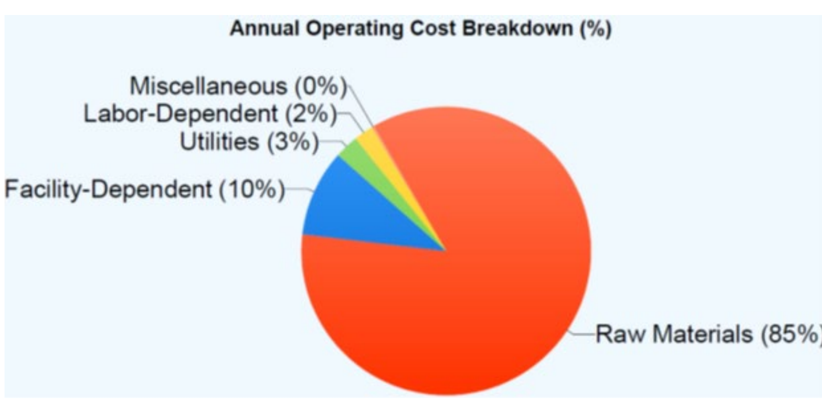
Summary of the economics

Total Capital Investment	12,377,000 $
Capital Investment Charged to This Project	12,377,000 $
Operating Cost	22,179,000 $/yr
Main Revenue	23,564,000 $/yr
Other Revenues	1,258,842 $/yr
Total Revenues	24,823,000 $/yr
Cost Basis Annual Rate	33,662,966 kg MP/yr
Unit Production Cost	0.66 $/kg MP
Unit Production Revenue	0.74 $/kg MP
Gross Margin	10.65 %
Return On Investment	31.36 %
Payback Time	3.19 years
IRR (After Taxes)	42.89 %
NPV (at 10.0% Interest)	17,315,000 $

MP = Total Flow of Stream 'Biodiesel'

Operational expenses

Cost Item	$	%
Raw Materials	18,896,000	85.20
Labor-Dependent	491,000	2.21
Facility-Dependent	2,153,000	9.71
Laboratory/QC/QA	0	0.00
Consumables	0	0.00
Waste Treatment/Disposal	0	0.00
Utilities	588,000	2.65
Transportation	0	0.00
Miscellaneous	50,000	0.23
Advertising/Selling	0	0.00
Running Royalties	0	0.00
Failed Product Disposal	0	0.00
TOTAL	22,179,000	100.00



Sugar Extraction

Acid hydrolysis was used to test the ability to extract sugars from pennycress and camelina whole seed and cake (after extracting oil). The whole seed was blended to a fine meal using a standard coffee grinder. The four materials tested were pennycress seed (blended), pennycress cake (product of oil extraction of blended seed), camelina seed (blended), and camelina cake.

For the camelina products, 1.25 g of camelina seed and camelina cake was measured out and placed in separate 100 mL bottles. For the pennycress products, 2.5 g of pennycress seed and pennycress cake was measured out and placed in separate 100 mL bottles. Less camelina materials were added to the reaction because the camelina whole seed and cake absorbed a large amount of water which led to complete absorption of the water if too much was added. Phosphate buffer (50 mM, pH 7) was added to each bottle up to a total volume of 45 mL including the solids. 5 mL of 5 M H_2SO_4 was added to each bottle. All four bottles were placed in a top loading autoclave with the caps loosened. The autoclave was set to heat to 120°C. Three time points were taken for each sample at 30, 60, and 120 minutes. At each time point, 15 mL of sample was taken from each bottle and stored at a cool temperature. Once all the time points were taken, the samples were shipped to AURI for analysis of glucose and xylose content.

Liberated Sugars as % of Starting Mass					
		Camelina		**Pennycress**	
	Rxn time	Glucose	Xylose	Glucose	Xylose
Whole Seed	30 min	ND	ND	ND	ND
	1 h	ND	ND	ND	ND
	2 h	1.53%	ND	5.18%	0.63%
Cake	30 min	ND	ND	ND	ND
	1 h	ND	ND	ND	ND
	2 h	2.68%	NA	8.61%	0.81%

More sugar was extracted from both pennycress materials than either of the camelina materials. Time was an important factor in the extraction process with most detectable sugars in each sample coming after 2 hours. Overall, the extraction method was ineffective in yielding high concentrations of sugars, either because the sugars in the materials were difficult to liberate, the materials did not contain much sugar, or the type of sugar extraction performed was not effective.

APPENDIX I

AG INNOVATION NEWS

AURI Explores Market Opportunities for Winter Annual Oilseeds

Join AURI Connects: Fields of Innovation and event sponsors Bremer Bank and the Mainstreet Businesses Focused on Food and Agriculture (MBFFA) Initiative on June 9 for "Growing and Developing Markets for Minnesota Oilseeds." You'll engage with industry stakeholders and learn more about the challenges and opportunities to meet the increased demand for renewable oil feedstocks, the shifts they represent in the marketplace and the potential utilization opportunities for these crops. You'll also have the option to tour the Ag Innovation Campus.

Free registration and agenda at: auri.swoogo.com/FOI-Oilseeds-2023.

Date: June 9, 2023

Time: 8:30 AM-1:00 P.M.

Where: Crookston, Minn. + Virtual

With the demand for low-carbon energy increasing, refiners and energy companies across the globe continue to look to biofuels as a solution for future energy production. As these markets develop and the industry looks to make continued use of existing production infrastructure, one fuel that appears set for rapid growth over the next several years is renewable diesel.

"Renewable diesel is a drop-in replacement that is chemically identical to conventional diesel," said Dr. Michael Stutelberg, an AURI scientist, chemistry who leads the organization's Analytical and Bioproducts laboratories in Marshall, Minn.

While it's made from the same feedstocks as biodiesel, Stutelberg notes that renewable diesel's chemical properties allow the energy industry to use existing infrastructure (refineries, pipelines, etc.) for renewable diesel production and distribution, and can be utilized in any application that currently employs conventional diesel, making it an attractive option for an industry that is seeking new, lower-carbon fuel options.

These qualities are set to drive a boom in the industry. Analysts at Goldman Sachs project that production capacity for renewable diesel is expected to increase by 500% by 2025. In addition to renewable diesel, biodiesel production and emerging markets for sustainable aviation fuels will also play a role in shaping the market, driving increased demand for crops and oilseeds like soybeans, canola and sunflowers.

Oilseed Boom?

While increased demand may offer new economic opportunities for Minnesota farmers and energy producers, it is also leading to concerns of feedstock shortages which could have notable impacts on markets for food, fuel, animal feeds and bioproducts that utilize seed, meal and oil from these established oilseed crops.

In an effort to identify options for addressing these opportunities and challenges, AURI is currently undertaking several projects with the University of Minnesota, Central Lakes College and other industry partners. Together, they hope to identify and develop uses for new winter oilseed crops that would be grown and harvested in addition to current crop acres, potentially providing additional options to meet the increased demand for oilseed feedstocks.

As part of these efforts, AURI is examining market opportunities for two winter annual oilseeds: pennycress and winter camelina.

The goal of this work is to "provide Minnesota's farmers with new options and opportunities to increase production from their land in a way that fits into current crop rotations," according to Alexandra Diemer, Business Development Director of Novel Supply Chains at AURI. As winter annual crops, pennycress and winter camelina offer cash cover crops that may complement production of existing crops in relay cropping rotations, opening new opportunities for producers.

While biofuel production will play a key role in developing a supply chain for winter oilseeds, market opportunities aren't limited to the energy industry. According to Diemers, biofuels are driving the market, but other interesting opportunities for new oilseed crops in non-biofuel markets also exist. Additionally, AURI and its partners are exploring uses for oilseed crops in food, animal nutrition and biobased products. If projections of increased biofuel production are realized, leading to further demand for soybeans, canola, sunflowers and other established crops, winter oilseeds may offer a new, additional option to supply chain stakeholders in multiple industries seeking a new source of oil or meal.

While the development of new market opportunities for Minnesota agriculture is a key driver for AURI's work on pennycress and winter camelina, interest in these nascent crops is also being driven by other factors. Winter oilseeds offer the potential to create positive ecosystem services, providing continuous living cover for farmland that can reduce soil erosion, lower carbon emissions, reduce nutrient runoff, enhance soil health and protect water resources.

The potential ecological benefits of these crops, coupled with their market potential, has led to wider interest from industry and driven increased funding for research and collaboration.

AURI's work on winter camelina is part of a wider project led by the Central Lakes College Ag & Energy Center in Staples, Minn. Funding for the project was provided by the Minnesota Environment and Natural Resources Trust Fund as recommended by the Legislative-Citizen Commission on Minnesota Resources (LCCMR).

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Supply chain development efforts for pennycress, meanwhile, are being pursued as part of the Integrated Pennycress Research Enabling Farm and Energy Resilience (IPREFER) project led by Western Illinois University and funded by the United States Department of Agriculture National Institute of Food and Agriculture (USDA-NIFA). AURI is part of the project's supply chain development team, working in direct collaboration with the University of Minnesota and other project partners as part of a 5-year effort to explore, assess and develop market opportunities for pennycress.

In addition to applied research, private industry partners are also part of efforts to develop market opportunities for winter oilseeds.

CoverCress, Inc. (CCI), is a St. Louis, Missouri based startup company that has converted field pennycress into CoverCress™, a new-to-market winter oilseed that creates a low-carbon source of fuel and feed. CCI is a key partner on the IPREFER project and is currently planning to make CoverCress seed more widely available to producers in 2024.

In Minnesota, MBOLD, a coalition of Minnesota-based food and agriculture business leaders and innovators, partnered with the University of Minnesota's Forever Green Initiative to explore and develop market opportunities for winter camelina and is supporting efforts to pilot the crop's production as part of a winter camelina-soybean relay-cropping system.

As these promising winter oilseed markets begin to emerge, AURI's research and market development efforts will continue, seeking to ensure that the crops are connected to technically feasible, market-driven utilization opportunities. While the environmental benefits of pennycress and winter camelina look set to play a key role in the crop's marketability, with government policies and consumer demand opening more markets for lower-carbon products, ongoing work characterizing and developing uses for the crops will be critical to developing resilient markets for winter oilseeds in Minnesota, the Upper Midwest and beyond.

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