African Journal of Rural Development, Vol. 9 (1): January –March 2024:37-52 ISSN 2415-2838

Ethiopian Mustard Emerging as Non-Food Feedstock and Environmentally Sustainable Crop: Current Status, Constraints, and Future Prospects

RAHIEL H.A.[1,2], WENDM, Y.[1], ABDULWAHAB, S.S.[2], BADJI, A.[3], OZIMATI, A.[3], EDEMA, R.[2], MUKANKUSI, C.[4] and ADIPALA, E.[5]

[1]Department of Plant and Horticultural Sciences, Mekelle University, College of Dryland Agriculture and Natural Resources, Endayesus Main Campus, P.O. Box 231, Mekelle, Tigray, Ethiopia

[2]Makerere University Regional Centre for Crop Improvement, College of Agriculture and Environmental Sciences, P.O Box 7062, Kampala, Uganda

[3]Department of Agronomy, Bayero University, Kano, Nigeria

[4]International Center for Tropical Agriculture, Kawanda, Uganda

[5]Research and Education Agency, Plot 2 Edimu Close, Naalya, Wakiso, P. O. Box 29152, Kampala, Uganda

Corresponding author: rahel4ever@gmail.com

ABSTRACT

Ethiopian mustard (*Brassica carinata* A. Braun) also known as Carinata is gaining an increasing significance as a non-food cover crop and fully non-GMO plant protein sources, highlighting its environmental sustainability attributes. Historically as a condiment and leafy vegetable, it has recently garnered attention as a promising source of oilseed for various industrial applications, including biofuels and lubricants. This paper provides an overview of the current status of Ethiopian mustard cultivation, elucidates the constraints faced by farmers and researchers, and delineates future prospects for its expansion and utilization as sustainable aviation fuel (SAF). Key factors contributing to its appeal include its adaptability to diverse agro-climatic conditions, relatively low input requirements, and potential to mitigate environmental impacts associated with conventional oilseed crops. However, challenges such as limited genetic diversity, agronomic practices, and market development necessitate comprehensive strategies to unlock its full potential. Through interdisciplinary collaboration, policy support, and technological innovations, Carinata holds promise as a sustainable alternative in non-food oilseed production, contributing to both agricultural resilience and environmental stewardship.

Keywords: biofuel, Carinata, oilseed, non-food feedstock, sustainable aviation fuel, sustainability

Cite as: Rahiel H.A., Wendm, Y., Abdulwahab, S.S., Badji, A., Ozimati, A., Edema, R., Mukankusi, C. and Adipala, E. 2024. Ethiopian Mustard Emerging as Non-Food Feedstock and Environmentally Sustainable Crop: Current Status, Constraints, and Future Prospects. *African Journal of Rural Development* 9 (1):36-51

RÉSUMÉ

La moutarde d'Éthiopie (Brassica carinata A. Braun), également connue sous le nom de Carinata, gagne en importance en tant que culture de couverture non alimentaire et source de protéines végétales entièrement non-OGM, mettant en avant ses attributs de durabilité environnementale. Historiquement utilisée comme condiment et légume-feuille, elle a récemment attiré l'attention comme source prometteuse de graines oléagineuses pour diverses applications industrielles, y compris les biocarburants et les lubrifiants. Cet article offre un aperçu de l'état actuel de la culture de la moutarde d'Éthiopie, explique les contraintes rencontrées par les agriculteurs et les chercheurs, et décrit les perspectives futures pour son expansion et son utilisation comme carburant d'aviation durable (SAF). Parmi les facteurs clés de son attrait figurent son adaptabilité à diverses conditions agro-climatiques, ses besoins en intrants relativement faibles, et son potentiel à atténuer les impacts environnementaux associés aux cultures oléagineuses conventionnelles. Cependant, des défis tels que la diversité génétique limitée, les pratiques agronomiques et le développement du marché nécessitent des stratégies globales pour libérer tout son potentiel. Grâce à une collaboration interdisciplinaire, un soutien politique et des innovations technologiques, le Carinata promet d'être une alternative durable dans la production de graines oléagineuses non alimentaires, contribuant à la résilience agricole et à la protection de l'environnement.

Mots-clés : biocarburant, Carinata, graines oléagineuses, matière première non alimentaire, carburant d'aviation durable, durabilité

Introduction

The global demand for sustainable oilseed crops has increased due to their pivotal role in various industrial applications, including biofuel production and alternative sources of oil. Ethiopian mustard (*Brassica carinata* A. Braun), also known as Carinata has garnered attention as a promising non-food oilseed (feedstock) crop, offering significant environmental benefits and economic opportunities (Seepaul *et al*., 2023; Mohd Saad *et al*., 2021). Carinata originating from the Ethiopian highlands, has prominent agronomic characteristics and adaptability that make it resilience to adverse environmental conditions and suitability for marginal lands (Hagos *et al*., 2020); therefore, demonstrating remarkable adaptability to diverse climates and soil conditions, making it a versatile crop for various regions around the world. Furthermore, the nutritional composition and potential health benefits associated with the oil extracted from Carinata seeds emphasize its significance as a functional food ingredient (Mehta *et al*., 2010; Odongo *et al*., 2017).

The global aviation industry is crucial for connecting people, cultures, and economies (Gittens *et al*., 2019). However, it contributes approximately 2-3% of global carbon emissions (WEF, 2024), hence, significant challenges are faced related to fuel consumption and sustainability. Conversely, Sustainable Aviation Fuel (SAF) represents a pivotal innovation in the quest for a more sustainable aviation industry (https://www.finboot.com/post/sustainable-aviation-fuels-decarbonization-of-air-transport). According to ICAO (2018), SAF is produced from renewable resources, such as biomass, waste oils, and agricultural residues, and can significantly reduce greenhouse gas emissions compared to conventional fossil-based jet fuels. Conventional aviation fuels notably have significant environmental drawbacks, as their combustion releases large quantities of greenhouse gases and pollutants (Valavanidis, 2022), contributing to climate change and air quality issues. As the aviation industry grows, the urgent need to mitigate its environmental impact is driving research and investment into alternative, and more sustainable fuel feedstocks like Carinata as a source for SAF (Seepaul *et al*., 2023; George *et al*., 2021). Currently, Carinata revolved as a non-food oilseed crop, offers a promising feedstock for SAF production due to its high oil content and ability to grow on marginal lands, unsuitable for food crops (Seepaul *et al*., 2021). It offers the advantage of being a "drop-in" fuel, meaning it can be used in existing aircraft engines and infrastructure without requiring modifications (Lau *et al*., 2024; Bhatt *et al*., 2023). This compatibility facilitates its adoption and integration into the current aviation system.

Furthermore, the UN Intergovernmental Panel on Climate Change (IPCC) recognizes SAF as a crucial element in mitigating the aviation sector's impact on climate change. According to recent IPCC reports, while SAF is not yet widely adopted, its development and deployment are accelerating, driven by both technological advancements and regulatory pressures (ICAO, 2018). The IPCC emphasizes the potential of SAF to significantly reduce carbon emissions, citing that SAF can achieve up to 80% lower lifecycle emissions compared to conventional jet fuel (ICAO, 2019). Carinata can contribute to reducing aviation's carbon footprint while not competing with food production. Besides to this, Carinata-derived SAF can significantly lower lifecycle greenhouse gas emissions, aligning with international goals to decarbonize the aviation industry (George *et al*., 2021). As research and development continue to improve yield and processing efficiencies, Carinata stands out as a viable and sustainable feedstock that could play a crucial role in achieving the aviation sector's sustainability targets.

Despite its promising attributes, Carinata faces various constraints and challenges that impede its widespread adoption and commercialization. These constraints include limited genetic diversity (Warwick *et al*., 2006), late maturity, moderate susceptibility to pests and diseases, susceptibility to residual herbicides, suboptimal agronomic practices, and insufficient market infrastructure (Adeniji and Aloyce,2014; Seepaul *et al*., 2016, 2022). Addressing these challenges will involve concerted efforts from various stakeholders, including researchers, policymakers, farmers, investors, and industry players. Realizing Carinata's full potential can be achieved by addressing the existing constraints and creating an enabling environment for its widespread adoption and commercialization, as it is practiced in the southeast US, Canada, southeastern Australia, southern Europe and South America (Masum *et al*., 2022; Christ *et al*., 2020; Agrisoma-US, 2019; Basili and Rossi, 2018; Cardone *et al*., 2003; Carinata Development - Mustard 21 Canada Inc.; nuseed.com/carinata).

There are ongoing research initiatives and technological advancements aimed at overcoming the constraints associated with Carinata cultivation, in different developed countries such as the southeast US (Seepual *et al*., 2020), Canada (Agrisoma-US, 2019), southeastern Australia, southern Europe (Christ *et al*., 2020; Cardone *et al*., 2003); and developing countries including Brazil, Argentina, Uruguay and Paraguay (Nufarm, 2023) under contract cultivation systems. These include collaboration among the breeding programs focused on enhancing yield potential (seed and oil), developing pest and disease-resistant varieties, and optimizing agronomic practices for improved resource use efficiency (Seepaul *et al*., 2023; Marillia *et al*., 2014). Pryde and Rothfus (1989) highlighted that the future breeding of oilseed crops will see a shift from petro-chemistry to botano-chemistry, as it is the case of Carinata in recent years. Thus, with advanced breeding techniques such as induced mutations and genome sequencing, the shift will go further to geno-chemistry.

Moreover, the role of policy support, market development initiatives, and capacity building programs in promoting the sustainable production and utilization of Carinata is needed. By fostering collaboration and innovation across the value chain, stakeholders can unlock the full potential of Carinata as a versatile non-food oilseed crop with sustainable environmental and socio-economic benefits (Carlsson, 2009; Zanetti *et al*., 2009, 2013). It is obvious, Carinata holds great promise as a sustainable alternative for biofuel production, offering a viable solution to the challenges posed by conventional oilseed crops (Bozzini *et al*., 2007; Cardone *et al*., 2003; Gatto *et al*., 2015).

Therefore, this review aims to provide an overview of the current status of Ethiopian mustard cultivation, elucidate the constraints faced by farmers and researchers in integrating Carinata in agriculture and environmental sustainability, and delineate future prospects for its expansion and utilization as SAF.

Carinata Emerges as Biofuel Feedstock and New Non-Food Cover Crop. Ethiopian mustard has a huge potential to adapt to a wider range of agroecologies including the Mediterranean regions. It is nowadays used as a cover crop without compromising the main crop season in Argentina, Uruguay, and the southeast US. It offers significant agronomic benefits, including soil erosion control, improved soil health, and weed suppression (Bhattarai *et al*., 2021; Seepaul *et al*., 2023; Lawton, 2019). Its deep root system enhances soil structure and promotes water infiltration, while its ability to anchor tightly to the soil during the winter season helps to reduce the need for synthetic fertilizers. As global interest in sustainable and environmentally friendly agricultural practices grows, Carinata's dual role in biofuel production and as a cover crop of positions it as a critical player in the future of sustainable farming (Seepaul *et al*., 2023).

The growing demand for SAF, driven by international regulations and the aviation industry's commitment to reducing its carbon footprint, provides a robust market for Carinata-based biofuels. This is not only contributing to energy security but also stimulates rural economies and supports agricultural sustainability (Christ *et al*., 2020). The aviation industry is one of the most challenging sectors to decarbonize, to meet the United Nations' Sustainable Development Goals (SDGs). Thus, adoption of biofuels like Carinata-derived SAF, is crucial in bridging the gap between current fossil fuel dependence and future low-carbon alternatives (ICAO, 2019). Research and development efforts continue to optimize the yield and processing efficiency of Carinata oil, making it a more competitive and scalable solution as it was approved as SAF on 12 March 2021 by the International Civil Aviation Organization (ICAO). As the technology matures and production scales up, Carinata biofuel could become a mainstream component of the aviation fuel mix, driving the industry towards a more sustainable future (ICAO, 2021; RSB, 2023).

The Need to Shift Carinata from a Food Crop to Non-Food Feedstock. In Ethiopia and some African countries, Carinata is cultivated as a leafy vegetable by small-scale farmers with limited commercial oil uses. However, it is more commercially profitable as an alternative energy source and biofuel product in developed countries (Hagos *et al*., 2020). Nowadays, due to climate change impacts on agriculture and environmental sustainability, researchers, investors, the private sector and governmental and nongovernmental organizations search for new promising alternative plant-based biofuels that can be decarbonizing emissions to mitigate global warming.

Carinata is certified as a low-carbon feedstock for fuel and non-GMO high protein meal (George *et al*., 2021), hence, it is used for the climate-positive goals of many companies and policymakers. It can decarbonize, conserve moisture, and rejuvenate soil, suppresses weeds, doesn't compete with food crops, and supports biodiversity (*i.e.*, it preserves soil microbes and provides a food source for pollinators like honey bees) and a scalable brassica crop (Carinata benefits the environment, farmers and end-users | Nuseed; Seepaul *et al*., 2023). This is why the interest of the crop is changing from more food (leafy vegetable) to more sustainable biodiesel crop production (Gesch *et al*., 2015; Hagos *et al*., 2020). Likewise, Woods *et al*. (2010) highlighted that there is an increasing need for sustainable energy sources due to dwindling oil reserves, environmental conservation concerns, and economic risks. To address these challenges, various initiatives have been undertaken in recent years in the United States (US), Canada, Australia, Europe, China and India, and elsewhere to promote biofuel production (Basili and Rossi, 2018; Schnepf and Yacobucci, 2010; Zanetti *et al*., 2013). Hence, Carinata, as a non-food oilseed feed stock, is of interest due to seed oil's physical and chemical properties which is equivalent to petroleum-derived fuels (Cardone *et al*., 2003). In addition, the economic feasibility and environmental sustainability of producing second-generation biofuel like Carinata, in a context of rotation with wheat (and eventually other crops) is also contributing to mitigate the Indirect Land Use Change (ILUC) problems overseas in Italy (Basil and Rossi, 2018).

Carinata has indeed garnered attention as a promising biofuel alternative to petroleum. This fast-growing, low-input crop offers year-round rotation and has several advantages in the realm of sustainable energy. For instance, its seed has about 40-45% high-quality inedible oil in winter environments (Basil and Rossi, 2018; Hagos *et al*., 2020; Roslinsky *et al*., 2021; Seepaul *et al*., 2016), making it an excellent alternative for the production of second-generation biofuel feedstocks (Lau *et al*., 2024). Therefore, it is a certified and sustainable crop that is inserted between existing rotations, providing the farmer with more alternatives for the diversification of crops in rotation. It also emerges as a new biofuel alternative and considered as "drop-in" biofuel source, which can replace the jet fuel from conventional fuel to biofuel that meets the sustainability criteria (Bhatt *et al*., 2023). With this in mind, Carinata shows potential to solve many challenges faced in agricultural and environmental sustainability, and hence widely emerges as non-food feedstock than food crop.

Environmental Benefits of Ethiopian Mustard (Carinata). Reduced greenhouse gas (GHG) emissions. Carinata has the potential to significantly reduce GHG emissions compared to conventional fuels (Lawton, 2019). When grown as a biofuel feedstock, it absorbs carbon dioxide during its growth phase (Agrisoma-USA, 2019), effectively offsetting emissions when it's burned for fuel. The oil extracted from Carinata seeds can be processed into SAF, which significantly reduces by 68% GHG emissions compared to conventional fuels (Alam *et al*., 2021; Masum *et al*., 2022; RSB, 2023). The crop is thus receiving attention in the aviation industry that is responsible for 13% of GHG emissions from 45% of the total transport emission (Karami, 2021; Tesfaye *et al*., 2023).

Non-competitive with food crops. Carinata is a resilience winter oilseed, which can be integrated into the fallow seasons of existing rotations (Seepaul *et al*., 2023; Taheripour *et al*., 2022), where food crops struggle to grow. This eliminates the concern of competing with food crops production for sustaining agricultural resources and it is considered as a non-food feedstock crop. It is one of the only oilseeds, that has received the Roundtable of Sustainable Materials (RSB) certification for sustainable oil and meal in northern America (RSB, 2023), and has a low ILUC risk certification in South America (George *et al*., 2021). Generally, Carinata doesn't replace a farmer's main crop season, but instead provides a second crop grown between food crop rotations during the harsh winter season. Its robust nature allows it to thrive in marginal lands, where traditional crops might struggle, thus contributing to sustainable agricultural practices and enhancing food security in challenging environments.

Presence of high energy content. Carinata seeds are rich in non-food oil, containing around 40-45% oil content (Hagos *et al*., 2020; George *et al*., 2021; Roslinsky *et al*., 2021;Seepaul *et al*., 2015, 2016;) as compared to camelina, canola, or sunflower seeds which have between 41% and 43% oil content (Sieverding *et al*., 2016). This high energy density makes it a suitable candidate for biofuel production (Figure 1). This "drop-in" oilseed crop produces seeds rich in inedible oil, with an energy density that rivals traditional fossil fuels.

The oil extracted from Carinata seeds can be refined into biodiesel and aviation fuel, offering a renewable and sustainable energy source.

Its robust energy profile not only supports efficient fuel conversion but also positions, Carinata as a critical player in reducing greenhouse gas emissions (Alam *et al*., 2021). Carinata has a high potential for use as low-carbon feedstock and in the production of jet biofuel for the aviation industry due to its attractive fatty acid profile, such as high erucic acid (> 40%), low content of saturated fatty acids and minimal processing during refining (George *et al*., 2021; Seepaul *et al*., 2016).

Carinata biofuel can reduce carbon emissions by up to 68% (Alam et al., 2021; Masum et al, 2022; Seepaul et al., 2023). This feature makes it suitable for sustainable aviation fuel production, thereby reducing GHG emissions. The use of Carinata as "drop-in" renewable fuel has resulted in the expansion of the crop in the world due to the current strong demand to replace fossil fuel by biofuel (Seepaul et al., 2021).

A) Carinata scalable from "field to flight" or from "seed to sky" concepts

B) A jet refuels: replacing petroleum-based aviation fuel with sustainable aviation fuel derived from Carinata

Figure 1. The use of Carinata as biofuels. (A) Biofuel derived from Carinata and (B) A jet refueling using Carinata-derived fuel (Source: Seepaul *et al*., 2019; Jet fuel Getty images).

Crop rotation benefits. Carinata can be integrated into crop rotation systems, providing agronomic benefits such as weed and pest suppression and improved soil health. Integrating Carinata into crop rotation systems offers numerous agronomic and environmental benefits (Tiwari *et al*., 2021). It requires limited herbicides, which ultimately reduces environmental impact due to the crop's aggressive nature, enabling it to outcompete many winter weeds (Seepaul *et al*., 2019). Carinata serves as an effective rotational crop, particularly in regions with semi-arid climates or marginal lands, where traditional crops may not thrive. For instance, Iboyi *et al*. (2023) highlighted that double-cropping Carinata between summer crops has potential to boost grower revenue and increase land use efficiency in the southeast US. Similarly, rotating Carinata with peanut needs critical agronomic practices since peanut is the second summer pollutant energy crop after corn, thus Carinata should be planted before peanut to decrease the risk yield of Carinata (Karmi, 2021). Indeed, its deep root system plays a crucial role in improving soil structure, enhancing water infiltration, and preventing erosion. This deep rooting also helps break up soil compaction and promotes nutrient cycling, making the soil more fertile and better prepared for subsequent crops. Furthermore, Carinata can help manage pests and diseases by interrupting the life cycles of pathogens that affect other crops, thereby reducing the need for chemical inputs (Rahman *et al*., 2018; Seepaul *et al*., 2016). Hence, the addition of Carinata to crop rotations can also increase biodiversity on farms, which is beneficial for ecosystem health. Overall, Carinata not only provides a sustainable feedstock for biofuel production but also enhances soil health and farm productivity, contributing to more resilient agricultural systems.

Economic viability for farmers. Growing Carinata can provide an additional income stream for farmers, especially in regions where traditional crops face drought or poor soil quality. According to Seepual *et al*. (2019), growing Carinata as a winter crop has two-fold benefits: (1) increases farmer's revenue and (2) provides ecosystem services.

Carinata shows significant economic viability for farmers, particularly those in semi-arid regions, cooler temperatures, and areas with marginal lands (Seepual *et al*., 2023). Hence, Carinata has resilience to harsh growing conditions and its low input requirements make it an attractive option for maximizing land use efficiency and reducing the financial risks associated with crop failure. As a non-food crop, it does not compete with food production, allowing farmers to diversify their income sources without disrupting their primary agricultural activities (Alam *et al*., 2021).

George *et al*. (2021) highlighted that Carinata can be commercialized as a winter cash crop in the southeast US for renewable fuels and bio-products. Carinata has the potential to be compatible with existing agricultural infrastructure, which means farmers do not need substantial new investments to cultivate and process Carinata (RSB, 2023). Additionally, the growing demand for SAF provides a profitable market for Carinata oil, additional revenue from animal feed during oil extraction (Schulmeister *et al*., 2019; 2021). This economic potential should be further enhanced by governmental and industry incentives aimed at promoting renewable energy sources. According to Seepaul *et al*. (2023), the economic modeling has shown that crop rotations that include Carinata and soybean were more profitable than winter fallow. Therefore, integrating Carinata into farmers' crop rotation systems can improve their soil health and productivity and tap into emerging markets, thereby enhancing their economic sustainability and resilience.

Potential for SAF feedstock. Carinata, 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, biodiesel, renewable diesel, and a suite of value-added co-products (George *et al.*, 2021). Furthermore, the plant's adaptability to various climates and soils enhances its potential as a globally significant energy crop. This could significantly reduce the carbon footprint of air travel (Alam et al., 2021). The potential of Carinata-derived SAF extends beyond environmental benefits, offering producers economic and financial benefits (Christ et al., 2020) and contributing to rural development. As research and production techniques advance, Carinata is poised to become a key player in the transition to sustainable aviation, providing a scalable and renewable alternative to conventional aviation fuels (Masum et al., 2022).

Carinata holds great promises as a scalable biofuel in the aviation industry, offering a sustainable alternative to traditional fossil fuels, and is considered as a successful golden opportunity feedstock. It is listed by the ICAO as a SAF feedstock with a similar GHG footprint as waste and residuals, like used cooking oil. The use of Carinata for producing SAF provides several advantages relative to other potential crops (Karami, 2021). As airlines and regulatory bodies increasingly prioritize reducing carbon emissions, biofuels derived from Carinata present an attractive solution for mitigating the environmental impact of air travel (Carlsson, 2009; RSB, 2023; Lau et al., 2024). One of the key advantages of Carinata biofuel is its compatibility with existing aviation infrastructure, requiring no modifications to aircraft engines or fueling systems (drop-in), thus enabling a smooth transition to sustainable aviation fuels (Sustainability Reports-Nufarm, 2023; RSB, 2023).

Furthermore, the scalability and versatility of Carinata cultivation make it well-suited for meeting the growing demand for SAF (Seepual *et al*., 2023). With advancements in agricultural technology and farming practices, the production of Carinata can be scaled up to meet the needs of the aviation industry without compromising food security or biodiversity. As research and development in biofuel technology continue to advance, Carinata biofuel holds the potential to play a significant role in reducing the aviation sector's reliance on fossil fuels and achieving long-term sustainability goals (RSB, 2023).

Generally, Carinata biofuel presents a compelling opportunity to address the environmental challenges associated with aviation while promoting sustainable agriculture and energy security. With continued investment and support from stakeholders across the aviation industry, Carinata biofuel has the potential to revolutionize air travel by offering a cleaner, greener alternative to traditional jet fuel.

Carinata as Global Agribusiness Nuseed. Carinata is emerging as a significant global agribusiness Nuseed with promising applications in both agricultural and industrial sectors (Figure 2) than other feedstock cover crops (https://www.agribusinessreview.com/nufarm). It is one of the top four Nufarm agribusiness seed technologies platforms (i.e., Sunflower, Canola, Sorghum, and Carinata). Among the Nuseed crops, Nuseed Carinata is attractive for several reasons, including its involvement with farmers from before the crop even goes in the ground (https://nuseed.com/Carinata/)

There is ongoing research on evaluating advanced Carinata lines. For instance, in plot studies, Nujet 400 certified Carinata cultivar matured in 170 to 180 days and produced approximately 2,800 kg/ha (Seepaul et al., 2023). Therefore, growing Nuseed Carinata on existing farmland, after the main crop harvest and before the next season’s planting, helps protect land, sequester carbon, and improve conditions for the following main crop (Seepaul et al., 2023). Nuseed Carinata has the environmental benefits of a typical cover crop with added profitability potential through yield and sustainability (Malins, 2022).

Nuseed Carinata is a non-food cover crop that can be used to produce low-carbon biofuel feedstock that is independently certified, sustainable, and scalable (Figure 2). Increased global demand for biofuels is being driven by the need to access sustainable sources of energy to help achieve global GHG reduction targets. Nuseed Carinata is a proven, “drop-in”, resilient crop solution for biofuel processors that’s ready to scale globally on existing farmland between main food crops (nuseed.com/us/Carinata). Hence, Nuseed Carinata demonstrates how agriculture and energy companies can work together to meet the demand for biofuels that lower lifecycle carbon emissions.

As Carinata is developed globally by Nuseed, it signifies the company's commitment to addressing global challenges such as energy security, climate change, and sustainable agriculture. By promoting the cultivation of Carinata and offering related agricultural solutions, the Nuseed aims to contribute to a more sustainable and resilient agricultural sector worldwide. Therefore, Nuseed Carinata oil is recognized by ICAO (2021) for industry-leading GHG reductions similar to waste and used cooking oil (UCO). It’s a scalable, lower-carbon drop-in replacement for conventional fuels that enables transport sectors to decrease carbon without the delay, expense, and carbon footprint of retrofitting existing fleets. Nuseed Carinata has numerous benefits over other SAF (Table 1).

A) Nujet 400 certified hybrid Carinata seed (above) and Nujet 400 grown in Texas field (below), it is the first ever *Brassica Carinata* hybrid cover crop

B) Nuseed Carinata tap roots tightly anchor soil

Figure 2. Nuseed Carinata at the field: **A)** certified Carinata and Nujet 400 and **B)** Nuseed Carinata tap roots (picture adopted

Many researchers proved that seeds of Carinata are rich in oil, which can be converted into biojet fuel, biodiesel, and other bioproducts, which is crucial for achieving environmental sustainability goals (Agrisoma-USA, 2019; Basil and Rossi, 2018; Lawton, 2019). This aligns with the global shift towards renewable energy sources and the reduction of carbon footprints. That is why major aviation companies and energy corporations are increasingly investing in Carinata as a sustainable alternative to fossil fuels.

To sum up, the global interest in Carinata is driven by its contribution to the circular economy. By integrating Carinata into agricultural and industrial systems, it is possible to create a closed-loop system where waste products are minimized, and resources are reused efficiently. This is not only supports environmental sustainability but also promotes economic viability for farmers and industries alike. As research and development continue to optimize Carinata breeding, cultivation practices, and processing technologies, its role as a global agribusiness Nuseed is set to expand, making it a key player in the quest for sustainable development and climate resilience.

Table 1. Carinata nuseed feedstock comparison with other sustainable aviation fuel (SAF) feedstocks (https://nuseed.com/Carinata/;_Lau *et al*., 2024).

Type of feedstock generation	Types of SAF feedstocks	**Environmental sustainability and economic benefits**					
		Cover crop	Non-food	Removes Atmospheric Carbon/Builds Soil Carbon	Scalable production	ICAO Approved For SAF	Fully Non-GMO Plant Protein Source
1st generation	Canola			✓	✓	✓	
	Palm			✓	✓		
	Soya			✓	✓	✓	
	Sunflower	✓		✓	✓		
	Corn gains	✓		✓	✓		
2nd generation	Carinata	✓	✓	✓	✓	✓	✓
	Lignocellulosic biomass		✓			✓	
	Camelina		✓			✓	
	Castor		✓			✓	
	Tallow		✓			✓	
	Used cooking oils		✓			✓	

Global Carinata Constraints. Despite its potential, Carinata faces constraints that hinder its widespread adoption and cultivation on existing cultivation techniques. One of the primary challenges is the lack of established markets and supply chains for Carinata producers (Karami, 2021), even though few significant integrated private companies have been started. While the biofuel industry shows interest in Carinata oil, the market demand is not yet sufficiently developed to encourage large-scale cultivation. For instance, farmers in the southeast US identified barriers to Carinata adoption at multiple scales, such as industry responsibility, Carinata variety improvement, and land grant extension activities (Christa *et al*., 2020). Carinata as a biofuel feedstock, is also a new crop to many regions worldwide, therefore, limited information on agronomic practices for successful production is available (RSB, 2023).

Farmers' attitudes towards adopting bioenergy crops are also affected by behavioral factors, such as the influence of neighboring farmers and individual risk preferences (Ullah, 2022). Some farmers in Florida and Brazil may be hesitant to adopt as a new cover crop without stable prices, which creates a significant barrier to entry. Another constraint is the limited availability of optimized agronomic practices and technical knowledge. Additionally, Carinata is susceptible to residual herbicides, thus fitting it into existing crop rotations is a big challenge (Seepaul *et al*., 2016, 2022). As it is a relatively new crop outside its native region, research on best practices for planting, growing, and harvesting Carinata is still in its promising stages. Hence, small-scale farmers may not have access to adequate information on pest management, fertilization, and irrigation specific to Carinata, leading to suboptimal yields and increased risks. Moreover, data on historical yield and price for new Carinata growers as an energy crop is limited (Karami, 2021). Therefore, involving multiple stakeholder groups for establishing the supply chain of Carinata-based SAF production with extension services and agricultural training programs need to be developed and disseminated to bridge this knowledge gap (Alam *et al*., 2021; Masum *et al*., 2023).

Furthermore, breeding programs for Carinata are not as advanced as those for other major crops, resulting in limited availability of high-yielding, disease-resistant varieties. Breeding efforts are crucial for improving the crop's resilience to biotic and abiotic stresses with climate change and enhancing its sustainable oil content. Carinata has a very low crossability with other Brassicas including *Brassica napus*, however, it has been suggested as a platform for the production of technical oil qualities, and recombinant proteins (Chaudhary *et al*., 1998; Jadhav *et al*., 2005). Until more robust and adaptable varieties are developed, farmers may face difficulties in achieving consistent and profitable production levels. With this, there is no clear information on the economics of Carinata-based SAF production, which is practically missing at the supply chain level for ascertaining a realistic overall cost, and hence as an energy crop limits the prediction of net present values using the exciting data for simulation (Karami, 2021).

Carinata is generally susceptible to residual herbicides. For instance, Seepaul *et al*. (2023), highlighted that herbicides used in cotton or peanut may reduce Carinata establishment, growth, and yield. In temperate climates, planting Carinata in late November may results in increased pest damage and late harvest. Likewise, lack of selective herbicides for post-emergence control of broadleaf weeds once Carinata is established is another challenge. Moreover, like other Brassica crops, Carinata should not be grown every year but once every three years on the same field to reduce disease problems (George *et al*., 2021; Seepaul *et al*., 2023).

Environmental constraints also pose significant challenges on Carinata, while adaptable to various conditions, may still face issues in regions with extreme weather patterns, such as prolonged droughts or excessive rainfall (irrigation), which can adversely affect crop performance and promotes disease emergence (Seepaul *et al*., 2019, 2023). Moreover, the crop's introduction into non-native ecosystems requires careful management to avoid potential ecological impacts, such as social welfare and competition with local flora or the unintended spread of pests and diseases. Additionally, economic and policy-related constraints cannot be overlooked. Christ *et al*. (2020) reported that Carinata promotion and expansion reinforces the complex interconnectivity of factors influencing adoption decision making and highlights the importance of clearly defining stakeholder roles within the public-private partnerships.

The success of Carinata as a global agribusiness Nuseed needs supportive policies and incentives from governments and international organizations (IRENA, 2019). Without subsidies, research funding, and favorable regulatory frameworks, it is difficult to stimulate investment in Carinata production and processing infrastructure. Moreover, the competition with established biofuel feedstocks and other crops for limited agricultural resources poses an ongoing challenge, necessitating strategic planning and coordinated efforts (IRENA, 2019) to integrate Carinata into existing agricultural systems sustainably.

Generally, Carinata constraints encompass a range of challenges and limitations that affect the current demand for biofuel jet adoption of Carinata as a sustainable and scalable crop. One significant constraint is the variability in regulatory frameworks across different regions, which can hinder the commercialization and trade of Carinata seeds and products. Furthermore, the limited information gap to access in suitable agricultural land and water resources like in developing countries, particularly in regions facing land use competition and water scarcity is challenge. Another crucial factor is the need for further research and development to optimize agronomic practices, enhance crop yields, and improve the efficiency of Carinata-based biofuel production processes (Ullah, 2022). Furthermore, economic factors such as market demand, price volatility, and investment in infrastructure can also influence the viability of Carinata cultivation on a global scale (Karami, 2021). Therefore, addressing these constraints requires collaboration network among stakeholders, including government agencies, research institutions, agricultural companies, and farmers, to develop tailored solutions and promote the sustainable integration of Carinata into global agricultural systems.

Future Prospectives of Carinata. Carinata is promising, driven by its potential to address global challenges in sustainable agriculture and renewable and traceable energy (George *et al*., 2021; Roslinsky *et al*., 2021; Seepaul *et al*., 2022). As the world increasingly seeks alternatives to fossil-based fuels, Carinata's high oil content (Seepaul *et al*., 2023) and suitability for biofuel production (Alam *et al*., 2021; Masum *et al*., 2023) position it as a key player in the green energy transition. Advances in agricultural biotechnology and breeding programs are expected to develop higher-yielding, short growth period, more resilient Carinata varieties (Seepaul *et al*., 2023), enhancing its commercial viability and attractiveness to farmers. These improvements could lead to widespread adoption, especially in regions with marginal lands where other crops may not thrive, thereby contributing to more sustainable agricultural practices and increased food security.

In addition to its biofuel potential, Carinata's role in promoting environmental sustainability and biodiversity is likely to expand (George *et al*., 2021; Seepaul *et al*., 2019, 2020, 2023). As a cover crop, Carinata can improve soil health, reduce erosion, and suppress weeds, making it an integral part of crop rotation systems (Bhattarai, 2019; Lawton, 2019). The development of best practices and agronomic guidelines will further support farmers in optimizing Carinata cultivation. Additionally, its use as a cover crop can help sequester carbon and mitigate the effects of climate change, aligning with global efforts to reduce GHG emissions (Karami, 2021; Lawton, 2019). As awareness of these environmental benefits grows, Carinata could see increased adoption in both developed and developing countries. Moreover, the economic prospects of Carinata are bolstered by its potential to create new markets and value chains. The integration of Carinata into the circular economy model, where its by-products are utilized efficiently, can stimulate economic growth and provide additional income streams for farmers. For instance, the residual biomass after oil extraction can be used as animal or poultry feed or in bio-based materials (Schulmeister *et al*., 2019, 2021; Yadav *et al*., 2022), adding value beyond the primary biofuel production. Notably, this multi-purpose utility can attract investments and foster partnerships between agricultural sectors and industries, enhancing the overall economic sustainability of Carinata cultivation likely to meet the United States' Sustainable Development Goals of number seven (affordable and clean energy) and thirteen (climate action).

International collaboration and supportive policies will play a crucial role in realizing the future potential of Carinata (ICAO, 2021; RSB, 2023). Governments, research institutions, and private enterprises must work together to create a conducive environment for Carinata development.

This includes funding for research and development, incentives for farmers, and the establishment of robust supply chains and processing facilities (Alam et al., 2021; Masum et al., 2022). Generally, as these frameworks take shape, Carinata could become a multi-purpose oilseed crop in the global agricultural landscape, contributing significantly to climate change mitigation, business economy, environmental sustainability, and sustainable renewable energy sectors. The ongoing commitment to innovation and sustainable practices will ensure that Carinata reaches its full potential as a versatile and valuable crop for the future.

Conclusion

Ethiopian mustard, also known as Carinata is gaining recognition as a valuable non-food feedstock with significant potential for enhancing environmental sustainability. Its adaptability, high biomass production, and soil-improving properties make it as a golden opportunity for biofuel production and sustainable agricultural practices. Despite its promising attributes, the full potential of Carinata is yet to be realized due to existing challenges such as optimizing cultivation techniques, improving pest resistance, and advancing biofuel distribution methods. Addressing these constraints through dedicated research and development will be crucial. As Carinata becomes more agro-business and high-value crop, and produced by private companies at large, its economic contribution will increase and the supply chain will be improved for the future sustainable aviation fuel supply and mitigations. As these challenges are solved, Carinata can play a pivotal role in promoting sustainable energy and agricultural systems, contributing to global efforts to reduce environmental impact and promote ecological balance. Different researchers and stakeholders have stands out Carinata as a promising crop with multifaceted benefits for sustainable agriculture and biofuel production. Its current status reflects its potential for high biomass yield, adaptability to marginal lands, and valuable contribution to soil health. However, realizing its full potential in developing and small-scale farming societies is hindered by constraints such as the need for improved agronomic practices, pest and disease management, and efficient biofuel processing technologies. Addressing these challenges through targeted research and innovation is essential for maximizing Carinata's benefits. Looking ahead, the future prospects for Carinata are bright, with the crop poised to play a significant role in advancing renewable energy sources and promoting environmentally sustainable farming practices, ultimately supporting global sustainability goals.

Acknowledgment

This paper is an output of the First Author's Post-Doc Fellowship Research at Makerere University Regional Centre for Crop Improvement funded by the Regional Universities Forum for Capacity Building in Agriculture (RUFORUM) grant from Carnegie Corporation of New York.

Declaration of No Conflict of Interest

The Authors declare No Conflict of Interest in this paper

References

Adeniji, O. T. and Aloyce, A. 2014. Participatory identification of agronomic and leaf quality traits in Ethiopian mustard (*Brassica carinata* A. Braun) genotypes in Tanzania. *Agriculture and Biology Journal of North America* 5 (6): 245–251. https://doi.org/10.5251/abjna.2014.5.6.245.251

Agrisoma, US. 2019. Southeast US 2017-18 Carinata Management Handbook.

Alam, A., Masum, M. F. H. and Dwivedi, P. 2021. Break-even price and carbon emissions of carinata-based sustainable aviation fuel production in the Southeast United States. *GCB Bioenergy* 13 (11): 1800–1813. https:// doi.org/10.1111/ gcbb.12888

Bhatt, A.H., Yimin, Z., Anelia, M., Emily, N., Kristi, M., Bruno, K. and Ling, T. 2022. Evaluation of performance variables to accelerate the deployment of sustainable aviation fuels at a regional scale. Energy Conversion and Management 275.

Basili, M. and Rossi, M. A. 2018. Brassica carinata- derived biodiesel production: economics, sus tainability and policies. The Italian case. Jour nal of Cleaner Production, 191, 40–47. https://doi.org/10.1016/j.jclepro.2018.03.306

Bhattarai, D. 2019. Brassica Carinata Growth and Yield Response to Nitrogen and Sulfur Fertiliz ers and Impacts on Selected Soil Parameters and GHG Fluxes. 115.

Bhattarai, D., Abagandura, G. O., Nleya, T., and Ku mar, S. 2021. Responses of soil surface green house gas emissions to nitrogen and sulfur fer tilizer rates to Brassica carinata grown as a bio- jet fuel. GCB Bioenergy, 13(4), 627–639. https://doi.org/10.1111/gcbb.12784

Bozzini, A., Calcagno, F. and Soare, T., Bozzini, A., Cal- cagno, F. and Soare, T. 2007. "Sincron", A new Brassica carinata cultivar for biodiesel produc- tion. Helia 46:207–214. https://doi.org/10.2298/HEL0746207B

Cardone, M., Mazzoncini, M., Menini, S., Rocco, V., Sena- tore, A., Seggiani, M., and Vitolo, S. 2003. Brassica carinata as an alternative oil crop for the production of biodiesel in Italy: Agronomic evaluation, fuel pro- duction by transesterification and characterization. Biomass and Bioenergy 25 (6): 623–636. https://doi.org/10.1016/S0961-9534(03)00058-8

Carlsson, A. S. 2009. Plant oils as feedstock alternatives to petroleum - A short survey of potential oil crop platforms.In:Biochimie, 91 (6): 665–670).https://doi.org/10.1016/ j.biochi.2009.03.021

Chaudhary, S., Parmenter, D.L. and Moloney, M.M. 1998. Transgenic *Brassica carinata* as a vehicle for the pro duction of recombinant proteins in seeds. *Plant Cell Reports* 17 (3): 195–200. https://doi.org/10.1007/s002990050377

Christa, B., Wendy-Lin, B., Broughtonb, D, Ramdeo, S. and Daniel, G. 2020. In pursuit of a homegrown biofuel: Navigating systems of partnership, stakeholder knowledge, and adoption of *Brassica carinata* in the Southeast United States, *Energy Sources and Social science* 70. https://doi.org/10.1016/j.erss.2020.101665

Carinata FAQ | Nuseed Global, accessed on June 20, 2024.

https://nuseed.com/Carinata-benefits, accessed on 15 June 2024.

Del Gatto, A., Melilli, M. G., Raccuia, S. A., Pieri, S., Mango ni, L., Pacifico, D., Signor, M., Duca, D., Foppa Pedretti, E. and Mengarelli, C. 2015. A comparative study of oilseed crops (*Brassica napus* L. subsp. *oleifer*a and *Brassica carinata* A. Braun) in the bio diesel production chain and their adaptability to dif ferent Italian areas. *Industrial Crops and Products*, 75:98–107.https://doi.org/10.1016/

George, S., Seepaul, R., Geller, D., Dwivedi, P., DiLorenzo, N., Altman, R., Coppola, E., Miller, S. A., Bennett, R., Johnston, G., Streit, L., Csonka, S., Field, J., Marois, J., Wright, D., Small, I. M. and Philippidis, G. P. 2021. A regional inter-disciplinary partnership focusing on the development of a carinata-centered bioeconomy. *GCB Bioenergy* 13 (7): 1018–1029. https://doi.org/10.1111/gcbb.12828

Gesch, R.W., Isbell, T.A., Oblath, E.A., Allen, B.L., Archer, D.W., Brown, J., Jabro J.D., Kiniry J.R. and Long, D.S. 2015. Comparison of several Brassica species in the north-central U.S. for potential jet fuel feed stock. *Industrial Crops and Products* 75: 2–7.

Gittens, A., Alexandre, J., Eric F., Simon, H. and Fang, L. 2019. Aviation Benefits Report.

https://nuseed.com/Carinata/. Nuseed carinata, accessed on 20 June, 2024.

https://www.finboot.com/post/sustainable-aviation-fuels-decarbonization-of-air-transport, posted by Juan Mi guel Perez, CEO, on 13th March, 2024.

Hagos, R., Shaibu, A. S., Zhang, L., Cai, X., Liang, J. and Wu, J. 2020. Ethiopian Mustard (*Brassica carinata* A. Braun) as an Alternative Energy Source and Sus tainable Crop. 1–13.

Iboyi, J. E., Mulvaney, M. J., Leon, R. G., Balkcom, K. S., Bashyal, M., Devkota, P. and Small, I. M. 2023. Double-cropping effects of *Brassica carinata* and summer crops: I. Effects of summer cropping histo ry on Carinata production. *Industrial Crops and Products* 194: 116364. https://doi.org/10.1016/ j.indcrop.2023.116364

IRENA (International Renewable Energy Agency). 2019. Ad vanced biofuels. What holds them back? Internation al Renewable Energy Agency, Abu Dhabi.

ICAO (International Civil Aviation Organization). 2019. Envisioning a "zero climate impact" international aviation pathway towards 2050: How governments and the aviation industry can step up amidst the climate emergency for a sustainable aviation fu ture.

ICAO (International Civil Aviation Organization). 2021. Doc ument International Civil Aviation Organization CORSIA. Default life cycle emissions values for CORSIA eligible fuels, CRSIA carbon offsetting and reduction scheme for international aviation.

Jadhav, A., Marillia, E. F., Babic, V., Giblin, E. M., Cahoon, E. B., Kinney, A. J., Mietkiewska, E., Brost, J. M. and Taylor, D. C. 2005. Production of 22:2Δ5, Δ13 and 20:1Δ5 in *Brassica carinata* and soybean breeding lines via introduction of Limnanthes genes. *Molecular Breeding* 15 (2): 157–167. https://doi.org/10.1007/s11032-004-4730-1

Karami, O. 2021. Assessing Environmental and Economic Impacts of Carinata-Based Sustainable Aviation Fuel Production in the southeast United States, PhD Thesis, Georgia University

Lau, J. I. C., Wang, Y. S., Ang, T., Seo, J. C. F., Khadaroo, S. N. B. A., Chew, J. J., Ng Kay Lup, A. and Sunar so, J. 2024. Emerging technologies, policies and challenges toward implementing sustainable avia tion fuel (SAF). *Biomass and Bioenergy* 186. Else vier Ltd. https://doi.org/10.1016/j.biombioe.2024.107277

Lawton, K. 2019. Growing Carinata in the Southeast U.S. *Crops & Soils* 52 (5) 18–21. https://doi.org/10.2134/cs2019.52.0506

Malins, C. 2022. Cerulogy Multiple and cover cropping in Brazil Status and opportunities for biofuel produc tion. www.cerulogy.com

Masum, F. H., Coppola, E., Field, J., Geller, D., George, S., Miller, J., Mulvaney, M. J., Nana, S., Seepaul, R., Small, I., Wright, D. and Dwivedi, P. 2022. Supply Chain Optimization of Sustainable Aviation Fuel from Carinata in the Southeast United States. *Re newable and Sustainable Energy* 171 (113032).

Marillia, E. F., Francis, T., Falk, K. C., Smith, M. and Tay lor, D. C. 2014. Palliser's promise: *Brassica carina ta*, An emerging western Canadian crop for delivery of new bio-industrial oil feedstocks. *Biocatalysis and Agricultural Biotechnology* 3 (1): 65–74. https://doi.org/10.1016/j.bcab.2013.09.012

Mehta, R. G., Murillo, G., Naithani, R. and Peng, X. 2010. Cancer chemoprevention by natural products: How far have we come? In *Pharmaceutical Research*, 27 (6): 950–961). https://doi.org/10.1007/s11095-010-0085-y

Mohd Saad, N. S., Severn-Ellis, A. A., Pradhan, A., Ed wards, D. and Batley, J. 2021. Genomics Armed with Diversity Leads the Way in Brassica Improve ment in a Changing Global Environment. In *Fron tiers in Genetics* 12, Frontiers Media S.A. https://doi.org/10.3389/fgene.2021.600789

Nufarm. 2023. Sustainability Reports-Nufarm. https://nufarm.com, accessed on 24 June, 2024.

Nufarm. 2024. Nufarm & Nuseed in the news – Cover story in Agribusiness Review, https://www.agribusinessreview.com/nufarm, accessed on June, 2024.

Odongo, G.A., Schlotz, N., Herz, C., Hanschen, F.S., Balder mann, S., Neugart, S., Trierweiler, B., Frommherz, L., Franz, C.M.A.P., Ngwene, B., Luvonga, A.W., Schreiner, M., Rohn, S. and Lamy, E. 2017. The role of plant processing for the cancer preventive potential of Ethiopian kale (*Brassica carinata*). *Food and Nutri - tionResearch* 61 (1). https://doi.org/10.1080/16546628.2017.1271527

Paula, E. M., Lorrayny, G. da S., Xiaoxia, D. and Antonio, P. F. 2019. Feeding Canola, Camelina, and Carinata Meals to Ruminants, *animals* 9 (704). https://doi.org/10.3390/ani9100704

Rahman, M., Khatun, A., Liu, L. and Barkla, B. J. 2018. Bras sicaceae mustards: Traditional and agronomic uses in Australia and New Zealand. *Molecules* 23 (1): 1–18. https://doi.org/10.3390/molecules23010231

Roslinsky, V., Falk, K.C., Gaebelein, R., Mason, A.S. and Eynck, C. 2021. Development of B. carinata with super-high erucic acid content through interspecific hybridization. *Theoretical and Applied Genetics* 134 (10) :3167–3181. https://doi.org/10.1007/s00122-021- 03883-2

RSB (Roundtable on Sustainable Biomaterial). 202. RSB Principles and Criteria RSB-Roundtable on Sus tainable Biomaterials Association International Environment House, RSB Principles & Crite ria. www.rsb.org

Schnepf, R. and Yacobucci, B. D. 2013. Renewable Fuel Standard (RFS): *Overview and Issues*. www.crs.gov.

Schulmeister, T.M., Ruiz-Moreno, M., Silva, G.M., Gar cia-Ascolani, M., Ciriaco, F.M., Henry, D.D., Lamb, G.C., Dubeux, J.C.B. and DiLorenzo, N. 2019. Evaluation of *Brassica carinata* meal as a protein supplement for growing beef heifers. *Jour nal of Animal Science* 97 (10): 4334–4340. https://doi.org/10.1093/jas/skz280

Schulmeister, T.M., Ruiz-Moreno, M., Silva, G.M., Garcia-Ascolani, M., Ciriaco, F.M., Henry, D.D., Lamb, G. C., Dubeux, J.C.B. and Dilorenzo, N. 2021. Characterization of dietary protein in *Brassica cari nata* meal when used as a protein supplement for beef cattle consuming a forage-based diet. *Journal of AnimalScience* 99 (1). https://doi.org/10.1093/jas/skaa383

Seepaul, R., Bliss, C. M., Wright, D. L., Marois, J. J., Leon, R., Dufault, N., George, S. and Olson, S. M. 2015. Carinata, the Jet Fuel Cover Crop 2015 Production Manual for the Southeast United States. *UF/IFAS Extension, University of Florida*, *SS-AGR-384* 1–8.

Seepaul, R., Bliss, C.M., Wright, D.L., Marois, J.J., Leon, R., Dufault, N., George, S. and Olson, S.M. 2016. Carinata, the Jet Fuel Cover Crop: Production Rec ommendations for the Southeast United States. http:// edis.ifas.ufl.edu.

Seepaul, R., Small, I.M., Mulvaney, M.J., George, S., Leon, R.G., Paula-Moraes, S.V., Geller, D. and Marois, J.J. 2019. Carinata, the Sustainable Crop for a Bio-Based Economy: 2018–2019 Production Recom mendations for the Southeast United States; Uni versity of Florida Institute of Food and Agricultur al Sciences: Gaines ville, FL, USA.

Seepaul, R., Michael, J. M., Ian, M. S. and Sheeja, G. 2020. Carinata growth, yield, and chemical composition responses to nitrogen fertilizer management. *Agronomy Journal* 1–15. https://doi.org/10.1002/agj2.20416

Seepaul, R., Kumar, S., Iboyi, J. E., Bashyal, M., Stansly, T. L., Bennett, R., Boote, K. J., Mulvaney, M. J., Small, I. M., George, S. and Wright, D. L. 2021. *Brassica carinata*: Biology and agronomy as a biofuel crop. *GCB Bioenergy* 13 (4): 582–599. https://doi.org/10.1111/gcbb.12804

2021 – 2022 Production Recommendations

Seepaul, R., Small, I. M., Devkota, P., Sintim, H. Y., Mulvaney, M. J., George, S., Leon, R. G., Paula-Moraes, V., Bennett, R., Pokrzywinski, A., Geller, D., Marois, J. J. and Wright, D. L. 2022. Carinata, the Sustainable Crop for a Bio-based Economy*:* for the Southeast USern United States. 2018–2019. https://edis.ifas.ufl.edu

Seepual, R., Small, I. M., Devkota, P., Sintim, H. Y., Mulvaney, M. J., Leon, R., Paula-Moraes, S., Esquivel,I., Bennett, R., Poknywinski, A., Geller, D., Marois, J. J. and Wright, D. L. 2023. Carinata, the Sustainable Crop for a Bio-based Economy: Production Recommendations for the Southeast United States. *EDIS*, (4). https://doi.org/10.32473/edis-ag389-2023

Sieverding, H. L., Zhao, X., Wei, L. and Stone, J. J. 2016. Life-Cycle Assessment of Oilseeds for Biojet Production Using Localized Cold-Press Extraction. *Journal of Environmental Quality* 45 (3): 967–976. https://doi.org/10.2134/jeq2015.06.0313

Taheripour, F., Sajedinia, E. and Karami, O. 2022. Oilseed Cover Crops for Sustainable Aviation Fuels Production and Reduction in Greenhouse Gas Emissions Through Land Use Savings. Front. Energy Res. 9:790421. https://doi.org/10.3389/fenrg.2021.790421

Tesfaye, M., Feyissa, T., Hailesilassie, T., Kanagarajan, S. and Zhu, L. H. 2023. Genetic Diversity and Population Structure in Ethiopian Mustard (*Brassica carinata* A. Braun) as Revealed by Single Nucleotide Polymorphism Markers. *Genes* 14 (9). https:// doi.org/10.3390/genes14091757

Tiwari, R., Reinhardt Piskáčková, T. A., Devkota, P., Mulvaney, M. J., Ferrell, J. A. and Leon, R. G. 2021. Growing winter *Brassica carinata* as part of a diversified crop rotation for integrated weed management. *GCB Bioenergy* 13 (3): 425–435. https://doi.org/10.1111/gcbb.12799

Ullah, K. M. 2022. Modeling Adoption of Carinata Production and Designing the Supply Chain of Carinata-Based Sustainable Aviation Fuel Production in The Southern United States, PhD Thesis, Georgia University

Valavanidis, A. 2022. Global Warming and Climate Change. Fossil fuels and anthropogenic activities have warmed the Earth's atmosphere, oceans, and land, University of Athens, Greece.

Warwick, S. I., Gugel, R. K., McDonald, T. and Falk, K. C. 2006. Genetic variation of Ethiopian mustard (*Brassica carinata* A. Braun) germplasm in western Canada. *Genetic Resources and Crop Evolution* 53 (2): 297–312. https://doi.org/10.1007/s10722-004-6108-y

World Economic Forum (WEF). 2024. Scaling Up Sustainable Aviation Fuel Supply: Overcoming Barriers in Europe, the US and the Middle East, *Insight Report*, March 2024: https://www3.weforum.org/docsWEF_Scaling_Sustainable_Aviation_Fuel_Supply_2024.pdf

Yadav S., Po-Yun, T., Janghan C., Amit Kumar S. and Woo, K. K. 2021. Nutrient profile and effects of Carinata meal as alternative feed ingredient on broiler performance, tight junction gene expression and intestinal morphology, *Poultry Science* 101:101411.https://doi.org/10.1016/j.psj.2021.101411

Zanetti, F., Monti, A. and Berti, M.T. 2013. Challenges and opportunities for new industrial oilseed crops in EU-27: A review. *Industrial Crops and Products* 50: 580–595. https://doi.org/10.1016/j.indcrop.2013.08.030

Zanetti, F., Vamerali, T. and Mosca, G. 2009. Yield and oil variability in modern varieties of high-erucic winter oilseed rape (*Brassica napus* L. var. *oleifera*) and Ethiopian mustard (*Brassica carinata* A. Braun) under reduced agricultural inputs. *Industrial Crops and Products* 30 (2): 265–270. https://doi.org/10.1016/j.indcrop.2009.05.002