

Article

An Assessment of the Potential to Produce Commercially Valuable Lipids on Highway Right-of-Way Land Areas Located Within the Southeastern United States

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Abstract: Right-of-way (ROW) land areas are required for all publicly owned transportation roadways representing over 40 million acres within the US alone. These relatively unused land assets could support potential farming land for plants and algae that contain high levels of lipids that could be used in the energy industry as an alternative fuel source. This process would offer many benefits including more efficient use of public land, eliminating mowing maintenance, increasing the bioenergy use in the US, providing visually appealing viewscapes, and helping to naturally reduce localized carbon dioxide. This paper analyzed the feasibility and potential optimization strategies of using this concept in the South-Eastern United States by scaling and comparing many of the benefits and risks associated with the selected lipid sources (soybeans, flax, sunflowers, Tung trees, Chinese tallow tree, and microalgae). Based on this assessment, the most attractive option appears to be growing flax in the winter and sunflowers in the summer with Tung Trees grown year-round as an alternative option. This would maximize lipids output while preserving and enhancing right-of-way land areas.

Keywords: lipids; biocrops; sustainable infrastructure; highway right of way land; biofuels

1. Introduction

All publicly owned transportation roadways including interstates, federal highways, state highways, county roads, and municipal roads are constructed on right-of-way (ROW) land areas that support the constructed transportation infrastructure, maintenance areas, and safety buffer zones [1]. Generally, ROW land areas associated with municipal and county roadways are mainly tied to drainage ditches (if they are present) or to the shoulder areas. Thus, these roadways have minimal land areas. Conversely, federal and state highways often have much larger land spaces tied to their ROW areas. Whitesides and Hanks [2] estimated the total available (or open) highway ROW land areas in the US at about 40 million acres. Figure 1 presents a photo of a typical highway ROW land area. Other non-traditional public lands similar to highway ROWs that Whitesides and Hanks [2] also assessed were municipal



airports (2 million acres), railroad ROWs (1.2 million acres), and military base land areas (90 million acres). At a modest 30 gallons per acre of lipid (plant oil) production, this represents about 1.2 billion gallons of lipids produced if just the highway ROW land areas are cultivated representing about 2% of the total amount of petroleum diesel burned in the US per year. Or, roughly \$2.4 billion of market value for this amount of lipids produced (assuming a \$2.00/gallon price, which is approximately the recent historical average). Therefore, if only 50% of these lands did produce the marginal yield of 30 gallons/acre of lipids, this would represent over 600 million gallons of lipids produced per year or over \$1.2B worth of lipids per year at the modest \$2/gallon price point.



Figure 1. Photo of an example highway right-of-way (ROW) (Photo Source: Idaho Transportation Department).

ROW land areas associated with most federal and state highway systems not only have road drainage control areas, but buffer areas for crash prevention/control, emergency stopping areas, and maintenance zones. Some even have sound insulation zones (often shrubbery) and limited access zones for bikers and pedestrians. The land within ROW areas often require mowing and, sometimes, erosion control and drainage system maintenance [3]. Still, often significant expanses of open land are available with highway ROW land areas that are relatively under-utilized according to the 2011 USU study. Holland is currently evaluating using their roadway ROW land areas for growing plants with an emphasis on biofuels production [4]. They found that for every km of roadway, about 0.3 to 1.5 hectares of land is available for plant cultivation. In their case, they focused on raw biomass for lignocellulosic processing (via enzymatic, thermal, and chemical conversion) and not plants that could produce feedstocks with a broader industrial appeal—like lipids. They looked at trees (poplar and willow) and dense grasses (switchgrass, miscanthus, and reed canary grass). Willow was selected as the crop of choice with the results of the study indicating significant promise for using the ROW land areas as a key source of biofuel for power production in Holland.

2. Study Objective and Goals

The objective of this study was to add to the body of knowledge on making highways and roadways more sustainable by assessing the potential to produce industrially valuable lipids and proteins using

the ROW lands associated with this vast infrastructure system within the SE-US. A thorough assessment was performed with the information generated used to provide the foundation for conclusions as to which potential lipid-bearing crops held promise to be cultured on ROW lands within the SE-US Region. The goals of the study were to (a) Generate a body of information concerning issues that may impact the current design function of highway ROW land areas; (b) Provide a technical framework, based on literature, discussions with highway and lipid experts, and our own experiences/knowledge, concerning the characteristics and pros/cons of various candidate lipid-bearing crops for use within highway ROW land areas; and, (c) Use a two-phase, decisional methodology for selecting the most promising crop option.

3. Envisioning Green Roadways of the Future

Global urban areas have and continue to be major energy and chemical resource consumers with very little self-generated life supporting chemicals and fuels given back to the human populations living there. In essence, energy and chemical mass transport vectors across the globe face inward toward cities with almost nothing but waste exiting these vast areas of dense populations. These urban areas are served by billions of miles of highways and roadways connecting these urban areas with each other and the surrounding suburban and rural communities where the bulk of the energy and chemicals used in the urban areas are produced. Future truly sustainable urban areas need energy and chemical production feedstocks (raw materials entering conversion factories that exit as consumer goods-fuels, chemicals, food, etc.) that are produced near the urban area. Producing tomorrow's biofuels and bio-based chemicals will entail the vast culturing of chemical crops that may or may not be food sources for both humans and farm animals. Clearly, valuable traditional agricultural lands cannot be used to grow industrial feedstocks when their productivity is needed to produce foodstocks [4]. Alternative land must be identified and evaluated if tomorrow's bio-based industrial economy is going to be realized. This paper presents a review and assessment of the potential for using highway ROW land areas as agricultural land opportunities for growing primarily bio-based feedstocks for fuels and other chemicals [5]. This assessment does not include using the highway ROWs to potentially produce foodstocks as an option for these lands; albeit, growing food crops may be profitable and viable. However, our focus in this study is on chemical crops and not traditional agricultural opportunities tied to ROW lands. In any case, the ROW land areas represent a potentially untapped, non-traditional agricultural asset that may be used to support the future bio-based industrial economy. The concept of making highways and roadways more sustainable from every aspect ranging from construction to maintenance to usage to resource generation on and around the roads is an area of fast-growing interest to the global community [6].

It was not until 1988 that states became empowered by the Federal Highway Administration (FHWA) to decide whether or not power utility systems could be placed within interstate ROW areas [7]. Shortly after that, most states also implemented a similar policy for their state highways. Poe and Filosa [7] discussed how many state departments of transportation were investigating the use of their ROW land areas for alternative energy production. Energy technologies that they listed include solar, wind, and biomass production (via crops). Mainly, solar and wind energy have been investigated, with Europe and Canada having significant experience with using their ROW land areas for power generation [8]. Power generation, whether solar or wind, does require access to the grid so issues with grid input and access to power generation systems may be a challenge with some ROW siting scenarios. In the US, several interested state highway departments united to form the State Smart Transportation Initiative, which is housed at the University of Wisconsin and supported by the university and the Smart Growth America Consortium [9]. Within the database of the SSTI, several past alternative energy initiatives housed on highway ROW lands are described. Almost all are solar projects, but other energy technologies are detailed along with policy and technical issues that those parties interested in using highway ROW land areas for alternative energy production may have to address. The FHWA [10]

listed several successful solar energy projects on US highway ROW lands but present little information on other options, like biofuels feedstock crops being cultivated on ROW areas.

A few groups have studied growing biomass crops on highway ROW lands [2,11]. Whitesides and Hanks [2] performed a one-year assessment of planting two bioenergy crops, canola and safflower, during the growing years of 2007 and 2008. Unfortunately, the poor climate conditions (above-average temperatures and below-average rainfall) experienced during both years hindered crop production. Thus, USU concluded based on these data that it was not economically feasible to grow the crops but also acknowledged that they had to use data from two poor years for crop cultivation in Utah. In response to the interest in cultivating crops as biofuel feedstocks within essentially unused public lands, the US government working with Utah State University formed a consortium of federal and state highway agencies with vast acreage of open lands that can be utilized to grow biomass crops. This program is entitled the "Freeways to Fuel National Alliance" or F2F National Alliance. The goal of the F2F program is to investigate the use of ROW, airport, and military bases for growing biomass crops (trees are considered a crop). These land areas when totaled are significant in area and considered non-traditional, potential agricultural lands. Shi [11] evaluated growing switch grass along Illinois highway ROW lands as well as using collected corn stover (post-harvest corn stalks) as biomass fuel/co-fuel within the various power plants and public large boiler operations across the state. One issue they identified is the distance from crop sites to power plants (customers) and how transportation to less than ideal locations could be expensive since both the power plants and ROW areas are essentially preset. Shi [11] concludes that the ROW land-grown switchgrass was difficult to compete with coal for straight power costing. Shi [11] also concludes that the availability of cheap stover widely available across the state also made the economics of ROW energy crop cultivation an economically challenging option. However, it must be pointed out that Shi [11] was studying a crop that is competing as a straight burn-fuel and not one that is producing a higher valued product such as lipids, proteins, or carbohydrates. In these cases, the ROW crops are directly competing with the same crops grown on traditional, often privately held, agricultural lands.

4. Sustainable Energy and Sustainable Chemicals

Sustainable energy is also often referred to as "alternative energy." The term actually encompasses electrical power, transportation fuels, and heating/burner fuels [5]. Under electrical power, sustainable power can include direct power generation such as solar or wind energy while sustainable fuels can include gaseous (biogas or hydrogen), liquid fuels (ethanol or biodiesel), and solid fuels (biocoal and wood). Sustainable heating fuels are almost exclusively gases such as biogas and synthesis gas (syngas or producer gas) that are produced from the biological or thermal conversion of biomass, respectively. Sustainable transportation fuels, excluding electrical power (for this study was not considered a fuel), are produced from the biological, thermal, and/or physical conversion of living components into a fuel capable of being burned in engines [5,12–14]. Examples include ethanol, biodiesel, butanol, green diesel, hydrogen, and syngas. The bulk of bio-based transportation fuels used across the globe are liquid fuels (primary alcohol and bio-based diesels) that are used as petroleum-based fuels displacement fuels, and not today, as true replacement fuels [13,15]. It is realized that one could argue that fuel cells could also fit into the definition of transportation fuels that was used in this paper, but in our present context, we will not include fuel cells as a transportation fuel.

Often times, particularly with liquid sustainable fuels, co-products may be produced, which can reduce the overall selling price of the fuel [16,17]. Example co-products produced at sustainable fuels production facilities include dried distillers' grain at corn ethanol plants, ash fertilizer from syngas to power plants, and protein from microalgae to biodiesel facilities. When multiple fuels and/or co-products are produced within a facility using a biological agent (crop, waste biomass, etc.) as a feedstock, then this facility design is classified as a "biorefinery" [18]. Sustainable chemicals can be fuels and their production co-products, but they can also be chemicals produced from sustainable feedstocks that are not used for producing energy. Lipids are somewhat unique in that they are used

for producing energy (e.g., biodiesel or green diesel) and/or other chemicals (e.g., lipid nutraceuticals, polymers, and glues) within a \$25B global market [19]. This paper will focus on the production of lipids from cultured crops that are grown within the ROW areas of highway systems in the Gulf of Mexico Region of the US through the detailed assessment of which crops are the best options for producing lipids within these land areas and associated climate.

4.1. Lipids

Lipids are a class of organic chemicals that are used by living organisms for storage of energy reserves [20]. Plants contain oil, while animals contain fats—yet both are lipids. Oils and fats both fall under the chemical category known as lipids, which is a large group of complex organic chemicals widely used as feedstocks for many industrial products [5,21]. Non-fuel example products made from lipids include personal healthcare products, glues, paints, insulation, waxes, lubricants, foods, and nutraceuticals. Biodiesel (fatty acid methyl esters) and green or renewable diesels (lipids refined in a petroleum refinery) are by far the two most commonly produced lipid-derived transportation biofuels. Lipids may be produced as an agricultural crop that is grown or cultured on terrestrial areas, thereby requiring large expanses of land areas to produce the large volumes needed for supporting the global market (also known as the oleochemical industry). However, lipids are also collected from non-land-based sources of production. Examples include fats from slaughtered animals, recovered waste oils from cooking operations, or captured oils and fats from industrial and municipal grease traps [20]. Albeit, these non-agricultural sources of lipids are viable feedstocks of great industrial interest, they are not considered viable sources of lipids for growing or culturing on the lands that represent the ROW areas within the Gulf of Mexico region of the US.

Lipids are often categorized as either saponifiable or non-saponifiable [20,22]. Saponifiable lipids include glycerides, waxes, phospholipids, sphingolipids, and glycolipids. Non-saponifiable lipids include steroids, terpenes, prostaglandins, and fat-soluble vitamins. Among the lipids of greatest interest to industry are those classed as x-glycerides: monoglycerides, diglycerides, and triglycerides. Glycerides have glycerine backbones with fatty acids attached. Generally speaking, triglycerides are of the most industrial value because of their widespread presence in commercial lipids, such as soya, corn, animal fat, rendered meats, corn, and canola. Fatty acids provide critical chemical characteristics to the lipid. They are composed of long chains of carbons, linearly bonded via single or double bonds, and ending with the signature carboxylic grouping at the end of the chain. Fatty acids can be branched but are most often found as straight chains in most industrial lipids of interest. Fatty acids that are composed exclusively of single C to C bonds are called saturated fatty acids. Those containing one or more double bonds are called unsaturated fatty acids. A commonly used notation for defining the chemical composition of fatty acids with regard to the number of carbons and degree of bond saturation is presented below for the fatty acid palmitic acid as an example, which has 16 carbons bonded with all single bonds (C-C):

C16

The next example is oleic acid, which has 18 carbons and one double bond and is notated as follows:

C18:1

Several example fatty acids of key industrial interest, including production of bio-based transportation fuels, are listed below. Note that these fatty acids are also used as nutraceuticals, polymer components, and animal feed supplements [20,22,23]:

- 2. Myristic Acid: C14;
- 3. Palmitic Acid: C16;
- 4. Palmitoleic Acid: C16:1;
- 5. *Oleic Acid: C18:1;*

^{1.} Lauric Acid: C12;

6. Linoleic Acid: C18:2.

The fatty acids attached to the glycerine background are very often critical in terms of lipid's value to an industry. Lipids that have been excessively heated repeatedly (during cooking) or stored for long periods of times will break down, thereby releasing fatty acids as free fatty acids or FFAs [24]. The rancid process is a classic example of a lipid breaking down. Hence, the amount of free fatty acids (or FFAs) is a very important factor determining the lipid's industrial value. The value is defined based on the ultimate intended use of the product being manufactured and how the lipid chemistry (FFA and/or glyceride present) supports that intended use. The issue of industrial uses and respective value of lipids will be further addressed later in this document in terms of their usage in bio-based diesel production.

Lipids of industrial value are most often extracted from oil seeds, such as soya, canola, and rapeseed. The lipid extraction or recovery process is actually referred to as "crushing" the beans and, in reality, is either typically physically compressed out of the solid matrix or chemical extracted via a solids (beans)/liquid extraction system [25]. Commonly used liquid extractants are solvents such as a hexane (most commonly used), methanol, or acetone [26–28]. Physical extraction methods employed as usually involve a normally loaded press or a screwed device such as an extruder that use screwed compression to physically force the lipids out of the solid matrix [28,29].

The most commonly used industrial sources of lipids are oilseed agricultural crops that have industrial value and their annual total gallons (lipid) per acre farming production are listed below [30–35]:

- 1. Soybeans—55 gallons/acre (common US biodiesel feedstock);
- 2. Sunflowers—100 gallons/acre;
- 3. Flax—100 gallons/acre;
- 4. Rapeseed—150 gallons/acre (common European biodiesel feedstock);
- 5. Jatropha—200 gallons/acre;
- 6. Tung Oil Trees—100 gallons/acre;
- 7. Palm—650 gallons/acre;
- 8. Chinese Tallow—650 gallons/acre;
- 9. Microalgae—approximately 1000 to 5000 gallons/acres.

The above-listed yield rates illustrate why there is a growing push to move away from foodstocks, such as soybeans, toward non-foodstock crops, such as jatropha and microalgae [31,36]. The issue with using foodstocks is that some experts feel that as fuel use grows, the result will be an increase in human food costs. For producing fuel feedstocks, ideally the land used should not be valuable foodstock agricultural land and instead low-grade agricultural land or land not in the food production chain—like highway ROWs. Azad et al. [36] list over 25 potential non-traditional lipid feedstocks that can be used to produce lipid-based biofuels. Yet, as the feasibility of turn-key crops to fuels systems are studied, one clearly sees that the level of development and associated low-risk calculations of return of investments (ROIs) are much more solid with the developed foodstocks as opposed to high potential, yet relatively undeveloped crops such as Chinese Tallow and microalgae [20,31,37]. However, do note that these "novel" sources all have major issues with their usage with cost often being one of the biggest concerns (algae).

4.2. Lipids Markets

The lipid market has traditionally been dominated by industries marketing the lipids as cooking oils. However, the processing of lipids into the renewable/sustainable biofuels and sustainable materials are continuously evolving. Other than the traditional use of oilseed lipids used as a cooking medium, lipids are finding their way into many new industries. Some examples evolving industrial uses of note are listed below [38,39]:

- 1. Biodiesel;
- 2. Renewable diesel (also known as green diesel or biocrude);
- 3. Nutraceuticals (lecithin, Omega III fatty acids, etc.);
- 4. Polymers (paints, inks, insulation, plastics, etc.);
- 5. *Candle wax;*
- 6. Adhesives;
- 7. Heating oils;
- 8. Cosmetics;
- 9. Lubricants.

Note that many of these markets are generally in the early stages of maturation as industries/ markets and as such tend to be volatile in terms of both industrial demand and associated pricing structure. However, all appear to be fast-growing industries that will all require significant lipid feeds as they mature.

Two of the products listed above are transportation fuels: Biodiesel and renewable diesel. Both of these "green" fuels offer society sustainable, bio-based transportation fuels that are fairly easily utilized by most current diesel engines across the globe [40,41]. Both of these biofuels are also well-established and have growing global markets. Biodiesel is actually a fatty acid methyl ester (or FAME), which is produced by cleaving the fatty acids off the glycerin backbone then reacting the acids under basic conditions with methyl alcohol to produce a FAME or biodiesel [42,43]. Note that ethyl alcohol (ethanol) can be used in place of methyl alcohol to increase sustainability, but slightly differing processing results are not uncommon [44]. A major by-product from this production is glycerin, which has become a limited value product at the resulting quality exiting a biodiesel plant. Also, biodiesel is chemically much different than petroleum diesel, but they both burn similarly within diesel engines. Additionally, biodiesel cannot be transported nor stored long-term within the same transport and storage systems as petroleum diesel because of the strong detergent nature of the biodiesel. It is noteworthy to mention that a good lipid biodiesel feedstock should have at least 65-70% unsaturated fatty acids tied to its triglycerides because saturated fatty acids will become solid at lower temperatures (the actual temperature to reach this solid state (known as the Cloud Point) depends on the actual fatty acid). A well-known example would be bacon grease, which is a liquid at cooking temperatures but a solid at room temperatures. Hence, a truck driving from warm to cold regions may have its biodiesel become viscous or even a solid within its fuel tank [21]. Renewable or green diesel is a product that is chemically identical to petroleum diesel because it is inputted and refined in petroleum refineries. Since the chemical structure of the feedstock lipid is cracked within the refining process, renewable diesel does not face temperature-based Cloud Point issues. The "biocrude" or lipid essentially replaces crude oil as the feedstock into the refinery with renewable diesel. However, with producing green diesel, hydrotreater processing within the refinery is required, which is not a commonly used step with most medium to light crudes. Green diesel is growing in popularity as the most suitable future bio-based diesel and has begun to replace biodiesel as the bio-based diesel of choice. Dufreche et al. [21] further discuss the differences and pros/cons of biodiesel and green diesel as transportation fuels in the US.

4.3. Other Co-Products from Cultured Lipid Crops

Once the lipids are removed or extracted from the whole input product (seed or cell), then the remaining delipified product is known as "cake." In any case, with most oilseeds or other lipid feedstocks only containing 15% to 30% lipids (w/w), the opportunity to produce co-products from the cake is becoming a significant developmental area to reduce the overall cost of producing bio-based diesel fuels. The current pricing of some selected example protein cakes is listed below [45–47]:

- 1. Soy Meal: ~\$380/ton;
- 2. Cottonseed Meal: ~\$260/ton;
- 3. Sunflower Meal: ~\$235/ton;

- 4. Canola Meal: ~\$275/ton;
- 5. Rapeseed Meal: ~\$300/ton;
- 6. Linseed Meal: ~\$420/ton.

Note that these prices are reflective of the cakes being used as a protein source; likely, for use within the animal feed supplement markets. However, there are numerous technology options to convert these and other cakes into co-products with varying prices yielded depending on the types and amount of product(s) produced. As stated above, new research is being focused on developing high payout markets for the cakes to offset the cost of the bio-based diesels—much like dried distillers grain offsets the cost of making ethanol from corn as a popular US biofuel.

5. Study Approach and Associated Methods

Assessment Method Goals

The goal of the methods development for this study was to use both external information and our experience with both lipids and biofuels processing to logically form concluding advice as to the best lipids crop for highway ROW areas within the SE-US Region. A secondary goal was to illustrate our evaluative method so other regions across the globe could use similar methods in their assessments for the most optimal lipids crop for their regional highway ROWs. This assessment, based on literature and author experience, was performed to evaluate what types of lipid bearing plants, trees, and other cultured crops capable of producing appreciable amounts of lipids could be reasonably cultured within highway ROW land areas. Additionally, the other co-products that could be classified as sustainable chemicals that may be produced along with the lipids were considered as an assessment factor. Particular focus was placed on the culturing of these crops within the Southeastern United States or SE-US (defined herein as Texas, Louisiana, Mississippi, Alabama, Florida, Georgia, South Carolina, Tennessee, Kentucky, Missouri, and Arkansas). For our study, we used the State of Louisiana as a general condition representative of the region. Numerous evaluation factors are proposed in this study and used to compare the various candidate lipid feedstocks assessed.

Assessment Methodology—A two-phased assessment was performed to select a candidate list of crops that could potentially be cultivated in the Southeastern United States (SE-US) highway ROW land areas to produce lipids and potentially value-added co-products (such as delipified cake). Phase I assessment involved a screening of a wide variety of crops that have been used or proposed for use in the US to produce lipids of commercial value. Albeit, a limited scope of evaluative factors was used; this phase reduced the list to a smaller candidate crop list that underwent a Phase II assessment in this study. The Phase II assessment involved a thorough evaluation based on 10 factors including the authors' opinions on how the candidate lipid crop aligned in terms of value toward each evaluation factor. The information/data utilized for both assessment phases were gathered from literature, discussions with experts (industry, government, and universities), and the experiences of the authors (who have spent years studying options for producing lipids). More details of each assessment phase are presented in each respective section below.

Phase I Assessment Methodology—The following assessment factors were used to evaluate the various candidate lipid crops as the Phase I Assessment: (a) Amenable to growing in the SE-US Region; (b) produces over 50 gal/ac/yr of lipids; (c) production of a secondary co-product of some economic value; and (d) not a human (first) nor animal (second) foodstock. A screening table of the evenly weighted evaluation factors listed above was developed with under each factor, a numerical score was given based on the review of the literature, our experience with lipid processing, information gained from discussions with various highway and other biofuels experts, and the chemical nature of the crop components. The numerical values given could range from 1 through 10 with 1 being a poor asset toward lipid production in the SE-US Region and 10 being a good aspect toward that goal. Thus, the higher the totalized numerical score, the more attractive the candidate crop for cultivation in the SE-US (based on our assessment).

Phase II Assessment Methodology—The Phase II Assessment involved significantly more research into the characteristics of each candidate Phase II crop and how they may fit into the SE-US climate and farming culture. An expanded range of evaluation factors were developed to perform a more detailed assessment leading to a suggested list of finalists that appear to be good fits for highway ROW land areas. The expanded evaluation factors used to develop a similar, equally weighted evaluative table (as used in Phase I) were:

- 1. Per annum oil yield (gallons/acres);
- 2. Productive crop in the SE-US (climate matching);
- 3. Culturing requirements (types and respective pounds of fertilizers/chemicals needed per year);
- 4. Access frequency to crop (entry into the highway ROWs for farming operations over time);
- 5. Water requirements (irrigation and the potential for too much precipitation—overwatering);
- 6. Available markets (access to processing facilities and later product markets/transport conduits).

To provide a foundational frame of reference with regard to data collection, regional issues of the SE-US, and associated farming practices in the region, the State of Louisiana was the base case when needed to provide decisional insights on assessing the Phase II candidate lipid-bearing crops. Again, the data used in the Phase II assessments were heavily based on literature information with additional insights of the project team (with years of experience in developing lipid resources) and discussion with various agricultural science officials.

6. Results

The assessment included the study of potential issues surrounding the use ROW lands as farming opportunities for lipid-bearing crops. This component of our study yielded identification of numerous benefits and challenges (based on our assessment of literature, discussions with industry experts, and our own experiences). Among the many benefits we identified are (a) more efficient use of public lands; (b) it may eliminate mowing maintenance; (c) supports the national plan for increasing bioenergy usage in the US; (d) can provide visually appealing viewscapes for passing motorists and/or pedestrians; (e) serves as a natural source for reducing localized carbon dioxide by being located near a major source of carbon dioxide production—traffic; (f) can support state and national biofuel usage goals; (g) can provide natural noise-suppressant barriers if trees are planted; (h) increase public awareness and appreciation of integrating long-term sustainable practices with commonplace infrastructure; and (i) can potentially provide an income stream to the land owner (federal or state agency) and regional partnering industries (farmers, crushing facilities, truckers, farm workers, and supply houses). The potential negative aspects of cultivated a crop within the ROW land areas are (a) some crops may require significant farming traffic access into and out of the ROW area; (b) the potential for erosion issues associated with soil manipulation, and even no-till options will require some level of groundwork; (c) the potential for drifting of suspended soil particles and/or chemicals being applied into traffic and pedestrian zones; (d) some potential crops, like Chinese Tallow and Tung Oil trees, do contain toxic components; (e) some crops may grow too high and too dense to the point of causing driver line-of-sight hazards for motorists; (f) damage to farming equipment by pollution (hubcaps, dropped freight/loads, wreck remnants, etc.); (g) loss of emergency space on side of road and buffer for accidents; and (h) crop cultivation-based soil manipulation may disrupt drainage flow paths causing flooding. Note that most of the negative aspects of planting energy crops on highway ROW land areas detailed above can be managed and the risks reduced. Note that many states, like Louisiana [48], have initiated native flower and plant growing initiatives to reduce mowing maintenance requirements, improve the vision-scapes of the highways, and, with some states, provide bees with more flowers (apparently, bee populations in the US are becoming reduced and increased access to flowers is one of the bee species preservation methods being used). Many of these pros and cons were reported by others [2,4,6,49].

6.1. Phase I Assessment Results

Table 1 presents our Phase I Screening of the various lipid-bearing crops. These lipid crops represent a wide variety of different types of crops that have been reported to be producers of lipids with some history of North America cultivation. From the table, in order of appearing to be most attractive via our assessment (Phase I): Microalgae, next tied for the second/third slots were the Chinese Tallow tree and Tung Oil tree, then Soybeans, and Sunflowers. Candidate crops having a total score less than 23 were not considered for advancement on to the Phase II assessment stage. Hence, the following lipid crops were carried forward to the Phase II Assessment: Chinese Tallow, Microalgae, Tung Oil, Soybeans, Sunflowers, and Flax. Do note, as discussed later in this paper, Chinese Tallow is currently considered a nuisance invasive tree species in the US and that both Chinese Tallow and Tung Oil trees also have toxins within this composition, but these are not regulated toxins as is ricin. Still, the ease of cultivating a tree over an annual planted crop involving significant farming-based ground manipulation and the lack of the need for different types of mechanized specialty farming equipment placed both trees as viable candidates for consideration via the Phase II Assessment in this study.

Table 1. Phase I Assessment Scoring Table (Note: All evaluative factors were equal-weighted and the numerical scores were given based on the opinions of the authors via their review of the literature, discussions with government and industry officials, and their own working knowledge of the lipid industry).

Candidate Feedstock	Easily Grown in the SE-US	Produces >50 gal. lipid/ac/yr	Considered a Foodstock	Potential Secondary Co-Products	Totals
Canola	3	5	4	6	18
Castor	7	5	6	3	21
Chinese Tallow Tree	10	8	9	1	28
Flaxseed	8	5	5	7	25
Microalgae	9	10	8	4	31
Mustard Tree	5	7	5	4	21
Oil Palm	2	9	8	2	21
Rapeseed	2	5	6	5	18
Safflower	3	6	5	7	21
Soybeans	10	5	3	8	26
Sunflower	9	6	4	4	23
Tung Oil Tree	9	8	9	2	28

6.2. Phase II Assessment Results

The results of the Phase II Assessment will be presented in the remainder of this paper. This will include more details on lipid sources, information on cultivation, markets, and other issues (pros or cons) that will help form a set of conclusions and recommendations at the end of the paper. A series of additional considerations that fed into the Phase II assessment were identified based on the Phase II literature search and discussions with those involved in ROW operations activities. These considerations are discussed below:

Categorization of candidate crops—Lipids can be collected from two types of cultured feedstocks: Row crop oilseeds and lipid-bearing trees/bushes. Additionally, a third type of lipid crop was included—microalgae—due to its emerging popularity as a much-discussed lipid source. Row crop oilseeds are much more developed with a long history of farming success as well-established crops in Louisiana. Example row crop oilseeds are soybeans, sunflowers, corn, and flax. Lipid-bearing tree or shrubs are less established and, in fact, are really not currently a widely used crop in Louisiana (or the US for that matter). Examples include Tong and Chinese Tallow. Microalgae are a developing crop and has little full-scale experience as a lipid production method; however, this situation is rapidly changing and, as such, the authors wanted to include its assessment within the Phase II stage of study (plus, due to its high potential, it did score relatively competitively during the Phase I assessment). Row crop oilseeds will require much more culturing activity within the ROWs than lipid-producing trees since they are much more managed, and the surface soils physically manipulated. Row crop oilseeds also pose the potential for erosion due to the level of surface soil activities. Tillage farming methods, albeit traditional, would likely pose much more of a treat to the erosion stability of the ROW surface soils than developing new methods of farming such as no-till operations. Hence, within this report, no-till farming will be considered as the only farming operation for consideration. No-till farming should also minimize the amount of dust drift occurring during soil preparation, planting, and harvesting. Oilseeds are also prone to attract deer, which could increase the population of deer around ROW areas over the grass areas found at most Louisiana highway ROWs. Lipid-bearing trees and shrubs will require much less surface soil manipulation due to the nature of this form of agriculture practice. In the case of these lipid feedstocks, most often only the harvest of the seeds is required to collect the lipid feedstocks. The negative aspect of using lipid-bearing trees and shrubs is that no protein cake co-product will likely be produced and that mowing around the trees will be required (particularly prior to harvest). Microalgae cultivation will require water and electrical power. The unique aspects of culturing microalgae are discussed in more detail later in the paper.

6.2.1. Candidate Phase I Row Crops

Row Crop Farming Issues—The following issues to consider with both row crops and tree farming are presented before:

- Row-cropping considerations—ROW surface soils are likely much better off when exposed to
 minimal physical manipulation. No-till planting will most likely have to be employed at highway
 ROW areas. No-till farming involves seed depths to no more than 1.5 to 2 inches, which has
 minimal impact on soil surface fabrics (suggested is 0.75 to 1.0 inches—slightly deeper for clayey,
 loamy soils—up to 1.5 inches). For sloping areas, contour farming is recommended to minimize
 erosion of soils. Acceptable slopes to minimize erosion using no-till farming are in the sub-15%
 slopes. Cover crops planted between soybean cultivation will reduce erosion losses. If a cover
 crop is considered, then the level of deer attraction should be considered.
- Buffer zones—The authors consider buffer zones of at least 100 feet on either side of center ROWs and 100 feet of roadside ROWs to provide some level of soil and applied agricultural chemical drift buffering. This is well in agreement with guidance of at least 30 feet provided by the North Carolina Highway Department for trees and shrubs along its highways [50]. Thus, 300 feet of center ROW and 200 feet of roadside ROW road-lengthwise areas are suggested that are continuous for at least 1 mile. Also, it is assumed that only tractor-applied chemicals would be acceptable since concerns over aircraft chemical application drifts into the highway traffic areas. Still, during times of high winds, chemical addition and soil manipulation would have to be ceased until the wind dies down (there are manufacturer and USDA guidelines on this topic). With chemical addition, larger drop sizes, low application heights (aircraft applications will likely not be acceptable), nozzle pressure, and chemical type are all factors that can control chemical drift. Agricultural activities located next highways are not uncommon, so the issue of drift (both chemical and soil) are manageable. The appropriate buffer zone is difficult to predict because each chemical and wind condition is unique. The use of a physical barrier made from a line of bushes or hedges is also feasible and with careful hedge selection may offer an attractive roadside view (flowering, colors, etc.). Also, with larger shrubs and trees, this growth may serve as a barrier to vehicles accidently running off the roadways.
- Highway ROW farming activity access points—one entry point from the highway is needed along with a staging area of at least 200 by 200 feet for parking, equipment storage, and farming staging (including harvest loadouts, chemical loading, and turn-arounds). The estimated distance between staging areas will be a function of continuous ROW culturing and/or easy access around any cultured ROW areas (maneuver around a discontinuation without having to enter the traffic zones—including shoulders).

- Potential implications to highway ROW maintenance/operations—one impact is that once the ROW area is taken over by a row crop oilseed agricultural operator, the cost of maintaining that area by the highway department is likely saved. However, that is likely not true for lipid-bearing trees and shrubs since they do require maintenance around the trees/shrubs. This maintenance may be passed on to the farmer, but likely may be retained by the highway department.
- Lipid processing from feedstocks—as seeds or fruits are harvested, the lipids must be removed from the crop [51]. Removal of lipids from oilseeds is known as "crushing," where lipid removal from tree fruit is more commonly known as "extraction." Technically, lipid removal is accomplished via chemical extraction or pressurized (squeezing) of the lipids out of the seeds/fruit [25,52,53]. This step can be accomplished via hexane extraction (most popular) or via physical extrusion, which involves the pressurized removal via screwed expellers [53]. Note that almost all lipids are liquids, with some at room temperature being solids, for example, bacon grease, which is caused by the presence of a large percentage of saturated fatty acids (over 50%) in the lipid source [20,54]. The northern portion of the SE-US region has several crushing facilities located within this region; however, most crushing facilities that service the southern half of the SE-US region are located along the Mississippi River [55,56]. The larger crushing facilities are found around Tennessee to Ohio area, but there are smaller facilities in Northern Mississippi. Crushing/extraction produces lipids and cake (with oilseeds-protein cake). Most of the SE-US Region does have excellent transportation conduits to move harvested soybeans to these crushing facilities. New Orleans and Houston are national hubs for exporting agricultural and energy products to global markets [55]. Most farming operations need access to temporary storage bins until shipping to crushing areas—particularly those not within 50 miles of a shipping or crushing facility. For example, Informa Economics [55] reports that only 25% of soybeans in the US are shipped directly to a crusher (deoiling or delipifaction facility) while the balance is stored via bins.

Phase II detailed assessment of each candidate row crop's potential—each candidate row crop evaluated within the Phase II assessment is discussed below based on key characteristics, production yields, markets, and other pertinent issues that were identified during our Phase II assessment study.

Soybeans (Glycine Max)

Introduction to soybeans—Argentina, Brazil, and the US produce 80% of the soybeans grown worldwide [57]. It is interesting to note that the US soybean production statistics indicate that the global production share of the US has declined over the past 10 years from 70% to about 35% today with Brazil (28%) and Argentina (18%) yielding the biggest gains on the US market share. Within the US, soybeans are the second most-planted field crop with corn being number one. Over 4 billion bushels of soybeans were grown in the US during 2016 [58]. Soybeans have been a popular crop in Southern US for many years [59,60]. Over 80% of US soybeans are grown in the Upper Midwest with the SE-US region being the second most productive area for soybean production [58]. All of the Southern US states are considered within the group of 32 US states known as soybean-growing states [57–59]. The densest area of soybean cultivation in the SE-US region is along the Mississippi River. Most of the production in this region is found within the middle to upper SE-US, but not along the coastal brackish plains to the south along the coastline. The quality of the lipids produced from soybeans is high with a 70%+ unsaturation level of the fatty acids [20]. Soybeans have a strong world market and are a crop that most farmers in the region have significant experience in terms of culturing and handling. A typical soybean yields about 60 to 80 pods with three beans per pod [58]. There are numerous varieties to choose from based on the regional climate and targeted products, such as lipids or proteins [60]. In terms of planted acreage, within the SE-US region, Arkansas (3100 acres) leads the region followed by Mississippi (2000 acres) then Kentucky (1700 acres). Figure 2 presents example photographs of soybeans.



Figure 2. Photo of soybean pods and cultivation rows (Photo Sources: USDA).

Soybean per acre annual production—the average per-acre yield of soybeans in the Southern US is highly weather dependent but ranges about 25 to 50 bushels per year [58–60]. A bushel of soybeans weighs about 60 pounds with 48 pounds being protein [58]. This will produce about 55 to 60 gallons/acre per year of lipids (soybeans are around 18–20% w/w lipids).

Culturing requirements for soybeans—a benefit of soybeans is that it can be cultured on a variety of soil types. Soybeans are planted during the April through June window (the earlier the better for higher yields, but sufficient temperatures are needed, ~20 °C to 30 °C) with a typical September through November harvest window [59,60]. The actual variety of soybean to plant is very much based on numerous conditions and this selection should be done in consultation with guidance from the local county agent or ag-extension service based on actual location. Row distances range from a low of 7 inches to a high of 40 inches with around 25 to 30 inches being commonly used [59,60]. Planting depths are usually in the 1- to 1.5-inch depths with most soils and up to 2 inches for sandy soils [59]. Rarely is nitrogen needed for soybeans, but potassium and phosphorous applications are sometimes needed (determined via annual soil testing). Seeding rates are generally in the 130,000 seeds per acre or three to seven seeds per row foot [60]. 15- to 30-inch row spacings are common. Smaller row spacings allow for more yield per acre as long as the density does not adversely impact cultivation. The seed pods become exposed in mid-fall (later September and October) with harvest usually occurring in November. One particularly interesting option for ROW areas could be organic culturing, but this is more oriented toward food production as opposed to a fuel feedstock. No-till farming is viable throughout the SE-US region with studies showing a 90% reduction in soil erosion comparing convention tilling to no-till farming. The use of no-till or soil conservation farming practices is growing within the SE-US [59]. However, there are smaller yields with no-till farming over conventional till systems. Soybeans have been used as a rotational crop with other crops like rice, wheat, or corn, which could work well within highway ROW areas. In the Deep South or southernmost zones of the SE-US region, cover crops are rarely planted because natural grasses tend to provide sufficient cover to the harvested areas. Well-draining, loamy soils are optimal, but soybeans are fairly hardy and will do okay in most soils. Irrigation appears to become more of a decision/need toward the northern parts of the SE-US region. Fertilization for cultivating soybeans is common [60], as each bushel will remove approximately 3, 0.8, and 1 pound of nitrogen, phosphorous, and potash (also known as N:P:K). Optimal soil pH is 6.5, which is a slightly acidic soil. Weed, pest, and disease management is a common culturing issue with

soybean farming, but the extent that each issue persist is a regional issue within the SE-US areas (local or state agricultural experts should be approached for guidance for a particular area). Dual-cropping or periodic rotation cropping is not uncommon with soybean farmers. For example, in Louisiana, a rotation with rice every three to four years then one with soybeans is common practice [59].

Soybean processing—the lipids from soybeans are removed via crushing. Harvesting is done in early fall (typically a two-month window depending on weather conditions prior and during harvest).

ROW access requirements when farming soybeans—soybean farming will require open land with relatively flat (less than 15% grade) areas. Based on review of typical farming operations, it appears that ROW areas that have 15% or less grades and widths of at least 100 feet are viable options; however, to make a venture acceptable to a farmer, at least contiguous 1.5 miles by 100 feet of ROW land expanses must be required to yield about one-third of a section of land [61].

Potential soybean component uses—soybean lipids are used for many products including cooking oils, nutraceuticals, lube oils, insulation, glues, paints, resins, and this list grows continuously [58,60]. The protein cakes are used as animal feeds, glues, human food supplements, and various polymers. Whole oilseeds are used for human and animal food. Soybean lipids and proteins are one of the most used oilseed components globally. These markets are wide and tend to be fairly stable. Lecithin, a waxy lipid compound, is a growing market for soy lipids in the nutraceutical and cosmetics industries [58,62]. Lecithin is also used in chocolates and cocoa butter-based candies. Soybean hulls are developing a growing market as fiber supplements in animal feeds and, lately, human foods.

Soybean financial markets—current soybean bulk prices are about \$9/bushel [58,63]. Soybean oil is currently selling at around \$0.30/pound [64]. Soybean protein (delipified cake) prices are in the \$300/ton range. Soybean production costs historically run around \$5 to \$8/bushel with a \$1 to \$2/bushel profit often yielded [57,63]. On a per-acre-basis, soybean culturing costs run about \$150 to \$300/acre [57,59]. Seed, machine depreciation, and fertilizer represent the largest costs (both about 15% each of costs) unless land rent is paid, then this cost is typically the largest (40% and seed/fertilizer are about 8% each). In general, soybeans will yield about \$50 to \$200 per acre of profit (total crop) depending on the success of the year's farming operations for that given year's weather, pests, and markets as well as the region where the crop is being grown [60,65]. The three biggest importers of US soybeans are China, Mexico, and Japan with China being the largest at almost 60% of US exports [57].

Summarized assessment data on soybeans—the summarized assessment via the established evaluation criteria are listed below:

- 1. Per annum oil yield (gallons/acres)—55 gallons per acre/year.
- 2. Productive crop in the region (climate matching)—currently widely grown in many of the areas across the Southern US with excellent results and widespread farming knowledge and resources to support a ROW crop.
- 3. Culturing requirements—generally requires relatively flat areas but some slope is allowable.
- 4. Access frequency to crop—seasonal access to the ROW areas is required including land preparation, seeding, pesticide application, and harvesting. Irrigation is rarely utilized in many parts of the region.
- 5. Water requirements—no irrigation is needed due to the crops ability to grow within the climate conditions along most of the regional highway ROWs.
- 6. Notes—soybeans are well established. There are concerns that soybean are a deer-attracting crop, which could pose safety issues for highway traffic. Also, drifting of chemical applications should be managed via best prevention practices and ensuring the adequate buffer zones are designed into the targeted ROW areas.
- 7. Recommendation—soybeans are a viable crop for highway ROWs. There are doubts that most farmers will not be interested in such potentially tight areas with access issues. Also, concerns over deer foraging may increase deer/vehicle collisions, but this issue must be addressed by the highway safety experts because most grassy areas currently on ROW areas are also prime deer forage areas as well.

Flaxseed (Linum usitatissimum)

Introduction to flaxseed—flax is believed to one of the first crops grown by man over 7000 years ago and first grown in North America during the early 1600s [66]. Two varieties are reported to be grown in the US—one for fiber and one for both fiber and oil [67]. The plants at maturity grow up to 48 inches [66,68]. Flax is also known as linseed when used as industrial feedstocks [69]. At one time, flax was a common crop throughout the US, but over the years, it has been grown mainly in the Dakotas and Minnesota. However, a resurgence of interest in flax oil, protein, and even the fibers has prices high and interest peaking for US regions not near-term historically growing flax. Note that flax is an interesting option for the Southern SE-US Region because it may be grown in the colder months, which would offset its growing period from other potential oilseed; thus, allowing two crops to be grown. Albeit promising, there are little actual data on flax culturing in the SE-US region (particularly the southern part) but reports from some SE-US states are encouraging. Flax is a beautiful flowering, semi-evergreen plant that is a proven erosion control cover crop and can also serve as food for wildlife. The blue flowers are very attractive as is a field of flax. Red Flax also may be grown, but reports indicate that it may be toxic to livestock and thus not considered as an option. The seeds are typically brown in color, but a new variety, Omega, has been developed that is a golden color to make it more appealing as a food [68]. Varieties differ mainly by the intent the crop with the shorter varieties being oriented toward lipid production and the taller most often for fiber, and there are some varieties that can offer both end-uses. Flax seeds are growing in use as a health food or nutraceutical product for human use due to its mix of healthy lipids (Omega III), the anti-cancer nutraceutical, lignan, and high-quality proteins [69,70]. Flaxseeds are about 40% weight proteins. Depending on the variety, flax grows from one to four feet tall producing flowers of blue, yellow, white, and red along with a bulb containing about 10 seeds (most are blue flowers). The seeds contain about 45% lipids with a particularly high percentage of linolenic acid (C18:3) making up about 50% of the total lipid yield [66]. Due to the high linolenic acid levels, flaxseed lipids are the most unstable because of linolenic acid's susceptibility to oxidation degradation (making storage challenging). Flax seed protein and lipids are also used in animal feed formulations. It is estimated that flax oil represents about 1% of the total world's annual oilseed production. Flax oil is well known for its use in wood varnishes, polishers, drying oil admixture, and paints. Flax fiber is known for its use in the making of fine linens, teabag paper, US currency, and high-end printing paper [66]. The US is the largest global per capita user of flax fiber with almost all being imported. Most of the global flax production is in Northern Europe and Russia. Within the US, the Upper Midwest is where the fairly small US farming operations are centered, but that is changing with higher prices being offered and as flax markets expand. Figure 3 shows images of flaxseed growth and cultivated product.

Flaxseed per acre annual production—total flax seed yield is about 300 to 1000 pounds per acre depending on rainfall and soil conditions or 20 to 40 bushels per acre. Per-acre lipid yield for flaxseed is about 50 gallons per acre (about the same as soybeans). Harvesting is done via a traditional grain combine.

Culturing requirements for flaxseed—flax does best on well-drained soil and can tolerate cold weather and winter draught. In fact, flax is capable of tolerating temperatures to as low as 25 °F [66]. It is not very heat tolerant (thus the potential for winter growing). In South Texas, it is recommended to plant in November or December [69]. Flax is tolerant of slightly salty and low pH soils (good for the lower SE-US region). Flax is seeded shallow in the 0.5- to 1.5-inch range, which is good for erosion management in ROW areas. Often times, different varieties are mixed in the seed stock with a recommended seeding density of around 25 to 50 pounds of seed per acre for oilseed varieties with fiber varieties seeded at rates as much as three times more [66,68,69,71]. Flax is cultured using 28- to 38-inch rows. Adding nitrogen and phosphorous does enhance yield but is not required. It is reported that flax should be rotated every two to three years thus it is not an every-year option if optimized yields are targeted. Thus, rotating with soybeans or sunflowers is possible. Also, hay production can also be a crop rotation option. Soils best for flax are clay-loams and silt-loams. Well drained soils, but those with good water holding, are best. However, flax is fairly adaptable and should grow in most soil conditions, but not flooded soils. An interesting aspect to growing flax in the deep US South is that it may be used as a winter crop, thus potentially double cropping of the ROW areas. Winter planting in the Southern US is between October to December (likely the latter for the coastal states, like Louisiana and Alabama). It is noted that flax does grow well within coastal climates due to the humidity and rain cycles. Flax has relatively low fertilizer needs with only nitrogen addition typically required (40 to 80 pounds/acre). The crop is a poor competitor to weeds, so herbicide addition is common with fungi infestation being a moderate risk and low insect issues noted for most areas [66]. Harvesting is done using combines and swathing with little issue with seed shattering observed. Fiber and lipid yields are about 2000 pounds/acre and 110 gallons/acre/year for lipids [51]. Flax is best grown when double-cropped or staggered cultured (grown every other year) if a single planting is done within a field [68].



Figure 3. Photos of flaxseeds, blossoms, and open cultivation (Photo Sources: USDA).

Flaxseed processing—flaxseeds can be crushed similarly to soybeans; however, the smaller size of the seed may poise challenges to some crushers. Flax is about 40% (w/w) lipids, and as stated above, over 50% is linolenic acid [68]. Thus, making it a poor cooking oil due to its poor oxidation resistance. It is one of the few oilseeds never really used as a cooking oil. Crushing using food grade processing (cold-pressing) could command a much higher price because this processing allows for use of the oil as a nutraceutical. The fiber can be processed into materials/linens. The fiber can also be pressed into fiberboards using traditional methods. The delipified cake is of similar market value to soya protein as an animal feed amendment. A warning about storing flaxseeds is that care should be taken when standing on a deep pile of the seeds within a bin because the waxy surface and small seed size can cause a person to sink into the pile and suffocate (reported as happening before by Myers [68]).

ROW access requirements when farming flaxseed—flaxseed farming will requirement open land with relatively flat (less than 15% grade) areas. Based on review of typical farming operations, it appears that ROW areas that have 15% or less grades and widths of at least 100 feet are viable options; however, to make a venture acceptable to a farmer, at least contiguous 1.5 miles by 100 feet of ROW land expanses must be required to yield about one third of a section of land.

Potential uses of flaxseed components—flaxseed lipids are used for many products including nutraceuticals, drying oils, paints, papers, linens, and resins [66]. Linseed oil was once a staple for wood restoration but lost its market-share to petroleum products; however, as the interest in green chemicals and biofuels has grown, linseed oil markets are rebounding [69]. Being a lipid with high levels of Omega-III fatty acids makes flax lipids an excellent nutraceutical source. In fact, flax fiber has been experiencing a double-digit growth usage for composite manufacturing in Europe. The protein cakes are used as animal feeds, human food supplements, and various polymers. Whole flaxseed seeds are used for human and animal food and has been found to reduce cholesterol levels [66]. The use of flaxseed components is also experiencing a rapid industrial usage in the US, which bodes well for significantly ore flaxseed farming in the US.

Flaxseed financial markets—flax seed prices generally range from a low of \$6 to a high of \$13 per bushel (currently about \$10/bushel, which is a good overall estimate that is close to an approximate average historical price) as reported by Morgan et al. [69]. The markets in the Southern US are not well developed for whole seeds. There are no flax fiber processors in the Southern US. However, flaxseed oils are easily incorporated into biodiesel and/or green diesel production. The egg industry has developed a growing market for flax oil and whole seeds as feed amendments to layers, which then markets the eggs as "Omega-3 eggs." Flaxseed oil prices have ranged from about \$0.40 to \$0.90/pound over the past 10 years [64]. Lately, it is listed toward the upper end of that range likely due to growing use as a nutraceutical product. Protein cake prices have generally ranged from \$150 to \$300 per ton and is currently at \$220/ton [51,64]. The fiber sells in the \$0.10/pound range [68]. Note that in its 2019 Oilseed Report, the USDA [72] expects more than a double in the US flaxseed planted acreage due to the recent high prices of flax oil. Note that at these prices, flax may not be a good crop for biofuels but a good crop for selling the lipid as a nutraceutical or animal feed supplement. The net profit for a whole flax crop is in the \$50 to \$140/acre range [66,68].

Summarized assessment data on flaxseed—the summarized assessment via the established evaluation criteria are listed below:

- 1. Per annum oil yield (gallons/acres)—50 gallons per acre/year.
- 2. Productive crop in Louisiana (climate matching)—currently not grown in the SE-US but the culturing methods are not too much different from soybean or other established oilseed crops.
- 3. Culturing requirements—generally requires relatively flat areas, but some slope is allowable.
- 4. Access frequency to crop—seasonal access to the ROW areas is required including land preparation, seeding, pesticide application, and harvesting. Irrigation is rarely utilized in Louisiana.
- 5. Water requirements—no irrigation is needed due to the crops ability to grow within the climate conditions along most highway ROWs in the region.
- 6. Notes—flax is not a common Deep US South crop, but due to high flax (linseed) oil prices, there is an increase in flax culturing in the region. However, at \$0.90/gallon lipid prices, this cost may prohibit the crop as a being a biofuels feedstock but could be profitable to ROW farming operations as a revenue generator for the Louisiana Department of Transportation and Development (LDOTD). A big positive for flax is that it can serve as a double-crop for winter culturing when another crop is being grown in the summer months—perhaps soy or sunflower.
- 7. Recommendation—if only energy-generating crops are of interest then flaxseed may be too costly. It could be recommended if maximizing income for ROW areas is the goal over just energy production. However, flax should be considered as a winter crop option for double culturing of row crops on ROW areas.

Sunflower (Helianthus annuus)

Introduction to sunflowers—there are a lot of varieties of sunflowers that are grown in the US and the world as a whole with Russia and Eastern Europe being the major producers for many years [73]. As a domesticated crop, evidence shows it was cultivated 3000 years ago as a native plant of the US [74,75]. As per McClure et al. [76], the US is considered a major producer of sunflowers at about 1 million tons per year representing about 9% of global production and is the fourth most-used food-based oil (behind palm, soy, and rapeseed). Of the top seven sunflower producing US states (the Dakotas being by far the largest producers), the only SE-US region state on that list is Texas [76]. Sunflowers are a hardy, forgiving crop and can be grown almost anywhere in the world [73,77]. Various varieties are grown depending on the end-use: Cut-flowers, confection (food and sometimes birdseed), and as an oilseed [78]. The confection seeds are larger and white striped with the oil-bearing seeds being smaller and black in color. The oil-bearing variety is also commonly sold as birdseed. Oil-bearing varieties are also categorized by fatty acid composition—linoleic (standard), mid-oleic (Nu-Sun), and high oleic [76]. The Nu-Sun variety has a low saturated fatty acid content and does not have to be hydrogenated and thus serves as an excellent fry oil with a long shelf life (resists oxidation). The high-oleic variety has the lowest saturated fatty acid levels and is most often used as an industrial feedstock for green lube oils and food coatings. Only rapeseed has a lower percent saturated fatty acid composition (6%) than sunflower (9%) with soy having 15% and both palm oil and lards having ~50% [76]. Again, for biodiesel, more than ~30% saturated fatty acid composition can cause cold-flow issues with the fuel (green diesel does not carry over the characteristics of the feed lipid, so it is not an issue for green diesels).

In general, sunflowers thrive during hot, humid summers. Approximately 90% of sunflowers grown in the US are oilseed varieties, yet confection varieties (also known as confectionery sunflowers) do bring in premium prices [78,79]. According to the United Nation's Food and Agricultural Organization, soybeans are the top oilseed grown in the world followed by sunflowers as the second, producing 13% of the global edible oil supply [77]. The plants bloom around 50 to 70 days (60 days is a good average) depending on the variety and weather. The three- to six-inch-diameter "flower" is actually many flowers all centered around the middle receptacle [75,78]. The oilseed-oriented varieties are generally taller (up to 9 feet) and provide a large flower with many seeds. Rotating sunflowers with soybeans over the years can improve the soybean yields (via reduced soybean cyst nematodes). Sunflowers are efficient water extractors from loamy, sandy soils. Well-draining, yet intra-particle water-holding soils are best. They can be planted later in the year than most other oilseeds and harvested earlier, which reduces work demands over longer periods. Sunflowers are known to be more heat and dry tolerant than most of the other oilseeds. The oilseed varieties generally are high in linoleic acid (C18:2) or oleic (C18:1) with both being considered Omega-6 fatty acids. Most varieties are over 90% unsaturated making the oil an excellent biodiesel feedstock or nutraceutical source. Typical sunflower oilseeds have around 60% linoleic acid with a seed having about 40 to 45% total lipids [78]. Ninety percent of the roughly 2.5–3 M acres of sunflowers planted each year in the US are used for oilseed varieties. Currently, most of the global growing of sunflower is in Europe or Russia. Within the US, most of the sunflowers are grown within the Midwest and Upper Midwest [80]. Figure 4 shows the growth and seeds of sunflowers.

Sunflower per acre annual production—a typical yield per acre is about 2000 pounds/acre with good rainfall or irrigation and 1000 pounds/acre during dry conditions [68,78]. Oil yields are in the 30 to 100 gallons per acre range depending on weather and crop health. Most yields are in the 80 to 100 gallons per acre range [74]. Sunflowers are light, weighing in the 20 to 30 pounds/bushel range [78].



Figure 4. Photos of sunflower seeds, flower, and open cultivation (Photo Sources: USDA).

Culturing requirements for sunflowers—the sunflower crop is considered to have the shortest maturation period of all the oilseed crops at around 100 days [74]. Sunflowers are planted at about 1 to 2 inches into the soil surface at about 0.5 to 1 foot of seed row placement distance [78,79]. Row distance is ideal at 30 inches [76]. Thicker planting rates are allowable, but the head seed density is heavier with thinner planting rates [78]. Planting density impacts the size of the seeds with the thinner density producing a larger seed. Sunflowers should not be planted until the soil temperatures hit 45 °F with 50 °F even better or April for most of the SE-US region [76]. They should be planted in areas that receive full sun; hence, open field plantings are best. Shallowing from nearby trees are acceptable as long as reasonable periods of sunlight are available. Sunflowers do not have to be nitrogen fertilized for growth, but N-fertilization will often increase yield. Nitrogen fertilizer rates are about 50 to 100 pounds N per acre—lighter when following soybeans and heavier when following a non-legume crop [78,79]. Phosphorous and potassium needs should be based on soil analysis and consultation with the regional agricultural extension service. Wider row widths have been shown to produce better yields (20- to 30-inch rows are often reported). Soils that are neutral pH are best, but pH values down to 5.5 are acceptable [78]. Row crop combine heads work well for sunflower harvesting. According to Kansas State University [78], sunflowers are best stored at 10% moisture or less (higher moisture levels open up for pest and fungal infestation). Sunflowers should do okay in most soils as long as they are well-drained and do not stay water-logged [79]. Thus, the alluvial clay soils along the Mississippi River may not be ideal for sunflowers [76]. Irrigation is not needed unless the area gets less than 30 inches of rain per year [78]. Soil pH is fairly flexible (within reason)—ideal ranging from 6 to 7.5. Sunflowers do well when double-cropped, but the land should not be planted with sunflowers every fourth year regardless if double-cropped or not [76]. Sunflowers are harvested using a combine set for sunflower harvesting with a fairly low air speed because of the lighter density of the seeds. Sunflower growing also requires managing weeds, diseases, and pests, but the extent of control is based on both region and climate [78]. Birds can also impart serious crop yield reductions [73,76]. This may also be an issue with locating next to highways if the birds approach the planted ROW area at a low flight angle.

Bird deterring methods most used are noise-based [76] and likely not viable candidates for highway ROW areas. Some deer feeding may occur but not to the level as the shorter oilseeds (like soy).

Sunflower processing—sunflower seeds are crushed much like soybeans [81]. The seed must be cracked, and the kernel removed, which is then crushed for lipid extraction. The meal is also handled and sold much like soybean meal. However, marketing to the birdfeed industry is relatively easy and avoids processing [76].

ROW access requirements when farming sunflowers—it appears that sunflowers will need ROW farming access slightly less than with soybeans. Planting and harvesting are the key periods of access [78]. Some level of chemical weed control and fertilizing may be needed [74].

Potential sunflower component uses—sunflower lipids are used as cooking oils, carrier lipophilic fluids, margarine production, a hypoallergenic latex, biofuel feedstocks (biodiesel and green diesel), birdseed, and food coatings [73,74,76,78,82]. High Omega-3 oil varieties are available allowing the lipid to be used as a nutraceutical, which can earn a pay premium [76]. The delipified cake is used as a protein source for animal feed [78]. The hulls are also used as animal feed fiber supplements. The Food and Agricultural Organization of the UN expects sunflower cultivation to steadily increase (over 60 M tons by 2050) and the products derived from sunflowers to expand [74].

Sunflower financial markets—sunflowers are experiencing a growing market for both lipids and as whole seeds for use as bird food. Sunflower lipid prices tend to hover around the \$0.50 to \$0.55/pound price point [64]. Sunflower meal runs about \$180/ton [76,78]. These prices have been stable over the past few years with no significant market changes expected. Whole seeds sell in the \$15 to \$18/100 weight range (pricing on a per-100-pound basis). There is a premium paid for the high oleic oil varieties of about 10% to 20% higher prices than the other varieties within the lipid markets [76].

Summarized assessment data on sunflowers—the summarized assessment via the established evaluation criteria are listed below:

- 1. Per annum oil yield (gallons/acres)—80 gallons per acre/year.
- 2. Productive crop in Louisiana (climate matching)—climate conditions in Louisiana are conducive to growing sunflowers within the state.
- Culturing requirements—sunflowers can be grown on flat to slightly sloped ground (up to ~20% grade). Comparatively minimal chemical addition is needed for growing sunflowers, but fertilization and perhaps rotation of the crop may be needed.
- 4. Access frequency to crop—sunflowers would be a viable crop for ROW areas but access to cultivation, maintenance, and harvesting equipment would have to be allowed.
- 5. Water requirements—no irrigation is absolutely required, but dry years will adversely impact lipid yields.
- 6. Notes—sunflower seeds are not a big attractant to large mammals like deer. However, the young sprouts will be eaten by deer but likely no more than grass shorts. Therefore, a crop of sunflowers within a ROW will not cause extraordinarily large wildlife concentration along the highways. Birds will be attracted to mature seeds and could impact recovered seed yields, but this is an issue faced by all sunflower farmers. Also, a stand of sunflowers along highway ROWs would provide a beautiful view for highway travelers.
- 7. Recommendation—sunflowers do appear to have some potential for be grown within highway ROW areas in Louisiana. Buffer zones would be required along with equipment staging areas scattered along the length of cultivation.

6.2.2. Candidate Phase II Tree Crops

Tree crop farming issues—the following issues to consider with both row crops and tree farming are presented before:

• Lipid-bearing tree cultivation—there are two species of trees, the Tung Tree and the Chinese Tallow Tree, that are considered viable options for culturing along highway ROW areas. Unique

aspects of culturing or farming trees with highway ROW lands that were identified are discussed below, followed by Phase II data generated for each of the two candidate tree species.

- Tree culturing methods—cultivating lipid-bearing trees will require very little disturbance of the ROW soils. Both seeding and small tree planting can be used to initiate a crop; however, it is likely small tree planting will be used. The suggested planting density is presented under each of the two candidate trees. Planting lipid-bearing trees provided very minimal access needs and disturbance of the ROW area.
- Buffer zones—stand tree planting buffer zones used by the most highway departments should be employed. It is noteworthy that both the Chinese Tallow and Tung trees do not appear to fare well in windstorms (like hurricanes common in the region), which should be a factor in deciding what buffer zone distance to use.
- Highway ROW tree farming activity access points—minimal access is needed except for mowing, pruning (very occasional), and fruit harvest in the fall. A small staging area is likely needed for loading harvested fruit into transport trucks—likely on the order of a 100-feet-by-100-feet area, but not at every ROW area planted. Staggered distances for staging areas would be acceptable and these areas do not have to permanent.
- Potential implications to highway ROW maintenance/operations—mowing and grounds upkeep will still be required with tree farming. Although, these operations may be passed on to the farmer, but it is speculated that would have to be negotiated via a contract.
- Lipid processing from tree fruit feedstocks—as tree fruit are harvested, the lipids must be removed from the harvested seeds. Essentially, the same crushing methods discussed in the Row Crop Section will be employed. However, since the tree components, including the lipids and proteins, are toxic, finding a crushing facility willing to accept this feedstock may be an issue.

Phase II detailed assessment of each candidate tree potential—each candidate tree *species* evaluated within *the* Phase II assessment (*Chinese Tallow* and Ting Oil) *are discussed below* based on key characteristics, production yields, markets, and other pertinent issues that were identified during our Phase II assessment study.

Tung Tree (Vernicia fordii)

Introduction to the Tung Tree—the Tung Tree is native to Asia and was brought into the US as a gift from China to the US around 1900. In Asia, the Tung Oil Tree provide a source of good-performing lamp oil for many years. The USDA actually planted Tung Trees across the SE-US as an oil crop [83]. However, due to storms, diminishing markets, and frost, almost all of these stands are gone. This one-time widespread growing of Tung Trees does indicate that the trees are easily cultured in Louisiana. The mature trees grow to around 60 feet in height and are considered an evergreen type tree (broad leaves). The bark of the tree is smooth and when cut into, seeps a sticky, white latex sap. The flowers are attractive white with a pink to purple colored center. The fruit produced is 2 to 3 inches long and is pear-shaped containing three to five seeds. The fruit starts out green, then when ripe, turns brown in the Autumn. One drawback of the tree is that most parts (including the lipids) are poisonous and in the case of the leaves, can cause skin reactions similar to poison ivy. One seed can be fatal to a human. The States of Florida and Texas consider the Tung Tree as an invasive species (listed by Florida as a FLEPPC Category II exotic pest plant). The Tung Tree is mildly cold-tolerant with long cold spells potentially greatly reducing the lipid yield the next harvest. Also, the Tung Tree is very resistant to pathogens and diseases. Weather (storms and cold) appears to be its most sensitive aspect to culturing. Figure 5 shows pictures of Tung Trees and their leaves.



Figure 5. Tung Oil Tree stands, fruit, and blossoms (Photo Sources: USDA).

Tung Tree per acre annual production—the seeds contain about 20% lipids. A good stand of Tung Trees can produce over 4000 pounds of seeds/acre/year yielding about 100 gallons of lipids/year [74].

Culturing requirements for Tung Trees—Tung Trees are grown on moist, well-drained, slightly acidic soils. Within three years of planting, the trees can produce fruit (with seeds). Seed production hits a maximum at around 10 years and is capable of sustaining production over 20 years beyond. Planting is done to allow about 30 feet between trees. Harvesting is done via ground collection of fallen dried fruit. Once on the ground, the fruit takes about four weeks to dry to harvest moisture contents. The trees are reported to grow well on slopes but have been widely cultured on flat terrain.

Tung Tree processing—reports from years ago indicate that Tung Tree nuts (seeds) are crushed similar to oilseeds. This process would produce a toxic oil that does have industrial uses, including biofuels. However, a toxic delipified cake will also be produced that does have potential markets, but no established Tung Tree delipified markets were identified. Thus, it is likely that disposal of the cake would be required with care taken given the toxic characteristics of the material [84,85].

ROW access requirements when farming Tung Trees—Tung Oil tree cultivation would require minimal access to the ROW areas during the first few years after planting. Once the trees mature to the point of producing nuts, then harvesting of the seeds will require ROW access during the Autumn harvest. These activities should have minimal impacts on highway operations.

Potential Tung Tree component uses—the lipids collected from the harvested seeds is used in paints, varnishes, and caulk. It is also proposed as a biofuel feedstock (biodiesel and green diesel) [83]. The wood of the Tung Tree is light but strong and can be used to replace bass wood. The lipid (oil) from the Tung Tree is over 90% unsaturated fatty acids with α -eleostearic acid being ~80% of these fatty acids; though this composition does make for a great bio-based diesel, the oil and most other tree components are toxic and thereby do not have value as a nutraceutical feedstock [86,87].

Tung Tree financial markets—there is a 60-acre Tung Tree farm in North Florida. This may be the only currently operating Tung Tree farm within the US based on our review of the recent literature and press releases. Furthermore, the owners have plans to expand. Tung oil does have commercial uses.

Bulk prices reported are in the \$60/ton of whole seed of global markets during the 2000 to 2005 period while during this period the oil sold in the \$0.90/pound range, which is a high price compared to other lipids (similar to flax) [88].

Summary of assessment data on Tung Trees—the summarized assessment via the established evaluation criteria are listed below:

- 1. Per annum oil yield (gallons/acres)—100 gallons per acre/year.
- 2. Productive crop in Louisiana (climate matching)—historically grown in Louisiana and other states within the region but not currently considered a crop within any of these states.
- 3. Culturing requirements (type and respective pounds per year)—minimal requirements that do align well with most ROW situations, but toxic tree components are of major concern.
- 4. Access frequency to crop—minimal access is needed, but mow around the trees would be required.
- 5. Water requirements—no irrigation is needed due to the trees ability to grow within the climate conditions along most highway ROWs within the region.
- 6. Recommendation—although the Tung Trees once was a thriving industry, concerns over finding crushing facilities allowing input of a toxic product into a crushing facility is believed to be another challenge. Plus, the liabilities of openly having toxic tree component with easy access to the public is considered a significant risk factor. Therefore, albeit intriguing, issues over the toxicity of Tung Trees should be carefully weighed. Although at one time in the region, there was a fairly large Tung Tree growth industry with little discussion made on this issue, liability and population safety should be a factor in the decisional framework for this option.

Chinese Tallow Trees (Triadica sebifera)

Introduction to the Chinese Tallow Tree—the Chinese Tallow Tree (also known as Chicken Tree, Florida Aspen, Candleberry Tree, or Popcorn Tree) is considered an ornamental tree that can reach maximum heights of 50 feet but typically are found at the 20-foot height across the Southern US [89,90]. From seed planting to first production of seeds only takes about four years with the tree remaining productive for 100 years. As its name infers, the Chinese Tallow Tree is a native tree from China (Japan and Taiwan as well) that was brought into the US in the 1700s as both an ornamental tree and a source of cheap lipids for lamp oil and other uses [91]. It is a flowering tree that yields a fruit ready for collection in late fall. It is considered a nuisance, invasive tree in most states [89]. This is likely to be an issue if Chinese Tallow would be considered as a viable option for culturing within ROW areas. The Chinese Tallow Tree is very hardy and grows exceptionally well in the Deep US South. It is highly drought resistant yet can survive cold spells common in the Southern US. The fruit and nuts of the Chinese Tallow Tree are toxic to both humans and livestock; thus, also causing issues with allowing their culturing within highway ROWs. The nuts are small and white, three to a pod, with a one-quarter-inch diameter [89]. In the Houston, TX area, Chinese Tallow Trees are reported to represent over 20% of all trees found in the region. Chinese Tallow Trees are considered the most aggressive tree species to take over the Chenier Plains Region of Louisiana. It is capable of producing 600 to 700 gallons per acre/year of oil. The seeds—about the size of a pea—produce two lipid products: The waxy outer coating and oil within the meal of the seed. Of the total weight of the seed, the waxy coating represents 23%, and the lipid fraction within the seed meal represents 68%. The waxy outer coating is composed of 81% lipids while the seed meal has 33% lipids. The lipids within the waxy coating are composed mainly of palmitic acid (C16:0) and oleic (C18:1) at 76% and 22% (w/w), respectively. This material is made up with over 78% saturated fatty acids (single C:C bonds) making it a feedstock for biodiesel that will have cold flow issues in the winter months, but an okay feedstock for green diesel. Conversely, the inner seed oil is made up of 92% unsaturated fatty acids (double and triple C:C bonds) with 31% linoleic (C18:2), 43% linolenic (C18:3), and 13% oleic (18:1) acids being the predominant fatty acids present. It is important to note that the components of the Chinese Tallow tree are poisonous to human [89]. Figure 6 shows examples of Chinese Tallow Trees.



Figure 6. Photos of Chinese Tallow leaves, fruit, and tree stand (Photo Sources: USDA).

Culturing requirement for Chinese Tallow Trees—Chinese Tallow Trees are hardy growing trees capable of thriving on both flat and sloped grounds. They are already present on many highway ROWs across the Southern US. The seeds are produced in light-green flowers that develop in late Spring; then, the seed pods fall onto the ground as a dark-brown nut with a waxy coating. The seeds are collected from the ground for lipid extraction. Hence, mowing of the undergrowth is needed during the dropping of the seed pods onto the ground. A healthy stand of Chinese Tallow Trees will produce about 20,000 seeds per acre/year.

Chinese Tallow Tree processing—the collected nuts can be used to produce two products. One is the waxy coating, which can be chemical extracted. The inner oil of the seed (nut) can be pressed or chemically extracted at a crushing facility. Traditional chemical crushing extractants (hexane or ether) work well with extracting lipids from the Chinese Tallow seeds. Note that ethanol was also found to work well with lipid extraction of the seeds.

ROW access requirements when farming Chinese Tallow Trees—the cultivation of Chinese Tallow Trees would require minimal access to the ROW areas during their early growing stages. Once the trees mature to the point of producing fruit, then harvesting of the seeds will require ROW access during the harvest activities. These activities should have minimal impacts on highway operations.

Potential Chinese Tallow Tree component uses—the waxy outer coating of the seeds can be used to produce waxes and soap making. The oil, once extracted, can be used for a variety of industrial uses including bio-based diesel production. Note that the oil is considered toxic and thus cannot be used for or as part of any human food or animal feed processing.

Chinese Tallow Tree financial markets—there is no currently known established market for Chinese Tallow wax or oil. Therefore, there are no pricing markets to quote prices. However, it can be speculated based on the chemistry of the oil that it should obtain a price mark a bit less than soybean oil for use as a feedstock into a biodiesel or green diesel facility. Thus, it is speculated that a \$0.20 to \$0.40 per gallon price may be obtained if sold as a biofuel feedstock [92].

Summarized assessment data on the Chinese Tallow Trees—the summarized assessment via the established evaluation criteria are listed below:

- 1. Per annum oil yield (gallons/acres)—650 gallons per acre/year.
- 2. Productive crop in Louisiana (climate matching)—historically openly found in Louisiana but not as a crop but a nuisance invasive tree. Even found on highway ROW areas. However, the SE-US climate and soils are ideal for culturing the Chinese Tallow Tree.
- 3. Culturing requirements (type and respective pounds per year)—minimal requirements that do align well with most ROW situations, but liability and human access issues over the toxic tree components are of major concern.
- 4. Access frequency to crop—minimal access is needed, but mow around the trees would be required.
- 5. Water requirements—no irrigation is needed due to the trees ability to grow within the climate conditions along most SE-US regional highway ROWs.
- 6. Recommendation—although the Chinese Tallow Trees could easily be grown on highway ROWs, concerns over finding crushing facilities allowing input of a toxic product is believed to be challenging. Plus, the liabilities of openly having toxic tree component with easy access to the public may place further consideration as too high of a risk. The same issues over concern of toxic tree components were discussed above for the Tung Tree. Plus, Chinese Tallow Trees are officially considered a nuisance plant in most, if not all of the states within the region.

6.2.3. Microalgae—A Novel Phase II Candidate Lipid Crop

There are numerous developing microbial sources that may be cultured to produce huge amounts of lipids on a per-acre basis (often >5000 gallons/acre/year for open field systems). Both algae and bacteria are promising new lipid sources. In fact, it is really microalgae, a subset of algae, that is considered a promising lipid source by most experts due to this high lipid production potential based on gallons per acre per year. Of the two microbes (microalgae and bacteria), only microalgae can be cultured via open outdoor areas. Therefore, only microalgae was considered in this report as being a viable option for highway ROW areas.

Microalgae farming issues—the following issues to consider with both row crops and tree farming are presented before:

- Microalgae culturing methods—microalgae culturing is very different from any other traditional lipid source (row crops or trees). There are numerous papers that provide thorough overviews of the cultivation and challenges for microalgae as a viable commercial lipid source [93–96]. Albeit, significant detail is presented below, essentially, a series of shallow, open, long-oriented ponds are used [97]. Note that this crop will need flat land to appropriately farm.
- Buffer zones for microalgae farms—it is envisioned that microalgae cultivation would require 150-foot buffer zones on either side of traffic access areas. This figure is derived from 100-feet nominal buffer from highway traffic and a 50-foot allowance for an access road around the culturing ponds.
- Highway ROW microalgae farming activity access points—a slightly more expansive activity area is envisioned to be needed for microalgae culturing. Access to water and power will be needed for make-up water and power to operate the continuously operating equipment (mix-wheels and pumps). Also, the farmers will need daily access into the culturing areas.
- Microalgae farming potential implications to highway ROW maintenance/operations—any ROW area used to grow microalgae will not require any maintenance from the highway department. Full maintenance will be handled by the grower. In fact, it is likely that some form of aggregate will be used along the culturing areas (gravel or limestone).
- Microalgae lipid processing—microalgae will have to be dried at off-site locations, then their lipids removed using almost identical crushing facilities as used with the oil seed crops. In fact, since microalgae have no toxic issues, they may be co-crushed with other lipid sources. The resulting delipified microalgal cake can be used as an animal feed amendment.

Microalgae (Chlorella vulgaris)

Note that only one microalgae source was considered—*Chlorella vulgaris*—which is a very commonly used and proposed microalgae crop for algae to fuels/other products facilities [96,98]. Details on these green algae are provided below:

Introduction to microalgae—microalgae have received significant attention over the past 10 to 15 years as a potential source of lipids for fuels and chemicals production [31,99]. Green microalgae (*Chlorella vulgaris* is a green algae) are the most commonly suggested algal type for use in algae culturing [31,100]. Microalgae for use in fuels and other chemical production may be cultured in open raceway-like ponds (long elliptical racetrack-looking shallow channels with an inner similarly shaped island allowing for flow around the raceway for mixing) and engineered photobioreactors, which can be found via a variety of designs. Only open culturing is considered as viable options for highway ROW utilization. Microalgae cells are primarily made up of three major components: Lipids, protein, and carbohydrates [31]. Typical ranges of these components (w/w) for most microalgae of interest are 15–30%, 20–50%, and 10–40%, respectively. Algae also contain ash and pigments both generally found in 1%-10% w/w range for most species. Vitamins within microalgae are also reported to have commercial potential. However, it is the lipid fractions that have spurred the high level of interest that continues today. The potential of microalgae for lipid production is tremendous in that the difference in land use for producing 1 kg of biodiesel is about a 150-times difference when comparing soybean to microalgae [99]. The use of high-lipid-producing microalgae to biodiesel operation would need only 1% to 2.5% of existing US agricultural to meet 50% of the current US diesel fuel needs or roughly equivalent to the land area of Connecticut. A review of published fatty acid profiles of various microalgae considered viable for biofuels production indicates that most generally have a degree of carbon-to-carbon bond saturation similar to that of soy oil at about 70% unsaturated fatty acids [31]. Commonly found fatty acids reported in most microalgae are palmitic acid (C16:0), palmitoleic acid (C16:1), stearic acid (C18:0), oleic acid (C18:1), linoleic acid (C18:2), and linolenic acid (C18:2). The bulk of the remaining lipid fractions for most microalgae species are diglycerides and phospholipids. Figure 7 shows two cultivation methods for microalgae.



Figure 7. Microalgae samples and open pond cultivation (Photo Sources: US DOE).

Microalgae per acre annual production—microalgae, more specifically *Chlorella vulgaris*, have been reported to produce as much as 5000 gallons/acre/year [96,101]. However, this production can vary widely based on climate and culturing success. Generally, it is safe to state that lipid production for microalgae is within the range of 1500 to 3000 gallons/acres/year [102]. Plus, with advances in the technology, this range can likely be expanded to the reported maximum of 5000 gallons/acre/year. The US DOE has initiated a significant R&D effort to reach the upper limits of this range and produce a final lipid cost of ~\$4.00/gallon.

Microalgae culturing—to date, there are no long-term operating, full-scale microalgae to liquid fuels production facilities within the US—primarily due to the cost of producing the lipids [96]. On the other hand, culturing of microalgae has been commercially successful for production of other products [103]. Over 1000 tons of microalgal biomass were produced in 1999 for use as an animal feed, and of this tonnage, two-thirds were used for mollusk raising and one-third used for growing fish and shrimp. Furthermore, most of these operations are open ponds—either raceways or rectangular ponds. Microalgae need four key growth factors to reach optimized growth conditions. These factors, listed below, are critical to not only growth, but also chemical composition and cultural integrity within culturing reactor systems [31]:

- Light—for supporting photosynthesis;
- Carbon Dioxide (CO₂)—serves as the primary carbon source for metabolic functioning (note that most microalgae are photo-autotrophs; however, some are heterotrophs);
- Temperature;
- Nitrogen—building biochemical block component;
- Phosphate—building biochemical block component.

The SE-US has a lot of available water, high humidity, but marginal land surface solar radiation [104]. The relative humidity of this region is typically high compared to most areas of the US, which provides conditions with minimum evaporation and hence very limited make-up water required due to atmospheric water losses. A review of DOE's Energy Information Agency (EIA) database on the locations of fuel refineries, storage, distribution pipeline networks, and power plants (CO₂ sources) in the US indicates that the coastal Gulf of Mexico plains contain the highest concentration of fuels-related facilities in the US [105]. Hence, the Southern US Region appears to be particularly attractive for microalgae culturing operations. The estimated biomass yield for microalgae, with regard to carbon dioxide input, is estimated to be approximately 100 tons of microalgae from an inputted 180 tons of carbon dioxide utilized by the cells. This microalgae biomass to carbon dioxide input dosing ratio is commonly reported in the 1.6 to 1.8:1 (w/w) range [31]. Unfortunately, for achieving targeted level of algal biomass in most systems, atmospheric sources of carbon dioxide alone will not meet the carbon needs for supporting the high densities of algal growth targeted for most systems (often in the 50 to 100 kg/L/day range); therefore, for most microalgae growth systems, carbon dioxide must be added (often via gas sparging). Atmospheric carbon dioxide only provides 5% of the required carbon dioxide for high-rate open ponds. Thus, finding and getting cheap carbon dioxide sources to ROW culturing areas may be prohibitive. However, there are new developmental works that are indicating the carbonates may be used as a liquid source for inorganic carbon in place of carbon dioxide (water solutions containing the carbonate species). The use of carbonates will eliminate issues with finding carbon dioxide sources close to the planned algae culturing site and mass transfer challenges of transferring the carbon dioxide gas into the culture water. Open pond systems (also known as raceways or high-rate ponds) are typically designed using a shallow earthen basin that may or may not be lined [96]. These open ponds are referred to individually as a raceway because of the usual elongated layout with semi-circular ends. Sewage lagoons that are square or circular can be used for microalgae production, but these systems are not generally considered viable options for mass production of algae to fuels and chemicals because of their less than ideal designs and operations capabilities. A raceway configuration is a commonly used design, which is essentially an oval open

ditch system with a paddle wheel bridged over some portion of the track to facilitate mixing and/or carbon dioxide introduction. Over 4000 tons per year of algal biomass is produced globally each year with most being cultured in raceway systems. This design has been used since the 1950s with the largest facility being over 440,000 m². Superficial or planar surface areas of the active area of individual ponds are often reported in the 0.1 to 0.5 ha range. The dimensions for length, width, and water depth of a raceway lane reported generally fall in the following ranges: 40 to 650 m, 1.5 to 30 m, and 10 to 60 cm, respectively. The depth of the channel should be not too deep to allow for sufficient sunlight penetration for photosynthesis and facilitate mixing. Lane length to width aspect ratios (L/W) are often in the ~3:1 to 15:1 range. It is often suggested that the optimal L/W ratio is 10 in terms of reducing dead zones and saving power. The paddle wheel mixer is often used and is simply placed over the channel (as a bridged structure) and is mechanically turned to achieve a desired superficial water velocity. The channel cross-sectional velocities are kept high enough to ensure adequate mixing is provided via vertical and horizontal mixing eddies (caused by low-energy turbulent flow) of the microalgae, which should offer exposure of the total biomass to the sunlight, yet the flows are low enough to not expend too much energy. Channel cross-sectional velocities reported to be successfully used are in the 10 to 50 cm/s range. These velocities, selected based on biomass density and algal cell size, are used to keep the algal solids from settling and thus cause them to "roll-over" to maximize exposure of the total algal biomass to sunlight. Many of the suggested raceway designs included lanes within the two curved ends to facilitate a smoother turn to reduce energy costs. Recent work is focusing on energy savings through improved raceway end configurations using computational fluid dynamic modeling, which indicated that the use of progressive bends, which resulted in mixing energy savings in excess of 80%. Note that electricity and water both will likely have to be supplied to the culturing areas, which may also make this option nonviable. Also, to support an algae pond, the land must be flat. There are some large ROW areas where this option may be feasible if the land user has contracts for algae components and a business plan to support their activities.

Microalgae processing—the microalgae must be harvested (mainly using screens), and dried (using natural gas or propane driven heaters—note the CO_2 from the drier could be used for culturing more algae); then, the dried whole algal cake is transported to a central lipid extraction facility where both the lipids and resulting cake can be sent to markets [106]. The lipid extraction facilities are basically the same as an oilseed crushing facility—in fact, an oilseed crushing facility may be able crush algae cells. Also, note in the markets assessment section that whole cells are valuable for animal feed supplements (albeit, this market is not a fuels market).

ROW access requirements when farming microalgae—the frequency of ROW access would be a daily requirement given the microalgae culturing is labor intensive, and at its current state of development, in need of considerable process oversight/sampling. A significantly more increased and diverse (not just farmers) labor pool will need access to a microalgae farm. Microalgae will clearly need more access than any other option. Plus, access to water and power will be required.

Potential microalgae component uses—the lipids from microalgae can be used as excellent feedstocks for both bio-based diesels—biodiesel and green diesel [107,108]. Some microalgae species capable of being cultured in open raceways have a high nutraceutical value thus increasing their value. The whole cells have developing markets as a high-end animal feed supplement. Finally, the delipified cake can be used as an animal feed protein cake (like soy) or within developing adhesives and other specialty chemical production systems.

Microalgae financial markets—the reality today is that the cost of a gallon of algae lipid today is simply not cost competitive at about \$6 to \$8 per gallon [31]. The production of polyunsaturated fatty acids (PUFAs) as health supplements to both human and animal diets are a fast-growing industry that often utilize both phototrophic as well as heterotrophic microalgae species to produce Omega-III and Omega-VI fatty acids as nutraceuticals. Three bio-based diesels deriving from microalgae are considered viable by most experts: Biodiesel (fatty acid alkyl esters), renewable or green diesel (lipids cracked within a traditional petroleum refinery), and thermo-depolymerized algal cells into a

hydrocarbon liquid (also known as bio-oils) that can later be refined into diesel cuts. This opens up a potential separation step with some microalgae culturing operations where if high levels of Omega III fatty acids are present, then separating these high value lipids for use in producing other high-end chemicals (co-products) may be economically viable; in fact, if present these co-products can be highly profitable as nutraceuticals. Currently, the lipid market for use as fuel places algae lipids as needing to be in the less than \$2/gallon range where it is not close at this time [31]. The delipified cake market at this time competes with the soy protein cake market and would bring in about \$250 to \$300 per ton. There is a growing animal feed supplement market where the whole cells (unextracted cells) are being used as a high-end nutritional feed supplement. At this time, the economics for an algae-to-fuels market simply are not feasible. There is a lot of promise but technological developments and increases in petroleum prices need to occur to place algae to fuels are a viable commercial option [109].

Summarized assessment data on microalgae—the summarized assessment via the established evaluation criteria are listed below:

- 1. Per annum oil yield (gallons/acres)—>3000 gallons per acre/year.
- 2. Productive crop in Louisiana (climate matching)—Louisiana and most of the other SE-US states (mainly the lower half—more southernly states) have good climates and location for supporting a microalgae culturing system.
- 3. Culturing requirements (type and respective pounds per year)—culturing microalgae requires flat land (at least 50 feet of width plus a 100-foot buffer zone on each exposed side) with access to water and electricity and likely a carbon dioxide source—all of which could be challenging except for some selected ROW areas.
- 4. Access frequency to crop—daily access will be required with staging areas also needed.
- 5. Water requirements—a significant amount of water will be needed as algae culturing is water-intensive.
- 6. Recommendation—although microalgae-to-fuels have received a lot of attention lately, the economics and ROW requirements are considered too costly and expansive to be considered a viable option for most ROW areas. However, with technology developments and a grower with unique markets, some ROW areas may be feasible. However, land cost and availability are rarely an issue for viable algae culturing enterprises—again, not showing much promise for ROW use by this potential lipid-bearing crop.

7. Comparative Assessment of Phase II Candidate Crops

A more detailed evaluation of an expanded group of assessment criteria was performed based on the above presented information. A relative score for each of the above candidate lipid-producing crops were given from the information obtained through the literature search. Note that "10" is the highest positive score (positive meaning that the crop would be a good fit) and a score of "1" indicating that the crop is a poor fit under that respective factor. Also note that this assessment was done from a biofuels production viewpoint first, then co-product opportunities or no energy production at all being produced from the crop (i.e., the crop used as a feedstock for a non-energy product/use).

A listing and brief explanation of each evaluation factor is presented below:

Quality of the lipids—the higher the level of unsaturation (C to C binding), the better. Note that nutraceutical value is not taken into consideration but could be if fuel production was not the goal. The potential for non-energy products could actually bring more profit or value to the ROW areas than energy production.

Amount of lipids produced—this factor assesses the annual per acre volume of lipids produced by the candidate crop.

Lipid selling price-point—the current market price for the lipid produced from the candidate crop is scored with this factor.

Estimated net per acre income—the dollars generated once the estimated cost to produce is subtracted from the income generated on an annual per acre is scored. Current US (first choice) or global (if a US figure could not be generated) lipid prices were used.

Strong, expanding markets—the potential for long-term, steady markets for the lipid generated is the factor under consideration. This factor goes take into account the overall market, which does not only include energy usage, but also takes into account co-product and non-fuel production valuation.

Good fit in region using Louisiana as the base case—the history of the crop being cultivated in Louisiana and/or the conditions needed to grow the crop in Louisiana is being scored. Even if the crop is not currently considered an agricultural crop, the conditions needed were assessed as if all candidate lipid sources were "crops." For example, Chinese Tallow is officially listed as an invasive, nuisance tree in most states but was treated as a crop in this report.

Chemical/water application—this factor assesses the amount/volume of chemicals and water that may have to be applied onto the crop. Mainly, fertilizers and pesticides were the issue with irrigation rarely needed in Louisiana. However, in the case of microalgae, access to water is an issue because of evaporative losses from the open culturing ponds. Note that there are rarely, if not never, water shortage issues in Louisiana and the region in general (often, quite the opposite).

Frequency of ROW access needed—the frequency that the farmer and his/her equipment must enter the ROW area from the highway is being scored. This assessment includes the parking zone requirement mentioned above within the factor scoring.

Potential co-products—The potential to produce a co-product that adds additional value or profit to the farming operation is being scored. Even developing co-product markets were included in this assessment factor.

Toxic plant components—the presence of any part of the crop that is toxic to humans and animals is being scored. It is realized that ROW areas, particularly center ROWs, have very low non-official personnel entry into the center ROW; still for this report, the presence of toxic components was considered a negative (thus lower scores).

Issue with attracting deer—this score evaluated the potential to attract deer into the crop due to the attraction of the crop to deer. The scoring is not a relative attraction to grass, but simply if deer are known to utilize the crop as a food source.

Value as a biofuel feedstock—this score evaluates both the quality and amount of biofuel(s) that can be produced along with the relative cost of the lipids produced by the candidate crop.

Winter crop—the ability to grow during Louisiana winters thus opening the opportunity for dual-cropping is being scored. Any potential to double-crop or second head (grow two crops of the same plant) was considered positive. Note that microalgae are a year-round crop (continuous operations).

ROW mowing requirements—mowing of ROW areas is a costly operation to highway departments. If the ROW area is completely maintained by the farmer, then the crop scored high. If the crop is a tree with significant spacing between then, then it is assumed that some of the mowing would have to be done by the highway department, thus a lower score.

The relative scores assigned to each candidate crop is presented in the Table 2. From the table, it can be seen that well-established oilseed crops all scored highest. This is likely the reason that they are established crops in the region. The trees, albeit easy to maintain, had issues with relatively weak markets and poison fruit that diminished their scores. However, if markets do expand, particularly for Tung Oil, then this crop may become more viable. Microalgae, for all of R&D ongoing developing it as a viable biofuel source, scored the lowest of the candidate crops. This is not surprising given the immature status of microalgae as a chemical/energy crop. It also is the most labor and equipment intense option. If microalgae do improve over the years as a viable energy crop, this scoring position should be revisited.

Three potentially viable options have emerged from the analysis of lipid-bearing crops within highway ROW areas. The top options and one integrated option, presented in no order-based preference, are: (1) Plant flax in the winter, (2) plant flax in the winter and sunflowers in the summer

(sunflowers were selected over soybeans because they attract less deer and have an expanding global market), (3) plant sunflowers in the summer, or (4) plant Tung Trees and culture them year-round.

Table 2. Phase II assessment scoring table (Note: All evaluative factors were equal-weighted and the numerical scores were given based on the opinions of the authors via their review of the literature, discussions with government and industry officials, and their own working knowledge of the lipid industry).

Candidate Lipid Sources	Soybeans	Flax	Sunflowers	Tung Trees	Chinese Tallow Trees	Microalgae
Quality of Lipids	8	9	9	9	8	8
Amount of Lipids Produced	5	5	7	5	8	10
Lipid Selling Price-point	8	4	5	5	6	0
Estimated Net Per Acre Income	5	6	5	7	8	0
Strong, Expanding Markets	5	8	6	6	1	5
Good Culturing Fit in LA	7	7	7	9	9	9
Chemical/Water Application	3	5	8	8	9	5
Frequency of ROW Access Needed	3	4	4	7	7	2
Potential Co-Products	5	8	6	5	3	8
Toxic Plant Components	9	9	9	2	2	8
Issue with Attracting Deer	8	4	3	1	1	1
Value as Biofuel Feedstock	6	2	3	7	8	0
Winter Crop	1	9	1	4	4	8
ROW Mowing Requirements	8	8	8	3	3	8

8. Suggested Options for Lipid-Producing Crops within ROW Lands

Several options appear both technically and economically feasible. All but Tung Trees will require frequent access into the ROW areas being cultivated. Also, only ROW areas that are fairly flat (less than 15% grade), drain fairly well (does not hold water often for long periods of time), will require some chemical application (pesticides and fertilizers), will require some level of surface soil disturbance (a) can cause some erosion, but this is an area well managed by current no-till farming practices and (b) can have periodic dust drift, but this can be managed with proper wind observation), and will require ROW areas likely with 200-foot widths and at least 500 feet in length (this equates to about 2 acres per plot). The actual area and safe buffer zones should be further investigated for each site. Tung Trees can be placed in almost any reasonable ROW area. However, the Tung Tree growing zones will require mowing (especially right before the fruit drop off the trees for harvesting reasons). The mowing can be placed into the grower's contract so that the highway department does not have the burden of upkeep. Also, the issue of having trees within ROW areas containing toxic components should be further investigated. Note that all options will require some form of farming operations staging areas (the size and frequency along long spans of growing areas will also be a site-by-site decision).

9. Conclusions

Based on all the data generated and the side by side comparisons, growing sunflowers in the summer followed by a winter flax crop and the Tung Trees grown year-round appear to be the most viable options. Again, toxicity issues with Tung Trees must be addressed if this option is to gain significant traction as a final option.

10. Final Comments

This study focused on growing lipid-bearing crops that can be used as feedstocks for producing energy (mainly transportation fuels) and potentially co-products. It did not evaluate all money-producing options (non-lipid producing options), which may be much more financially attractive than only focusing on energy and then co-products to provide price offsets for the energy feedstocks.

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