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A regional oilseed crop partnership for a resilient global bioeconomy

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ABSTRACT

Brassica carinata or Ethiopian mustard, a non-edible oilseed brassica, is a low carbon, purpose-grown, and none-to-low indirect land-use change bioenergy feedstock for the production of drop-in Sustainable Aviation Fuel (SAF), biodiesel, renewable diesel, and a suite of value-added coproducts. Carinata oil converted to drop-in fuel using an ASTM approved Catalytic Hydrothermolysis process has already been successfully tested in commercial and military aviation. Carinata meal, the residue after oil extraction, is a high-protein feed supplement for livestock, poultry, and swine, and can also yield specialty products. The Southeast Partnership for Advanced Renewables from Carinata (SPARC) is a public-private partnership formed with a two-fold mission: (1) Removing physical, environmental, social, and economic constraints that prevent regional intensification of carinata production as a low-carbon feedstock for renewable fuel and coproducts; and (2) Demonstrating enhanced value across the entire value chain by mitigating risk to farmers and other stakeholders. The partnership's goal is to energize the US bioeconomy through sustainable agriculture and thus contribute to energy security and economic diversification. SPARC relies on a combination of cutting-edge multidisciplinary research and active industry engagement to facilitate adoption of the crop. This involves informing stakeholders along the entire supply chain, from producers to end-users, policymakers, influencers, and the public, about the opportunities and best practices related to carinata. This article provides context and background concerning carinata commercialization as a winter cash crop in the Southeast US for renewable fuels and bioproducts. The advances made to date in the areas of feedstock development, fuel and coproduct development, meal valorization, supply chain logistics, and stakeholder engagement are outlined.

Keywords: bioenergy; *Brassica carinata*; winter crop; low-carbon fuel; public-private partnership; southeast U.S. cropping systems; Sustainable Aviation Fuel

1. Introduction

Coupling sustainable agriculture with the development of a bioeconomy seems like a perfect marriage because the mandates for both are synergistic and complementary. Sustainable agricultural practices should be resource-efficient, carbon building, natural resource enhancing, all of which are foundational principles of a sustainable bioeconomy (RSB, 2018). However, with increasing demand for bioenergy, conflicts arise regarding land use for energy crops to the point that bioenergy is portrayed as an unsustainable option. This apparent conflict necessitates taking a holistic approach to meeting bioenergy needs through sustainable agriculture.

Demand for Alternatives: The greenhouse gases (GHG) contributed by the transportation sector are significant, and therefore, the sector's contribution to climate change cannot be understated. Commercial aviation is responsible for 13% of transportation GHG emissions (US EIA 2020b). According to the US EIA (2020a), the 400 billion liters global commercial jet fuel market has the potential to grow to over 850 billion liters by 2050. However, the aviation sector is also the first to make a significant commitment to carbon-neutral growth using non-fossil-sourced fuels or sustainable aviation fuel (SAF) (CAAFI, 2020). Specifically, their goal is to reduce emissions by 50% by 2050 (Airlines for America; IATA 2020). In 2018, 7.4 million liters of SAF and over one billion liters of renewable diesel were produced which fell short of the real demand (USDOE EERE, 2020). The Federal Aviation Administration set a goal of using 15 billion liters/year of renewable fuels by 2018. By 2030, civil aviation alone will consume close to 96 billion liters of fuel making the airline industry a prime driver of carbon-neutral growth through the displacement of fossil-based fuels by SAF. According to the Commercial Aviation Alternative Fuels Initiative (CAAFI) the airline industry's commitment to renewable fuels is emphasized by the over 1300 million liters worth of offtake agreements per year, already in place (Csonka, 2020). In the US, the Renewable Fuel Standard (USEPA, 2014) is targeting the use of over 136 billion liters of a combination of biofuels by 2022. The Renewable Energy Directive (RED) of the European Union (EU) is likewise promoting the use of renewables equivalent to about 66.6 billion liters of biodiesel by 2022 (Schnepf and Yacobucci, 2010; Env. Canada Inquiry Centre, European Parliament). All of this activity and policy underscores the serious global commitment to alternative fuels in the aviation sector. Besides, there is consumer preference for the replacement of fossil-based products, like plastics and other chemicals, by plant-derived biobased products of equal quality https://www.biopreferred.gov/BioPreferred/faces/pages/AboutBioPreferred.xhtml).

Not all Biofuels are Equal: While it is well established that renewable fuels and biobased products are needed to successfully combat emissions and climate change, it is also important to take into account systems-level sustainability of procuring and using biofuels and bioproducts. System-level metrics to assess the life cycle impact of bioenergy production systems are important to ensure the sustainability benefits of these systems compared to fossil energy use (Wiebe et al., 2009; Hertwich et al., 2010). The largest responsibility in the biofuel supply chain could be attributed to the sustainability of producing the feedstock itself. Sugarcane, jatropha, corn, palm oil, and other crops are discouraged from the renewable space due to a variety of reasons, including loss of biodiversity and habitat, water consumption, and impact on carbon sequestration (Manning et al; 2015). Second-generation biofuels could circumvent the direct food competition issue but still cannot undo the fact that they directly compete for land meant for food and fiber crops.

Concerns regarding food-versus-fuel conflict and other unintended consequences of first-generation biofuels have driven bioenergy research towards novel feedstock that minimize competition with food-crop production (Tilman et al., 2009). The Carbon Offsetting and Reduction Scheme (CORSIA) was set forth by the International Civil Aviation Organization (ICAO) as a framework of standards concerning the assessment and adoption of SAF that demonstrate reduction of GHG emissions in international aviation (IATA, 2020). A CORSIA approved SAF is a renewable or waste-derived fuel that meets the sustainability criteria of CORSIA (ICAO, 2018). As of June 2020, the United States and 82 other countries have committed to participate in CORSIA from 2021-2026. Low carbon feedstocks, therefore, are gaining prominence in the effort to develop renewable fuels (Scarlat et al., 2015; UNEP, 2011, 2014).

Bioenergy feedstocks can be sustainably produced through ‘sustainable intensification’ or, extensification, which is the targeted use of underutilized land or biomass residues or the intensification of conventional crop rotations (Heaton et al., 2013). Among such crop rotations, purpose-grown oilseeds and other lipid feedstock with proven conversion pathways for their oil and favorable energy characteristics hold promise for meeting the regulatory specifications of SAF and other renewable fuels. Specifically, the use of lipid feedstock as a source of renewable liquid fuels is particularly significant because they can produce drop-in fuels that have been tested successfully in commercial and military operations, and are market-ready (ASTM, 2019). Lipid feedstocks include waste greases, animal fats, municipal waste and sludge, algae, and purpose-grown oilseed crops, such as carinata (*Brassica carinata*), camelina (*Camelina sativa*), canola (*Brassica napus, Brassica juncea, Brassica rapa*), and pennycress (*Thlaspi arvense*) (Yilmaz & Atmanli, 2017; Gesch et al, 2015). Several industrial oilseed crops fit the criteria of no direct land-use change (Wicke et al., 2012; Shi et al; 2019) due to being non-food crops and non-land displacing especially since these are suited for winter production in most regions. Winter oilseeds, like carinata, are an example of temporal intensification in which feedstock crops are integrated into the fallow seasons of existing rotations, thus avoiding the direct and indirect land-use change impacts associated with agricultural intensification (Fargione et al., 2008) or displacement of existing crop production (Searchinger et al., 2008), respectively. They may also provide a means of achieving the ecosystem service benefits of cover-cropping, such as erosion control and reduced nutrient leaching, at a net profit to farmers rather than at a significant cost (Plastina et al., 2018). Winter oilseeds are known to be effective in various rotations to break disease and pest cycles, recycle nutrients in the soil, reduce nutrient leaching, and reduce or eliminate weed problems (Seepaul et al; 2016; Shi et al; 2019). Biomass returned to the soil with only the seed being harvested is a major differentiating factor between oilseed crops and other biomass crops. This results in maximum sequestration of carbon and return of nutrients to the soil for the following crops (Seepaul et al; 2019).

Oilseeds for the Southeast US: Soybean, peanuts, cottonseed, rapeseed, sunflower, and canola are the major oilseeds grown in the US with soybeans being the most prominent. However, soybeans alone cannot meet the demand for biofuels. Moreover, they are a food crop and with high carbon intensity. So soybean alternatives are being pursued actively (Sindelair, 2015; Moser 2012; Hill, 2006; Bill Gibbons Personal Communication, 2020). Other oilseed crops gaining prominence due to their low indirect land-use change characteristics are canola, camelina, pennycress, rapeseed, mustard, and sunflower. These have superior agronomic, environmental, and market characteristics due to both oil and meal market applications (Moser, 2012). Oilseeds have greater adaptability to local growing conditions, drought tolerance, low agricultural inputs, compatibility with fallow land, and rotational fit with other cash crops (Embaye et al, 2018). The Southeast US with its mild winters and ample annual rainfall is very amenable to year-round agriculture with no impact on normal food and fiber production. Several oilseeds have been explored for yield stability and rotational suitability in the region. Rapeseed with 35-40% oil content has good biofuel potential due to its high erucic acid and reasonable seed yield that can range from 1,000-1,600 kg per hectare (Wright, 2018). Camelina has very limited production in the Southeast due to previous research indicating less than favorable yields and low yield stability (Wright, 2018). Currently little to no research is pursued on camelina in this region as compared to the Northern Plains and Western regions of the US. Among other oilseed species, tung (*Aleurites fordii*) has about 18.5 to 20% oil content by weight, and orchards can produce about 1,000 kg of fruit per hectare (Minogue, 2019). Pongamia (*Millettia pinnata*) is another oilseed tree with potential in the biodiesel market that is suited to the Southeast. (Gilman et al., 2018). Comparative field studies conducted in North Florida show that carinata has by far the highest seed yield among oilseeds (Table 1). In replicated yield testing in North Florida, carinata produced 2,800 kg/ha compared to canola (1,456 kg/ha) and camelina (952 kg/ha). In addition to its superior oil yield, carinata contains 45% crude protein, which is used as an animal feed supplement.

Table 1: Performance of oilseed crops averaged across several growing seasons at the North Florida Research and Education Center in Quincy, FL.

Crop	Seed yield (kg ha^{-1})	Oil content (%)	Oil yield (L ha^{-1})	Crude Protein (%)	Crude Fiber (%)

Camelina	952	35	361	45	11
Canola	1,456	43	679	41	11
Carinata	2,800	40	1,214	45	11

2.]. Addressing the Demand for A Low Carbon Bioeconomy

Ecosystem Services Afforded by Carinata

The Southeast US has over 5 million hectares of row crops producing corn, soybeans, peanuts, and cotton. Less than 10% of this land is cropped during the winter months. This fallow land is subject to topsoil erosion, leaching of excess nutrients from the previous crop, weed pressure, and other unfavorable factors leading to a cycle of negative land impact and untenable practices. Carinata has agronomic characteristics that suit the region for winter production without any indirect land use impact. It is resistant to seed shatter and less sensitive to drought, heat, and N deficiency compared to canola (Seepaul et al., 2016). It also has greater oil yield and higher biomass productivity (Gesch et al., 2015). It is one of only four crops in North America, and the only oilseed, that has received the Round Table of Sustainable Materials (RSB) certification (RSB, 2018) for sustainable oil and meal and a low indirect land-use change (ILUC) risk certification in South America. The RSB has developed one of the most robust sustainable frameworks for biofuels (Collotta et al., 2019). This differentiates carinata from other feedstocks as it is certified as a low carbon feedstock for fuel and non-GMO high protein meal. Thus, carinata is a winter cash crop that can seamlessly fit into the Southeast US cropping system with little to no augmentation of infrastructural requirements or knowhow. From an ecosystem services perspective, it provides the ecosystem services of a high residue cover crop (6,000-10,000 kg ha^{-1}per year) with over 40 kg of nitrogen and 90 kg of potassium returned to the soil in the residue. Though it requires reasonable amounts of nitrogen in season and especially during its reproductive stages, it can extract nitrogen from the soil making it highly nutrient efficient (Seepaul et al; 2020). This underscores its role in nutrient scavenging, which correlates to reducing nutrient leaching. It also has a low water footprint needing water mostly during reproductive stages. Water infiltration in a carinata system is greater than in a winter fallow system. Nematode and weed pressure are significantly lower in the summer crops following carinata, as compared to the fallow system (Seepaul, 2018a). Moreover, carinata has a moderate weed risk potential (USDA-APHIS, 2014) with its low pod-shattering and dormancy (Patane and Tringali, 2011). It supports over 50 species of pollinators and 75 species of non-pollinators, thereby providing biodiversity benefits (Stiles, 2019).

Another ecosystem service value of winter cover crops is maintaining or improving soil organic matter levels. Soil organic matter, often measured in terms of its carbon content (soil organic carbon or SOC), is a key element of soil fertility affecting water infiltration, water-holding capacity, and availability of nitrogen and other nutrients (Campbell et al., 2018). Soil carbon levels reflect the dynamic balance between organic matter inputs and losses via heterotrophic respiration. Cover cropping using crops like carinata increase total plant production over a given agricultural rotation, generating more organic matter inputs to supplement SOC levels. Meta-analysis has shown that cover cropping is on balance associated with increased SOC, particularly in temperate climates and fine-textured soils (Jian et al., 2020). Such SOC enhancement provides dual benefits of both improving soil health and productivity and sequestering atmosphere-derived carbon (Paustian et al., 2016).

Every metric ton of carinata produced is associated with an additional ~1.2 ton of carbon in leaf, stem, and root biomass available to supplement soil carbon levels. Accounting both for these new carbon inputs to the soil and the additional tillage operations associated with carinata cultivation, ecosystem modeling suggests that integrating a winter carinata crop into the cotton–cotton–peanut rotations common in the Southeast US would sequester carbon at an average rate of 15 (2–28) kg C ha^{-1} y^{-1}. Carinata production does require supplemental nitrogen fertilizer, which leads to trace soil emissions of nitrous oxide (N_2O), a potent greenhouse gas (GHG). However, modeling efforts suggest that N_2O emissions from carinata production offset only 14% of the crop's carbon sequestration value, resulting in a net soil GHG balance equivalent to 48 (6-102) kg CO_2 sequestration per hectare per year (excluding all other positive life-cycle impacts of carinata).

Feedstock of choice for proven conversion technologies: Carinata oil has high erucic acid (40-44%) concentrations as compared to canola (<1.0%). It also has a lower concentration of oleic acid (6-10%) and linoleic acid (14-17%) as compared to canola (58-62% and 20-22%, respectively), and distiller's grain corn oil (26-29% and 47-54%, respectively). The high concentration of unsaturated fatty acids relative to saturated fatty acids makes carinata oil suitable for many conversion technologies, as unsaturated fatty acids are more reactive and form cycloparaffin and aromatic compounds more easily. Carinata oil has a higher molecular weight than soybean, canola, or jatropha, which results in a higher yield of hydrocarbon fuels and chemicals relative to oilseeds with greater C18. This yield increase is equivalent to over 13.7 MT/day for an almost 700MT/day commercial refinery using the Catalytic Hydrothermolysis Jet (CHJ) pathway, one of the ASTM approved pathways to produce commercial jet fuel from carinata oil. This pathway combined with hydrothermal cleanup (HCU) process (Applied Research Associates Inc.) reduces total metals to less than 10 ppm and phosphorus to less than 2 ppm. The first flight test using fuel produced from carinata performed better than fossil Jet A fuel with a reduction in black carbon, oxides of nitrogen, and aerosol emissions. Fuels produced from this process include renewable Jet A (50:50 blend with petroleum), renewable JP-5, renewable marine diesel, ultra-low sulfur diesel, renewable naphtha and renewable chemicals. Jet A can be used at 100% although it is currently approved at 50% by ASTM. ARA fuels from carinata have the same hydrocarbon types and boiling range distribution as their petroleum counterparts.

Coproduct-driven carinata bioeconomy: Carinata offers coproduct molecules with functions other than fuel with significant economic benefits, as summarized in Table 2. While the seed oil is mainly targeted for conversion to reduced hydrocarbon fuels, it is also the source of the most abundant coproduct, erucic acid (C22:1) that makes up 42% of the seed's fatty acid profile. In principle, 23 kg of carinata seed can be produced from about 4 hectares of land and ultimately provide 3,400 kg of erucic acid. This mono-unsaturated, 22-carbon fatty acid is non-digestible by humans and somewhat rare among vegetable oils. To date it has been produced mostly from a genetically modified high erucic acid rapeseed, HEAR, with over 50% erucic acid content, but carinata offers the highest erucic acid content among non-GMO crops. Hydrogenation of erucic acid gives behenic acid, a 22-carbon saturated fatty acid that has applications in hair products, lubricants, paints, and detergents. Further reduction of behenic acid yields behenyl alcohol, 22-carbon saturated alcohol used as an emulsifier and thickener in cosmetics, but also as an FDA-approved topical anti-viral medication (Abreva®). Alternatively, erucic acid can be oxidized selectively at its double bond to yield brassylic acid, a 13-carbon molecule that would be very challenging to synthesize from fossil fuels. Brassylic acid has been converted to nylon 13-13 and shown to have thermal properties (T_m= 183 °C) very similar to those of nylon 11 (T_m = 190 °C), which has been produced commercially by Arkema (as Rilsan^{TM}) for decades from the ricinoleic acid in castor seed oil. A niche application of brassylic acid is its cyclization with ethylene glycol to yield ethylene brassylate, a valuable perfume ingredient. The byproduct of erucic acid oxidation is pelargonic acid, a 9-carbon fatty acid that is the same byproduct obtained by the industrial oxidation of oleic acid. Pelargonic acid is present in a variety of plants and has FDA approval for use in foods, but is gaining popularity as an environmentally friendly herbicide, fungicide, and sanitizer. The corresponding amides of erucic acid and behenic acid, erucamide and behenamide, respectively, continue to be used as additives in plastics and coatings.

Table 2. Financial Benefits from Co-Products Unique to Carinata[1]

Co-Products	Annual Market	Unit Value	Potential Annual Income or Savings
Free fatty acids for erucic acid recovery	>7,000 MT	$0.80/lb	$10-20M
Glycerin to propylene glycol	0.2-4M MT	$0.50/lb	$10-20M
n-paraffins for LAB (linear alkylbenzene) production	4.3B MT	$0.80/lb	$2-4M
Crude glycerin animal feed		$0.08-0.10/lb	$0.5-1.0M
Hydrogen savings	4.5M lKg/yr	$0.50/lb	$5M
Increase yield from high molecular wt	13.64MT/day net increase		$3M

[1] MT: metric tons, M: million, B: billion

High protein meal for animal feed: Livestock production in the Southeast US represents an important economic activity, favorable weather and precipitation allow for a continuous supply of forages, which are the basis of livestock nutrition in the region. However, despite the abundance in forage quantity for livestock, forage quality can be limiting for livestock production. There is a constant need for protein supplementation in beef and forage systems in this region of the US. Common protein supplements for livestock in the region include byproducts from soybean, corn, and cotton, but price volatility and over-reliance on transportation of some of these byproducts from the Midwest US are some of the challenges faced by livestock producers in the Southeast when procuring protein supplements to meet cattle demands. Carinata meal has been documented to have great potential as a livestock supplement given its high protein concentration (Table 1) and the protein quality when used for ruminants (Schulmeister et al. 2019). Carinata meal fed as a protein supplement to beef heifers resulted in daily weight gain without any negative consequences on the attainment of puberty or thyroid hormone status (Schulmeister et al., 2019). When compared to common protein sources supplemented to cattle, such as cottonseed meal, distillers grains plus solubles, and soybean meal, carinata meal was similar in terms of ruminal metabolism and digestibility of nutrients (Schulmeister et al., 2019).

Carinata meal also contains glucosinolates, which are mustardy compounds that deter animal consumption. The most abundant compound, sinigrin, constitutes 4–7% of the meal. Its removal or decomposition through mild heating is important to make the feed more palatable. Another bitter component of the seed meal is sinapine with a reported content of up to 1.6%. Sinapine seems to be the seed’s source of aromatics for initial lignin synthesis. It is a choline ester and its hydrolysis yields sinapic acid, which is the main extract of the seed meal when saponification conditions are employed. Sinapic acid possesses two methoxy groups and is structurally related to naturally abundant ferulic acid (one methoxy group) and coumaric acid (zero methoxy groups), which are found as crosslinkers of the lignin and cellulose components in lignocellulosic biomass. Interestingly, all three of these bioaromatics exhibit anti-oxidant and anti-microbial functions. Ferulic acid (320 tons per year, natural) and coumaric acid (160 tons per year, synthetic) are relatively small market commercial products that are used in cosmetics, sunscreens, or as food preservatives. While there is no significant commercial production of sinapic acid, presumably it could expand into the markets held by ferulic acid and coumaric acid, especially as a food preservative, taking advantage of negative consumer feelings towards probably harmful BHT (butylated hydroxytoluene) and BHA (butylated hydroxyanisole). Another application of sinapic acid is its polymerization to high glass transition temperature (T_g) bioaromatic polyesters. Fossil fuel-based polyethylene terephthalate (PET) has a softening temperature (T_g) near 72 °C, a value suitable for many packaging applications, but not for hot food or hot water applications. The novel polyesters, polyethylene coumarate, polyethylene ferulate, and polyethylene sinapate have T_g values of 109, 113, and 118 °C, respectively. The sinapic acid variant affords the highest T_g value and exceeds that of polystyrene (Styrofoam, PS, 95 °C), a polymer targeted for replacement because of its environmental impact. Moreover, the fiber contained in carinata meal (Table 1) could be biochemically converted to value-added organic acids and other commodity or specialty chemicals via enzymatic hydrolysis and fermentation, similar to sugarcane bagasse (Lo et al., 2020).

3.]. Southeast Partnership for Advanced Renewables from Carinata

The purpose of SPARC: Sustainable agriculture seeks solutions that are resilient in the face of complex, interrelated challenges such as national security, climate change, preserving and enhancing natural resources, and economic diversification on the farm. SPARC was established to ensure that a carinata-based supply chain would provide renewable liquid fuels and green coproducts without undermining natural resources and socio-economic benefits in a region that is amenable to sustainable farm diversification. It is by no means the first bioenergy project to unite a multidisciplinary team under a common goal. Other USDA-NIFA funded Coordinated Agricultural Projects (Northwest Advanced Renewables Alliance-NARA, Bioenergy Alliance Network of the Rockies-BANR, Sustainable Bioeconomy for Arid Regions-SBAR, Integrated Pennycress Research Enabling Farm and Energy Resilience-IPREFER, Southeast Partnership for the Integrated Biomass Supply Systems-IBSS, and others; https://nifa.usda.gov/afri-regional-bioenergy-system-coordinated-agricultural-projects) have the same guiding principle for their respective feedstock group and regions of operation. SPARC employs a systematic approach to building and disseminating a body of scientific information to meet stakeholder needs and address market opportunities. It is designed to respond to changes in mandates in the renewable fuels space and deliver scientifically vetted metrics to key stakeholders in a format most relevant to them. It is generating useful literature through multidisciplinary research on carinata-based cropping systems, fuel and coproduct development from carinata, sustainable supply chain establishment, and workforce development. Toward that end, SPARC's objectives are to:

(1) Generate feedstock in the Southeast US using superior, high-yielding carinata genotypes and best management practices (Kumar et al., 2020)

(2) Demonstrate conversion of carinata oil to sustainable aviation fuel, biodiesel, renewable diesel, and other coproducts

(3) Evaluate carinata seed protein as an animal feed supplement and source of bioproducts

(4) Conduct a systems-level life cycle analysis integrated with a techno-economic analysis

(5) Demonstrate commercialization potential by leveraging existing industry partnerships

(6) Provide a cost-revenue analysis through transportation and site selection optimization tools, assess supply chain resiliency

(7) Through outreach programs develop and implement processes to ensure that all stakeholders realize value

(8) Provide education to K-12, undergraduate, and graduate students and prepare the bioenergy workforce of tomorrow.

Ultimately, through these objectives, the partnership hopes to enable a mechanism of trust among the entire carinata value chain to ensure the commercial development of this renewable liquid fuel feedstock in the Southeast US.

Enabling a secure feedstock supply within the sustainability framework: While there is a demonstrated need for renewable fuels and coproducts, supply chain establishment mainly hinges on uninterrupted feedstock supply. That directly correlates to farmer awareness and adoption, farmer risk alleviation and confidence building, consistent crop performance, and tailoring management practices that align with the principles of sustainable production of renewable fuel feedstock. SPARC aims to develop a body of knowledge and practices that will support the sustainable expansion of carinata feedstock supply using high grain and oil yielding carinata genotypes, best management practices (BMPs), and risk management tools through field and controlled experiments across FL, GA, AL, MS, SC, NC. Although management aspects of carinata after frost events are outlined (Mulvaney et al., 2018), frost tolerance has emerged as one of the top traits in regards to crop improvement/selection to make carinata suited to more northern geographies within the Southeast US. As high yielding varieties continue to be identified, SPARC continues to focus on identifying factors that ensure yield stability relative to field variability for consistent high production and risk elimination. Hybrids have routinely outperformed commercial varieties in preliminary evaluations; therefore, developing hybrids that are cold tolerant with high harvest index and high oil levels (46-47%) is a priority for SPARC. High biomass production also remains an important goal for maximizing carbon sequestration. Early maturing and herbicide-resistant varieties are important traits as SPARC works toward making the transition to carinata as seamless as possible for the farmer. Nuseed, an industry partner of SPARC, is the holder of the world's most extensive carinata germplasm collection and are developing carinata as one of the crops in their "Value Beyond Yield" portfolio. Commercial and research operations in various countries (Argentina, Uruguay, Canada, France, and Southeast US) facilitate robust data collection in various geographies, soil types, climates, and socio-economic scenarios. Expansion into multiple geographies not only ensures a year-round supply of the feedstock but also enhances learning and knowledge-sharing across geographies (Bennett, 2020). Aspects of crop modeling to understand the crop's growth and development as it relates to ecoedaphic factors with a focus on yield maximization and carbon intensification are being investigated.

Product development and farmer training to ensure in-season crop monitoring and protection are key steps to scaling carinata in the Southeast US. SPARC has been screening the efficacy and safety of multiple herbicides used in major agronomic row crops and some vegetable crops to identify those that can provide adequate weed control for carinata without reducing yield from herbicide injury. This work led to the identification of several commercial herbicides for effective weed control against broadleaved and grass weeds. Likewise, disease and insect thresholds of common pests are being determined to help with early detection, intervention, and prevention. Integration of fertility management is important on the characteristic sandy soils of this region to meet crop demand and limit nutrient movement to water bodies and groundwater. Related to this is an effort to evaluate the potential to reduce the use of inorganic sources of nitrogen by replacing them with organic sources, such as poultry litter. Existing common cropping systems in the region include corn (Zea mays L.), cotton (Gossypium hirsutum L.), peanut (Arachis hypogaea L.), soybean (Glycine max (L.), and sorghum (Sorghum bicolor (L.) Moench). The effects of preceding summer crops on winter carinata production as well as the effects of carinata production on subsequent summer crops are being studied in multi-year crop rotation studies. These studies lend themselves to robust integrated life cycle analysis incorporating environmental and economic elements of a carinata rotation system. Utilizing precision agriculture techniques to maximize yield and reduce inputs at a system level is critical for sustainability and profitability. Finally, improving the fit of carinata by using harvest aids to facilitate timely planting of summer crops is another critical line of research that helps identify compatible products (Seepaul et al., 2018b).

Developing useful system metrics: The purpose of an interdisciplinary approach is to bring together field experts and modelers, end-users, and policymakers to determine what metrics will help make the business case for each stakeholder. SPARC's hydrology team uses the Soil and Water Assessment Tool (SWAT) to simulate and estimate changes in runoff and overall effects of carinata production on runoff quality and quantity at a field-scale. The hydrologic simulations will provide an assessment of the potential for carinata production to generate secondary impacts associated with altered streamflows, increased loading of sediment, phosphorus, and nitrogen, and eutrophication relative to other regional land uses. Comprehensive life cycle analysis of the carinata crop rotation system (winter carinata versus winter fallow followed by traditional summer crops) using best management practices are underway to help compare the carbon intensities of other feedstock with carinata globally and regionally. These analyses will help identify opportunities to tailor location and/or management to maximize yield, nutrient and water use efficiency, and carbon sequestration at the farm level while reducing GHG emissions from the overall seed-to-fuel use operation.

Building social support through stakeholder engagement: SPARC's social science experts along with the land grant extension system began with broad questions directed to the many stakeholders involved in the carinata bioeconomy. Through surveys at field days and phone interviews, they constructed a scalar model of the barriers and opportunities relevant to producers in the Southeast US. This information is directed back to SPARC and represents the farmers' collective voice as researchers continue their work to develop an improved "package" suited to farmers in the region. A Carinata Community of Practice (CCoP) has been established in the region to serve as a platform of learning and support for carinata growers. The degree to which farmers rely on one another for advice and inspiration cannot be understated, and the CCoP aims to capitalize on this practice by identifying "champion" carinata growers in various regions and facilitation knowledge diffusion to other farmers. Key informant interviews led to the understanding of barriers and perceived opportunities for carinata adoption in the Southeast US (Christ et al; 2020). The findings identified farmer unfamiliarity with carinata as the most significant barrier within the farm gate, whereas market proximity and limitations of crop insurance were the topmost barriers beyond the farm gate. Unfamiliarity with, or limited knowledge of, carinata and consequent spread of misinformation could potentially be major obstacles in the path of carinata adoption. Continued deliberate engagement with farmers will be crucial to maintaining a healthy feedback mechanism of learning and improving and building mutual trust and confidence (Christ et al; 2020). SPARC aims for the CCoP to eventually be managed by the farmers themselves, ensuring ownership in the creation of learning opportunities and its endurance as a driver of producer adoption beyond SPARC.

Traditionally viewed as non-sustainable, contract farming today could be considered more progressive and environment friendly and risk-free depending on the terms of the contract. These agreements are moving away from the model of input-intensive to input-conservative and from structural demands for high-yield production to concepts of "Value Beyond Yield" (Nuseed). These shifts are an attempt to protect natural resources and further incentivize farmers for adopting sustainable practices and could perhaps reduce some of the aforementioned barriers (Christ et al; 2020). Increasing constraints providing market access only to sustainably produced goods come from recognizing the need to address climate change mitigation and natural resource protection. SPARC's stakeholders also include the consumers that demand transparency in the process of manufacturing and movement of goods. As a result, educating K-12, undergraduate, and graduate students on the concepts, technologies, and business of bioenergy helps fill information gaps and prepares the green workforce of the future. Key to these efforts has been a program to educate and provide classroom material to K-12 teachers about sustainable agriculture and bioenergy using carinata as the model crop for enhancing the three pillars of sustainability (environmental, economic, and social).

The regional focus on global resilience: SPARC has both an opportunity and an obligation to add value by focusing equally on all aspects of the carinata value chain. The supply chain team seeks to ensure that all participants meet at a minimum their investment thresholds in our collective pursuit. The importance of a local/regional supply chain is best stated by the perspective of state economic development stakeholders from the states of Alabama, Florida, and Georgia, who have engaged with SPARC during the initiation, planning, and now execution phases of the project. Dialogue indicates that there is as much as a 5X multiplier that can be applied to farm jobs by developing a local/regional supply chain (Chris Chammoun, Georgia Department of Economic Development, Personal Communication). The public-private partnership positions SPARC well to orchestrate a sustainable, viable supply chain development. The partners with valuable input from the industry and government members of the advisory board help define the near-term and long-term objectives of making a market reality a carinata-driven bioeconomy in the Southeast US. Significant contributions from the supply chain team include a bottoms-up distribution optimization analysis using the Freight and Fuel Transportation Optimization Tool-FTOT of the US Department of Transportation and the Federal Aviation Administration to evaluate both the economic and environmental performance of the carinata feedstock and product distribution system. (https://github.com/VolpeUSDOT/FTOT-Public/wiki/Documentation-and-Scenario-Datasets). Moreover, supply chain resilience modeling is undertaken to assess the impact of natural phenomena and market volatility on the carinata bioeconomy. The supply chain team works horizontally across all SPARC teams to ensure full integration and engagement of crucial state agencies, such as Departments of Agriculture, Natural Resource Conservation Service, rural development, state departments of economic authority, land grant university extensions, commercial and military aviation, Department of Energy, U.S. Department of Agriculture, Environmental Protection Agency, Federal Aviation Administration, Department of Transportation, environmental NGOs, green product end-users, and manufacturers, who are aligned in their interests in renewable energy and products.

4.] Conclusion

Carinata is a winter cover crop that can be produced sustainably on primarily unutilized fallow lands to meet market demand for drop-in liquid fuels, animal protein, and valuable coproducts that are not fossil-fuel based, while generating extra off-season income for farmers and downstream processors. From what began as modest trials with a few carinata varieties in Quincy, FL, this project has grown into a large public-private undertaking to establish a carinata bioeconomy in the Southeast US. This progress could not be achieved without a promising product that has the potential to deliver on the principles and criteria of sustainability in the renewable fuel arena. Essentially, what SPARC has set out to do is to create a toolbox for success for every stakeholder in the carinata enterprise (George, 2018). This encompasses the farmers, the handlers and warehouse owners, the transportation businesses, the fuel manufacturers, the technology developers and licensees, the investors, the regulatory agencies, the state, and federal policymakers, the workforce engaged in this enterprise, the commercial and military aviation, the animal and feed producers, and the consumers at large. SPARC's resolve is to make the carinata supply chain not only efficient but also resilient to uncertainties whether emanating from the weather or the marketplace (George, 2018). Adding to that is a strong commitment to sustainability as it pertains to protecting our natural resources and enhancing socio-economic benefits. That commitment has our team looking at ways to optimize the supply chain in a way that minimizes impact on the environment while maximizing profitability. Mitigating risk to the farmer and all the stakeholders downstream of the farm gate continues to be central to the SPARC mission. Integrating precision agriculture strategies has emerged as a top priority to precisely manage water, nutrients, and other inputs and optimize carbon sequestration taking into account field variability. Collecting extensive data that document inputs, outputs, and effects on natural resources (soil, water, air) to perform a comprehensive life cycle analysis will be important as a comparative metric for carinata with other oilseeds and biomass feedstock. Techno-economic analysis of the feedstock and technology in its current state is the immediate priority to properly guide SPARC activities and provide insight to industry, end-users, and stakeholders regarding investment strategies, policy modification, and near- and long-term targets. The papers in this series are some of the initial outcomes of the first three years of SPARC research involving agronomists, crop physiologists, weed specialists, nutrient specialists, plant pathologists, crop modelers, cropping system modelers, hydrologists, economists, environmental modelers, chemical engineers, and chemists united by the common passion for sustainable bioenergy development through carinata.

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