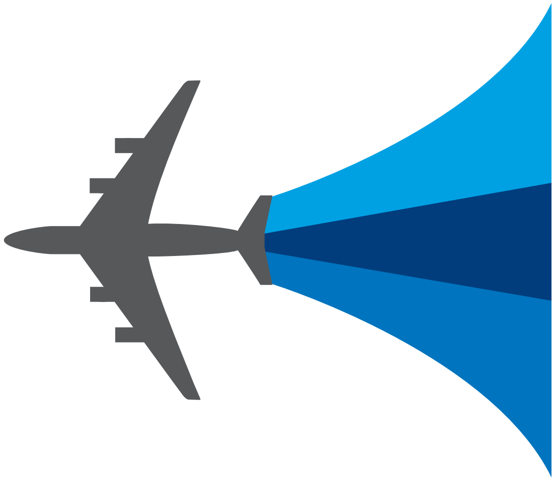

PART III

TECHNOLOGY DEVELOPMENT STRATEGY

11 ANALYSIS OF IDENTIFIED PATHWAYS

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11 ANALYSIS OF IDENTIFIED PATHWAYS

The previous sections presented an overview of the main findings from previous workshops, more specifically 2nd, 3rd, and 4th workshops concerning feedstock, refining technologies and sustainability issues. Those findings provide a wide variety of technical and commercial issues that may lead to the identification of R&D and commercialization gaps. Each of the identified pathways was object of discussion in 7th Workshop, in order to identify R&D needs and commercialization gaps.

In the first place, technical issues in each pathway can be broadly defined in terms of:

(i) the probability to develop a strong and protectable patent, or to develop a proprietary position in the technologies relevant to that specific pathway (Technical Criterion #1: Intellectual Property);

(ii) the probability that the technical resources available may have the capabilities needed to develop a successful pathway (Technical Criterion #2: Capabilities);

(iii) the pathway's technical complexity impact on its success probability (Technical Criterion #3: Technical complexity);

(iv) the effect of external technologies availability and the effect of organizational skills to use such technologies in the pathway's probability to meet its goals (Technical Criterion #4: Access and efficient use of external technology) and;

(v) the probability that an organization (or a group of organizations in the Brazilian aviation industry) has the capabilities (internal and external) to manufacture the product ("drop in" sustainable jet biofuel) or incorporate the production process to its operations (Technical Criterion #5: Production capacity).

In the second place, commercial issues in each pathway can also be broadly defined in terms of:

(i) the probability of existing a market ready for the product, or a big need for the process that results from the pathway in question (Commercial Criterion #1: Market/customer needs - internal or external);

(ii) the probability of the product – "drop in" sustainable jet biofuel – being accepted in the market due to market forces and/or brand recognition in the market of interest – aviation industry (Commercial Criterion #2: Market/business recognition);

(iii) how easily the product will be introduced and made available to customers in the market (Commercial Criterion #3: Channels);

(iv) the probability of success/failure based on customer strength in the business area of interest (Commercial Criterion #4: Customer strength);

(v) the effect of supply and or availability of essential components or materials in the pathway's probability of success (i.e.: feedstock availability) (Commercial Criterion #5: Raw materials or essential components supply); and

(vi) the probability of health, safety and environmental issues affecting the pathway's success (Commercial Criterion #6: Safety, health and environmental risks).

Moreover, an assessment of financial issues complemented the commercial aspects of each pathway, in terms of the probability that the economic agents will receive financial rewards, considering market value, profit margins, typical time it will take to start profiting (positive margins) and, specially, investment (capital expenses and operational expenses) and corresponding financial risks.

Finally, each pathway has a specific potential to comply with the roadmap's vision and goals. Aspects considered in sustainability involved: low land use, promote rural development, low water use, no harm to air quality, maintain or improve soil fertility, no competition with biodiversity and food security, and positive social development. Some specialists simply summarize the sustainability aspects to be considered in biofuels production in 3 aspects: environment, social and economics. However, a pre-requirement and "**raison d'être**" of the *Sustainable Aviation Biofuels for Brazil Project* is to evaluate how sustainable biofuels can contribute to mitigate CO_2 emissions. Therefore, low CO_2 emissions with high potential reduction can be considered a pre-requirement or "**sine qua non**" condition.

This assessment, naturally, depended on the focus or perspective from which the biofuel was evaluated. For example, if the evaluation is being conducted for cost analysis, each step of production and distribution needs to be quantified. It is well known that in general the feedstock cost plays an important role in biofuels production. In case of sugarcane ethanol it can be close to 70% and in case of biodiesel up to 80 or 90%. Another perspective, actually the main objective of the *Sustainable Aviation Biofuels for Brazil Project*, is to analyze the proposed biofuel (feedstock and refining technology) from the CO_2 emissions perspective. In this case the entire LCA will need to be performed to analyze its CO_2 mitigation potential and where the main questions to be answered remain.

In sum, the assessment made more visible the areas in need of more research. During the two days of 7th Workshop, specialists were invited to participate in panels to present their views on what are the R&D and commercialization gaps in each of the four groups of feedstock alternatives: sugars, oil bearing, lignocellulocics and wastes.

The second day of this workshop also included a group discussion to perform a multicriteria analysis of each of the identified pathways for biofuels for aviation in Brazil. The audience was divided in four groups, according to the four feedstock alternatives, and each will begin the multi-criteria analysis of potential strategic impact of each pathway, followed by technical risks and commercial risks and financial rewards, ending with an overall discussion of pathways considering feedstocks and refining technologies.

The purpose of the multi-criteria analysis was to gather specialists and foster a fruitful discussion on what are the key issues in terms of R&D and commercialization gaps that should be brought to attention in this roadmapping process. Each group had a facilitator and an editor. The facilitator's role is to support everyone to do their best thinking and practice, encourage full participation, promote mutual understanding and cultivate shared responsibility (KANER et al., 2007). His/her deliverable was to reach an answer for each question, according to a printed template and time constraints and to present a synthesis of the group's discussion. The editor's role was to identify important issues being discussed by the group in each criteria, and his/her deliverable was a written summary of groups discussions, according to a printed template, including rationale for each answer, points of divergence, knowledge gaps in the group, disruptive technologies and future decision points any other observations.

That analysis showed that all identified pathways have strategic potential to be compliant with the roadmap goals (**Figure 83**), but technical and commercial risks need mitigation and are somewhat specific to each combination of feedstock and refining technologies being considered, as shown in previous sections of this report.

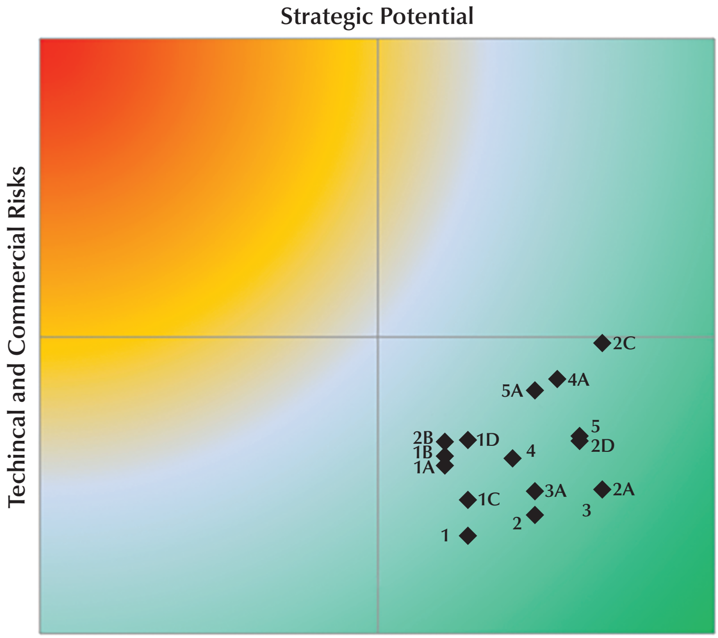

Figure 83 Multicriteria analysis of different identified pathways.

Figure 84 presents an overview of all identified pathways pertinent to Brazil, including the denomination and status of the ASTM approval process. As depicted, three of the final jet fuel production processes are already approved (green boxes in **Figure 84**), including the last one in June/2014 denominated SIP Annex 3. This figure contains essentially the same pathways and intermediary products previously presented in **Figure 78**, and that were discussed in detail in Section 1.3. With the rearrangement it was possible to group the conversion processes into "Lipid", "Biochemical" and "Thermochemical", besides highlighting the products and writing down the name of the processes, bringing more information in a cleaner picture. It was also possible to include the catalytic hydro-thermolysis route and to detach a special box for phototrophic algae as feedstock for production of cellulosic biomass or oils.

Table 35 Pathways submitted to multi-criteria analysis.

1	Oil-bearing plants through HEFA
1A	Tallow and fats through HEFA
1B	Used cooking oil through HEFA
1C	Sugar-bearing plants through fermentation to lipids and HEFA
1D	Ligno-cellulose through hydrolysis to sugars to lipids and HEFA
2	Sugar-bearing plants through fermentation to ethanol and ATJ
2A	Ligno-cellulose through hydrolysis to fermentable sugars to alcohols and ATJ
2B	Flue gas (CO, CO/H_2) through fermentation to alcohols and ATJ
2C	Ligno-cellulose through gasification to CO/H_2 to alcohols to ATJ
2D	MSW through fermentation to organic acids to alcohols to ATJ
3	Ligno-cellulose through gasification&reforming to syngas to FT
3A	Ligno-cellulose through pyrolysis to biochar&bio-oil to gasification to syngas to FT
4	Sugar-bearing plants through fermentation by GMO to hydrocarbons (DSHC)
4A	Ligno-cellulose through hydrolysis to sugars to hydrocarbons (DSHC)
5	Ligno-cellulose through fast pyrolysis to bio-oil via deoxigenation (HDCJ)
5A	Ligno-cellulose through direct liquefaction to bio-oil via deoxigenation (HDCJ)

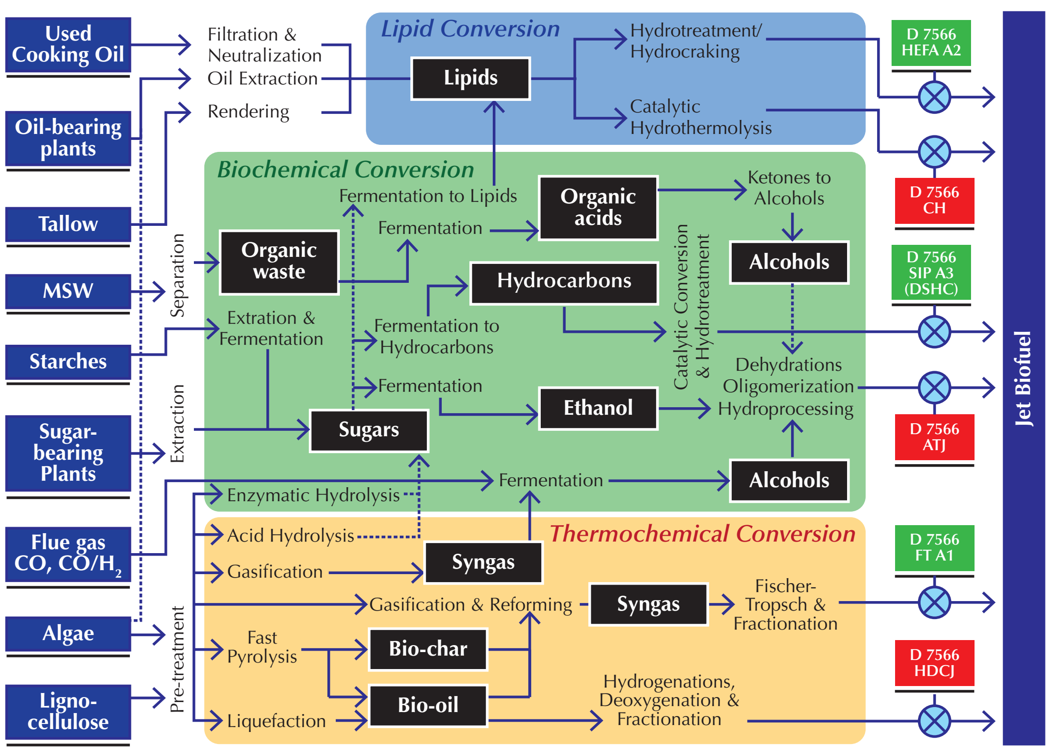

Figure 84 Identified pathways for the production of sustainable jet biofuel in Brazil.

R&D for Identified Pathways

The lipid conversion route is well established and approved by ASTM as HEFA – hydro-processed esters and fatty acids. Investment cost for hydro-processing is considered to be low, but the cost of feedstocks can represent more than 70% of total cost (EC, 2011). The availability of inexpensive hydrogen can affect significantly the final cost. The main gap in this case is a commercial one. The Brazilian Biodiesel Program competes for the same feedstocks – plant oil, tallow and used cooking oil. Eventual niche markets for supplying airports distant from refineries but near agriculture fields could be promoted by the production of hydrogen from biomass, aspect that needs to be better developed in Brazil. The high oil productivity of palm has to be better explored for the Brazilian conditions and R&D on its agriculture side needs to be incentivized. R&D on other oil producing plants can help to improve agriculture gains on lands that are not presently used for agriculture, but it is necessary to treat Brazilian biofuels in an integrated way to avoid the competition for feedstock between jet biofuel and biodiesel. Another possibility of feedstock is microbial lipid produced by fermentation of soluble sugars (heterotrophic) or directly produced by algae (phototrophic). The R&D gaps for these pathways range from applied biology to improve microbe stability to construction of demonstration units large enough to obtain competitive prices. If cellulose can be used as feedstock some cost benefits are expected on the long run.

The biochemical conversion route actually includes diverse feedstocks such as municipal solid waste, flue gas rich in carbon monoxide and fermentable sugars, either from plants, starch conversion or hydrolysis of cellulosic material. Most of the pathways produce alcohols as intermediate products that are transformed into jet biofuel through the ATJ process, which is going through the approval process as an annex by ASTM. The other possible route, which has beem treated in this report as DSHC (Direct Sugar to Hydrocarbon), was approved by ASTM in June/2014 as Annex 3 – Synthesized Iso-Paraffins (SIP) for blending of up to 10% with conventional jet fuel. The route uses genetically modifies microbes to convert the sugar, followed by a soft hydrogenation to obtain the jet biofuel. Another possible fermentation route, which was not represented due to process complexity and high cost, is through biomethanation of residues, followed by GTL (gas to liquid) processes to obtain liquid biofuels.

There are several R&D gaps to be filled according to the development stage of each particular pathway, as for example: to develop more selective catalysts to convert alcohols more efficiently to jet biofuel; to improve the conversion efficiency of sugars to hydrocarbon; to develop microbes more resistant to contamination by synthesis gas produced through gasification; to advance municipal waste separation and to improve fermentation of the organic fraction; to reduce the cost of enzymatic hydrolysis to produce fermentable sugars or ethanol; to overcome the phase of demonstration units and reach commercial ones for all the pathways.

The main commercial gap for the pathways that go through sugars or ethanol, is that the market price of these intermediate products is high due to possible uses as food or road biofuel. Due to the large Brazilian experience in producing sugar and ethanol from sugarcane and the existence of a well-established agro-industrial sector dedicated to the field, the natural reference price for liquid biofuels probably will be ethanol. In energy terms, the actual ethanol consumption in Brazil as road biofuel is more than one and a half times all aviation fuel consumption (ANP, 2012). Once again, it is necessary to establish a governmental program to treat Brazilian biofuels in an integrated way to avoid the competition for feedstock between aviation and road biofuels.

The main feedstock for the thermochemical route is lignocelluloses that is available in sufficient amounts to substitute all conventional liquid fuels in the country. An ASTM approved pathway using this route to get to jet biofuel using the Fischer-Tropsch process already exists. The origin of the lignocellulosic material can be sugarcane bagasse, wood, forestry residues or any other biomass.

Although the cost of the raw material in the field can be very low, the transportation cost is important and limits the size of the processing plant, with large implications on investment cost. Other possible route using lignocellulosic biomass is to start with pyrolysis, obtaining bio-oil and biochar, intermediate products that could be transported economically through longer distances, to be then submitted to gasification and synthesis by the Fischer-Tropsch process. The cost of the process is still considered high due to the very special conditions required by the reactions (high temperature and pressure), demanding large reactors to decrease cost. Worth mentioning that the F-T process produces not only jet biofuel but also renewable diesel and gasoline, which should be considered together in a biofuel integrated program.

The main development gap in this pathway is the gasification and gas cleaning processes that are not designed for the available Brazilian biomass.

A promising pathway alternative to Fischer-Tropsch, which has being researched mainly outside the country, is to obtain a bio-oil through fast pyrolysis or solvent liquefaction, which could be upgraded in an existing refinery infrastructure, reducing costs of up-grading.

The transformation of the bio-oil in jet biofuel is done by deoxygenation processes. The main R&D gap in this case is that hydrodeoxygenation of bio-oils needs extreme conditions of temperature and pressure, with specific catalysts and expensive hydrogen.

Table 37 presents a list of pros/cons of the selected crops/feedstocks and the refining technology discussed.

Table 36 Pros and cons of selected crops/feedstocks and refining technologies.

FEED-STOCK GROUP	SELECTED CROPS/ FEED-STOCKS	REFINING TECH-NOLOGY	PROS	CONS	CO-PRODUCT	REMARKS
Oil	**Palm**	**HEFA**	- Present high productivity ~5,000 liters of oil/ha.year. - High productivity and is considered an "energy crop".	- There is potential in Brazil, however planted area is still small (Brazil still imports palm oil, mainly for food). - The main gap is to create conditions for the expansion of the planted area.	- Palm kernel oil has potential. - Palm plant also produces high quantities of lignocellulosic material. - Food security and deforestation will probably not be a barrier for palm oil as long as plantations are developed in low yield pasture lands.	- Deforestation may be an issue because palm requires much water and is best grown in rain forest regions (closer to the Amazon) - Needs long term R&D.
	Soybean	**HEFA**	- Traditional crop, produced in large areas in Brazil (27 Mha). - Brazil is presently the world largest exporter of soybean. - Consolidated scientific research in Brazil.	- Low oil content, low energy yields and reduced perspective for research focused on increasing oil content, given that the protein market is still more relevant for soybean producers and crushers. - Monoculture	- Soybean meal (cake) is used as animal feed	- Although oil and meal do not compete, because they are co-products, soybean is strongly connected to the food markets.
	Camelina	**HEFA**	- Can be planted in intercrops in the Brazilian "cerrado", therefore requiring "no extra" land.	- Oil yield of this crop is still not known in Brazil, although potentially higher than that of soybean, is lower than palm. - Requires N fertilization.	- Camelina meal (cake) is rich in Omega 3, therefore with high commercial value.	- Barriers can be overcome if camelina turns out to be an efficient second crop, which still needs to be proved for Brazilian conditions. - Needs long term R&D.

Table 36 Pros and cons of selected crops/feedstocks and refining technologies (continued).

FEED-STOCK GROUP	SELECTED CROPS/ FEED-STOCKS	REFINING TECH-NOLOGY	PROS	CONS	CO-PRODUCT	REMARKS
	Jatropha	**HEFA**	- Does not compete with food.	- Commercial production is limited because several agronomic improvements still need to be solved through research. - The toxification problem of the jatropha cake has to be overcome.	- Detoxified meal as feed.	- Needs long term R&D.
Sugar/ Starch	**Sugarcane sucrose ATJF**	**Amyris Solazyme**	- Traditional crop, produced in large areas in Brazil (9 Mha). - High productivity. It is considered an “energy crop”. - Brazil is presently the largest exporter of sugar and largest producer of ethanol from cane. - Consolidated scientific research in Brazil.	- Sugarcane is facing a short term gap due to supply shortage and lower yields. Sugarcane is not performing yield increases as found in the past, which requires larger investments to promote the expansion of the production. -Increasing yields is the main gap, also because production costs have increased in the last years. - Monoculture. - Sugarcane expansion is taking place towards regions with longer water deficit periods, low fertility and non-traditional areas, increasing risks and costs.	- Sugar has very good commercial value (~30% higher than ethanol)and the use of low quality sucrose helps to produce a low cost ethanol	

	Sweet sorghum sucrose	**Amyris Solazyme ATJF**	- Once integrated to sugarcane, the main gaps are related to genetic breeding oriented to increasing yields and to extending the harvesting period.	- Non traditional crop in Brazil. - The main gap is to create conditions for the integration of the crop in the sugarcane production chain. The economic rationality of sweet sorghum arises if the crop is integrated to sugarcane. - To develop an industrial process to allow the use of the starch contained in the grain is a gap in the industrialization, specially having in mind that the sorghum is to be processed in sugar mills.	- Grains and lignocellulosic materials.	- Needs long term R&D.
	Cassava	**Amyris Solazyme ATJF**	- Traditional crop in Brazil. Brazil is the largest producer.	- The main gap for cassava is that Brazil has no tradition in producing energy from starch. - Although being a rustic plant and cropped in different regions, examples in Brazil show that the achievement of high yields requires good crop management. - Mechanization is a barrier for allowing the use of cassava as a feedstock for biofuels.	- Food products.	- Needs long term R&D.

Table 36 Pros and cons of selected crops/feedstocks and refining technologies (continued).

FEED-STOCK GROUP	SELECTED CROPS/ FEED-STOCKS	REFINING TECH-NOLOGY	PROS	CONS	CO-PRODUCT	REMARKS
Lignocel-lulosic	**Eucalyptus**	**Gasifica-tion Fischer Tropsch Hydrolysis**	- Traditional crop in Brazil. Brazil presents the highest yields in the world. - High productivity. It is considered an "energy crop". - Does not compete with food. - Consolidated scientific research in Brazil.	- Similar to sugarcane, expansion is occurring in degraded areas and in areas susceptible to high degrees of water and thermal stress. Given that is very difficult to balance in a same genotype biotic resistance, tolerance to drought or frost, good productivity and good quality of wood, it is necessary to produce interspecific hybrids. - Creating the facilities and the infra-structure necessary to allow the use of residues for producing biofuels is also a gap.	- Electricity generation - Charcoal or thermal energy production - Pulp for cellulose - Pellets - Oil extractions - Wood for saw mills.	- Not available in industrial plants in Brazil.
	Grasses (elephant grass)	**Gasifica-tion Fischer Tropsch Hydrolysis**	- High productivity. It is considered an "energy crop". - Does not compete with food.	- The use of grasses to produce energy is something new in Brazil. Grasses have been used for animal feed; management practices such as the use of fertilizers, are still not common. - Cut, collect and dry (wet climate) large amounts of biomass is a barrier.	- Electricity generation - Charcoal or thermal energy production - Pellets.	- Needs long term R&D.

Lignocel-lulosic	**Grasses (elephant grass)**	**Gasifica-tion Fischer Tropsch Hydrolysis**		Costs are not known and solutions and machinery are not in the market. - Selection of more productive and efficient genotypes is also a gap.		
	Sugarcane bagasse and trash	**Gasifica-tion Fischer Tropsch Hydrolysis**	- Does not compete with food.	- A barrier for the use of sugarcane in the jet biofuel market is the high opportunity cost of the cane (sugar and ethanol markets) and the bagasse, given that it is largely used for electricity generation. Although being a residue of the cane crushing, the bagasse is not a tip free residue.	Pellets	
Wastes/ Residues	**CO_2 - algae**	**HEFA**	- Does not compete with food.	- Costly alternative. - Availability.		- Needs long term R&D.
	Steel Mill Flue Gases: CO, H_2	**Anaerobic fermenta-tion and ATJ**	- Does not compete with food. - Low cost feedstock. - Does not require large scale. - Point sourced - Global Availability	- High CAPEX alternative - Logistic and separation issues are key barriers. Uniformity of organic fraction needed - Biogenic MSW collection costs must be competitive with current costs, unless turned mandatory by law. - Environmental legislation can potentially be a constraint because the use of solid waste should require different permits.	- Cleaner emissions	- Needs demonstration at commercial scale

Table 36 Pros and cons of selected crops/feedstocks and refining technologies (continued).

FEED-STOCK GROUP	SELECTED CROPS/ FEED-STOCKS	REFINING TECH-NOLOGY	PROS	CONS	CO-PRODUCT	REMARKS
Wastes/ Residues	**MSW**	**Fermentation Gasification Fisher Tropsch**	- Does not compete with food. - May have a "negative cost" if the proper residues policy is implemented.	- High CAPEX alternative - Logistic and separation issues are key barriers. Uniformity of organic fraction needed	- Cleaner environment.	- Needs long term R&D.
		Anaerobic fermentation of organic fraction and ATJ		- Biogenic MSW collection costs must be competitive with current costs, unless turned mandatory by law. - Environmental legislation can potentially be a constraint because the use of solid waste should require different permits.		
	Tallow	**HEFA**	- Use of residue. - Does not compete with food. - Adds value in a food chain.	- Limited quantity since it is a by-product of beef production. - Presently used for biodiesel production.	- Cleaner environment.	- Not likely to be produced in much bigger quantities due to high collecting costs.
	Used cooking oil	**HEFA**	- Use of residue. - Reduces disposal costs. - Does not compete with food. - Collecting difficulties and high costs.	- Already used in small quantities for biodiesel production.	- Cleaner environment.	- Not likely to be produced in much bigger quantities due to high collecting costs.