Comparative Life Cycle Assessment Approach for Sustainable Transport Fuel Production from Waste Cooking Oil and Rapeseed

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Abstract

Greenhouse gases (GHGs) emitted by road transport vehicles as a direct result of fossil fuel combustion and other environmental pollutants released throughout the life cycle of petroleum based fuels, encourage a shift towards more sustainable, biomass derived transport fuels. Within this frame, a life cycle assessment (LCA) was performed to evaluate the environmental implications of replacing petroleum-based diesel with 5 and 20 percent waste cooking oil (WCO) and rapeseed biodiesel blends in city buses of Istanbul, Turkey. The results were evaluated in terms of their impacts to global warming, acidification, eutrophication, photochemical ozone formation, winter smog formation, carcinogenesis and heavy metal potential with the main focus on the climate change. Gabi 4 LCA software was used for the analysis and Eco-indicator 95 Life Cycle Impact Assessment Methodology was implemented for the normalization and weighting of the obtained environmental impact potentials. The results showed that B20 WCO had the lowest global warming potential among considered fuel alternatives, followed by B20 rapeseed, resulting in 21% and 11% lower GHG emissions respectively, compared to petroleum-based diesel. On the overall however, weighted results determined B5 and B20 rapeseed to be least environmentally favorable fuel alternatives due to high acidification and eutrophication potentials mainly resulting from use of nitrogen rich fertilizers for rapeseed cultivation. The acidification and eutrophication potentials of B20 rapeseed were 22 and 53% higher compared to B20 WCO and 14 and 45% higher compared to petroleum-based diesel respectively. The same pattern but, to a lesser extent was observed for 5% biodiesel blends. Considering these findings, it is concluded that the replacement of petroleum-based diesel with B20 WCO biodiesel in city transport of Istanbul is a viable option for combating the climate change along with an array of other environmental challenges.

Keywords: Life Cycle Assessment, biodiesel, climate change

1. Introduction

Increasing petroleum and petroleum-based fuel prices and stricter emission regulations imposed by the majority of industrialized nations in response to growing concerns over the negative environmental impacts of those emissions, not least of which are global warming and climate change, have facilitated a shift towards utilization of more sustainable, biomass derived transport fuels such as biodiesel and bioethanol. According to the US Energy Information Administration, the world's total energy consumption had reached 487 EJ in 2005 with transportation sector consuming roughly 20% of the total and is projected to increase up to 733 EJ by the year 2030 [2, 3]. The share of transportation sector in total liquid fuel consumption is expected to increase from 52% to 58% during the same period [3]. Transport sector is also a significant source of air pollutant emissions; in the year 2006 greenhouse gas (GHG) emissions from this sector had reached 1.3 billion $MtCO_2e$ in the EU-27 countries with 71.2% of it resulting from the road transportation [4]. Emission of GHGs is not the only environmental issue related to the transportation sector. Particulate matter (PM), ozone precursor, smog-forming pollutant and carcinogen emissions associated with various stages of transport fuels pose serious dangers to human health and the environment. According to the Annual European Community LRTAP Convention emission inventory report 1990–2006, even though EU-27 countries have substantially lowered their air pollutant emissions in the past several decades, the transportation sector still remained the primary source of nitrogen oxides (NO_x), carbon monoxide (CO) and non-methane volatile organic compounds (NMVOCs) in the year 2006 [5].

As a rapidly developing country Turkey faces with a dual challenge of providing an adequate energy supply for population and economic growth and reducing the GHG emissions and waste production. The recent approval of the Kyoto Protocol by the Turkish parliament has highlighted the country's commitment to tackle the climate change (Official Gazette of Turkey, 2009).

1.1. Transportation in Turkey

GHG emissions of Turkey from the transport sector have increased by 68.9% from 1990 to 2006, parallel to a 60% increase in total freight transport demand during the same period [6]. Although the car ownership in Turkey have increased by 71.4% between 1995 and 2006 and reached 84 cars per 1,000 inhabitants, it still remains the lowest among 32 European Economic Area (EEA) member countries [6, 7]. Lower car ownership drives the huge transport market of future with increasing population and growing industry, creating ghost carbon footprint of the transport sector for the near future. Turkey also has the largest bus and coach fleet among EEA member countries (about 35% of the total) [6]. Moreover, the road transport vehicles are unevenly distributed within the territory of country with highest density being in Istanbul that roughly contains one-fifth of all road motor vehicles creating additional local air quality concerns [8]. These figures underline the importance of moving towards a more sustainable transport system and utilization of biomass derived liquid fuels such as biodiesel in public and passenger transportation.

1.2. Biodiesel as an Alternative Transport Fuel

Biodiesel is a nontoxic, renewable diesel fuel substitute composed of monoalkyl esters of long chain fatty acids usually derived from vegetable oil or animal fat. Utilization of biodiesel offers environmental, economic and energy security benefits by resulting in lower emission levels of GHGs and other regulated air pollutants, creating new jobs in rural areas as well as reducing dependence on limited fossil fuels [9]. However, biodiesel production is highly dependent on many local variables such as feedstock and land availability, costs associated with feedstock procurement, government subsidies and tax reductions as well as interactions with the food industry. According to the European Biodiesel Board (EBB) report, the European Union (EU) biodiesel production has doubled between the years 2004 and 2006, reaching 4.9 million metric tons in 2006 [10]. Some 450,000 to 878,000 metric tons of biodiesel was produced in Turkey in 2005, with wide range being due to inconsistencies between different statistical sources [11].

Biodiesel production from two feedstocks, rapeseed and waste cooking oil (WCO), was considered in this study. Edible vegetable oil derived from rapeseed is the most widely used feedstock for biodiesel production in the European Union [12]. Currently Turkey is a net importer of both rapeseed seeds and crude rapeseed oil with domestic rapeseed seed production constituting only one tenth of the imported amount but, availability of fertile agricultural lands create a potential for future domestic biodiesel feedstock production [13].

Synthesis of biodiesel from waste cooking oil is can be considered as a technically feasible and economically sound way of waste vegetable oil minimization and transport fuel production although almost always pre-treatment procedures are required depending on the feedstock quality. Approximately 1.5 million tons of vegetable oil is consumed as food in Turkey each year resulting in generation of nearly 350,000 tons of waste cooking oil [14]. Regulation on Control of Waste Vegetable Oil published in the Official Gazette of Turkey no 25791 on April 19, 2005 prohibit discharge of waste cooking oil into sewer systems and other water bodies, mixing with edible, crude or mineral oils, direct utilization of WCO as a fuel and require municipalities to take necessary actions for collecting WCO from residential areas [15]. These requirements imposed by the government along with economic and environmental benefits, strongly favor the utilization of WCO as a feedstock for biodiesel production in Turkey.

1.3. Life Cycle Assessment of Biodiesel

As a cradle-to-grave life cycle analysis system, life cycle assessment (LCA) is a method of choice for evaluation of the environmental impacts of products and processes. The assessments performed with this method are in agreement with the ISO 14040 requirements and obtained results provide policy and decision makers with realistic and data based criteria [16, 17]. An LCA approach was applied in this study in order to assess and contrast the environmental impacts of 5 and 20 percent blends of biodiesel fuels (B5 and B20) produced from rapeseed and WCO feedstocks with petroleum-based diesel. Environmental burdens associated with the complete life cycle of each fuel were grouped into seven separate impact categories; global warming, acidification, eutrophication, photochemical ozone formation, winter smog formation, carcinogenesis and heavy metal emission. GaBi 4 LCA software was used for modeling of the LCA scenarios [18].

2. LCA Approach for Diesel and Biodiesel

Two biodiesel blend ratios, B5 and B20, prepared from two different feedstocks, rapeseed oil and WCO, were considered for the analysis in this study. The environmental impacts of the blends were evaluated and compared with the results obtained for the petroleum-based diesel with Eco-indicator 95 LCIA Methodology [19]. Lurgi's process of transesterification was used in this study as it is one of the most efficient and common systems for biodiesel production [20]. Fuel combustion data were obtained from the BIOBUS project, a comprehensive study on using biodiesel blends in real transport conditions conducted by the Canadian Renewable Fuels Association (CRFA) [21]. Since the BIOBUS project lacked sulphur dioxide emission data, data from a similar LCA study conducted by the U.S. Department of Energy was used to simulate sulphur dioxide emissions [22].

2.1. Funcitonal Unit

The functional unit of the study was defined to be 100 km distance traveled on the city core route by a city bus equipped with four stroke, 250 HP, 2200 rpm Cummings engine with electronic fuel injection. It was assumed that the buses consume 65 liters/100km on city core routes on average [21]. Since engine performance and efficiency is affected by the type of fuel used in the engine, necessary adjustments were made to amounts of fuel consumed per distance travelled for petroleum-based diesel and biodiesel blends. Engine efficiencies of the biodiesel blends and petroleum-based diesel fuel are listed in Table 1.

Table 1. Inventory data for the engine efficiencies of fuels [21, 26]

Fuel type	Consumption (Lt/Mj)	Efficiency (%)
No.2 Diesel	0.08508	32.27
B5 Rapeseed	0.08587	31.90
B20 Rapeseed	0.08616	32.08
B5 WCO	0.08486	32.40
B20 WCO	0.08553	32.32

2.2. System Boundaries

All stages of the fuel life cycles were considered except for the byproduct usage stages of the biodiesel fuels. The main stages of the fuel systems included within the boundaries of the study are shown in Figure 1. Economic allocation was implemented for two byproducts of the rapeseed biodiesel lifecycle, glycerine and rape meal, according to real market prices while rapeseed straw byproduct was neglected in the allocation. Economic allocation was also applied to the glycerine byproduct of the WCO biodiesel life cycle.

2.3. Inventory Analysis

GaBi 4 process data were used wherever possible and additional information was collected from the governmental reports, scientific papers and the trial version of the SimaPro 7 LCA software database. All sub-plans were adjusted for 1,000 kg product output.

The main stages of the rapeseed biodiesel life cycle considered in this study were rapeseed production, rapeseed oil extraction, rapeseed biodiesel production and combustion of rapeseed biodiesel in a city bus. The water content of rapeseed, a parameter that affects both rapeseed transportation and oil extraction processes was determined to be 13% by considering the evaluated literature and taking developments in the agricultural industry into account [23, 24]. Hexane process data was used for the rapeseed oil extraction step of the rapeseed biodiesel life cycle [22]. An average of 200 km pathways were assumed for rapeseed and rapeseed oil transport stages and 300 km pathway was assumed for the biodiesel transport to fuel distributors. Long distance truck process with 22 tons of total capacity and 14.5 ton payload from GaBi 4 database was used for all transportation processes in the rapeseed biodiesel life cycle.

The main life cycle stages of the WCO biodiesel included in the study were WCO collection, WCO biodiesel production and WCO biodiesel combustion in a city bus. There are many different values for the water and solid content of WCO in the literature, a parameter that increases the environmental burdens of biodiesel during WCO collection and pretreatment phases [25, 26, 27, 28]. 15% water and solid content was accepted for the WCO feedstock used in this system. An average of 350 km pathway was considered for WCO collection; 175 km of forward and 175 km of return distance. Gabi 4 small transporter truck with 3.5 tons of total capacity and 2 ton payload was used to simulate the WCO collecting vehicle. A 75% capacity usage was accepted for the return way. An average of 300 km pathway was considered for the WCO biodiesel distribution.

Technically, 100% rapeseed and WCO biodiesel fuels (B100 rapeseed and B100 WCO) produced by transesterification between methanol and triglycerides contain one carbon atom of non-biological origin per each methyl ester molecule which comes from methanol while glycerin co-product only contain carbon of biological origin that comes from glycerol group of triglycerides. For simplicity reasons, in this LCA study, the inorganic carbon content of methanol was assigned to glycerin co-product, leaving biodiesel product completely fossil-carbon free. The approach is valid only if glycerine co-product substitutes the fossil derived glycerin which was the case in this study.

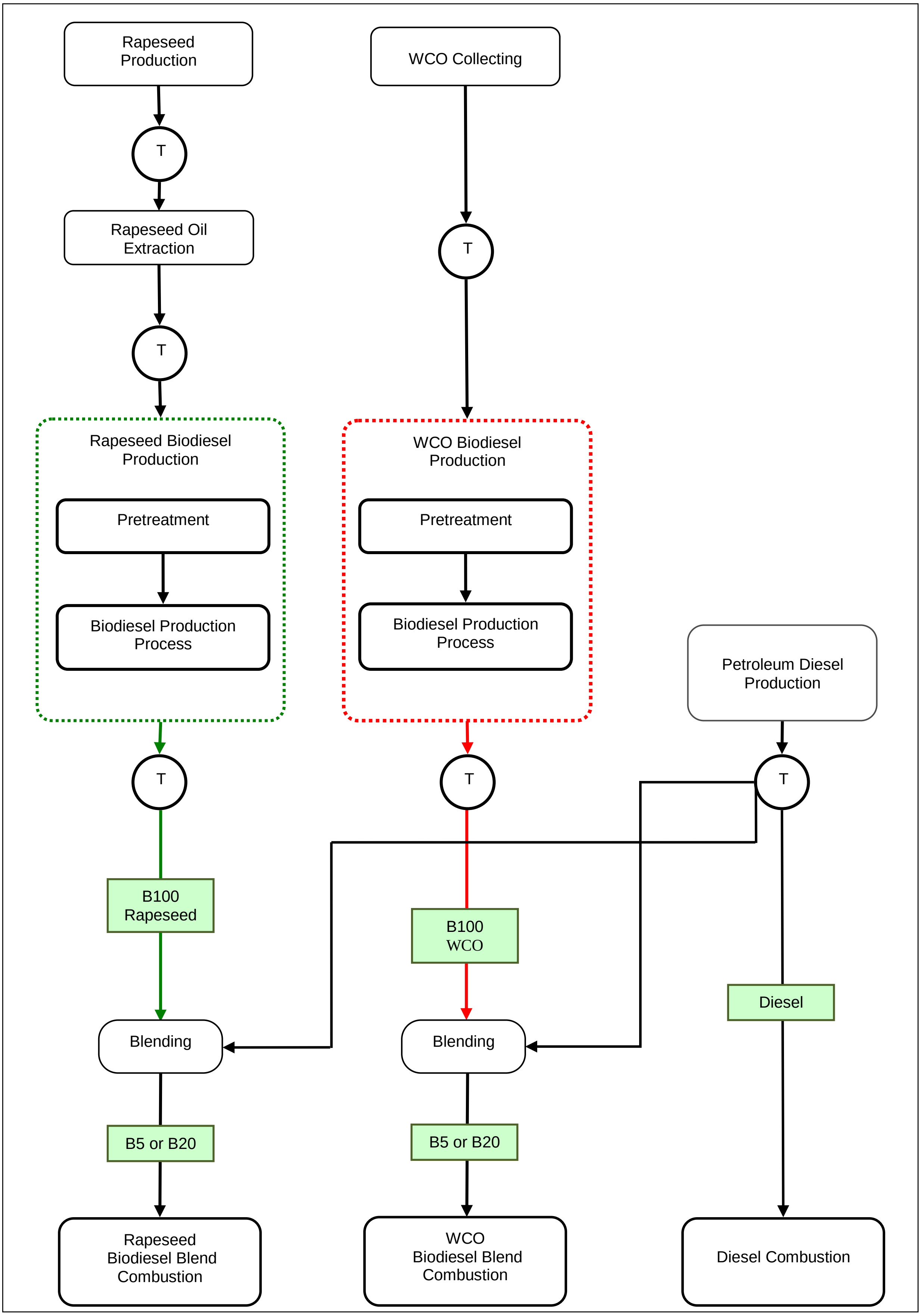

Figure 1. System boundaries for biodiesel and diesel utilization included in the study (T: Transport)

Diesel production from crude petroleum, diesel distribution and combustion stages of the petroleum based diesel fuel life cycle were evaluated. Gross calorific value of the produced diesel was adopted as 43.5 Mj/kg, though actual calorific value of the produced diesel may vary depending on the characteristics of the crude petroleum oil [21]. All environmental burdens associated with crude oil extraction are pre-assigned to the diesel refinery process by GaBi 4 software.

The environmental impact potentials of biodiesel and diesel fuels were normalized and weighted according to Eco-indicator 95 LCIA methodology and expressed in Eco-indicator points (Pt) for comparison [29].

3. Life Cycle Impact Assessment Results and Discussion

Life Cycle Impact Assessment (LCIA) interpretation has been performed for B5 rapeseed, B20 rapeseed, B5 WCO, B20 WCO and petroleum-based diesel fuel and the results have been evaluated in terms of their environmental impacts in seven different categories; acidification potential, eutrophication potential, global warming potential, winter smog, carcinogenic substances, heavy metals and photochemical oxidant potential.

As for any process that involves combustion of fossil fuels, the normalized results revealed the global warming potential as the largest impact category for all biodiesel blends and petroleum-based diesel (Figure 2). According to the normalized impact scores for the greenhouse effect, both WCO and rapeseed biodiesel blends have lower global warming potentials than petroleum-based diesel, with up to 21% reduction for the B20 WCO and 11% for the B20 rapeseed. The lower GHG emissions are mainly due to biogenic origin of the carbon contained within the biodiesel component of the blends. The results are less pronounced for 5% blends. As a result of nitrous oxide emission arising from application of nitrogen rich fertilizers during rapeseed cultivation phase, B20 rapeseed contributes to global warming almost twice as much as the B20 WCO does (Figure 3).

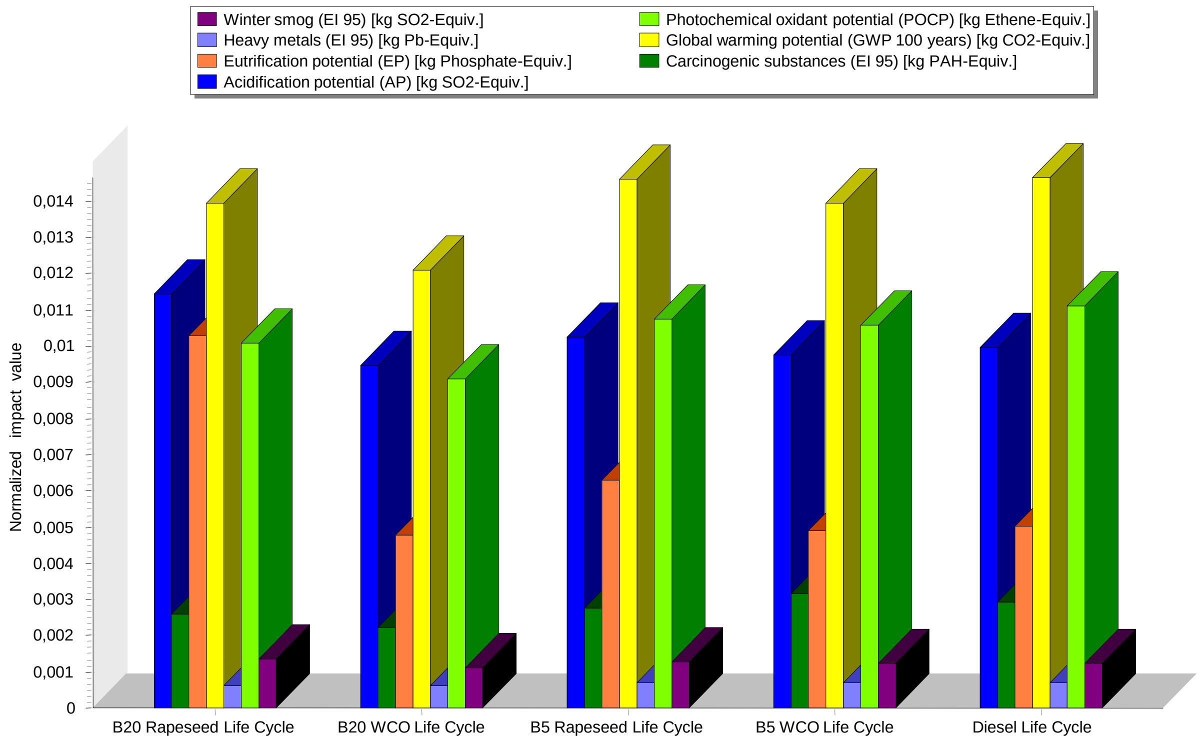

Figure 2. Normalized impact potentials of biodiesel and diesel fuels

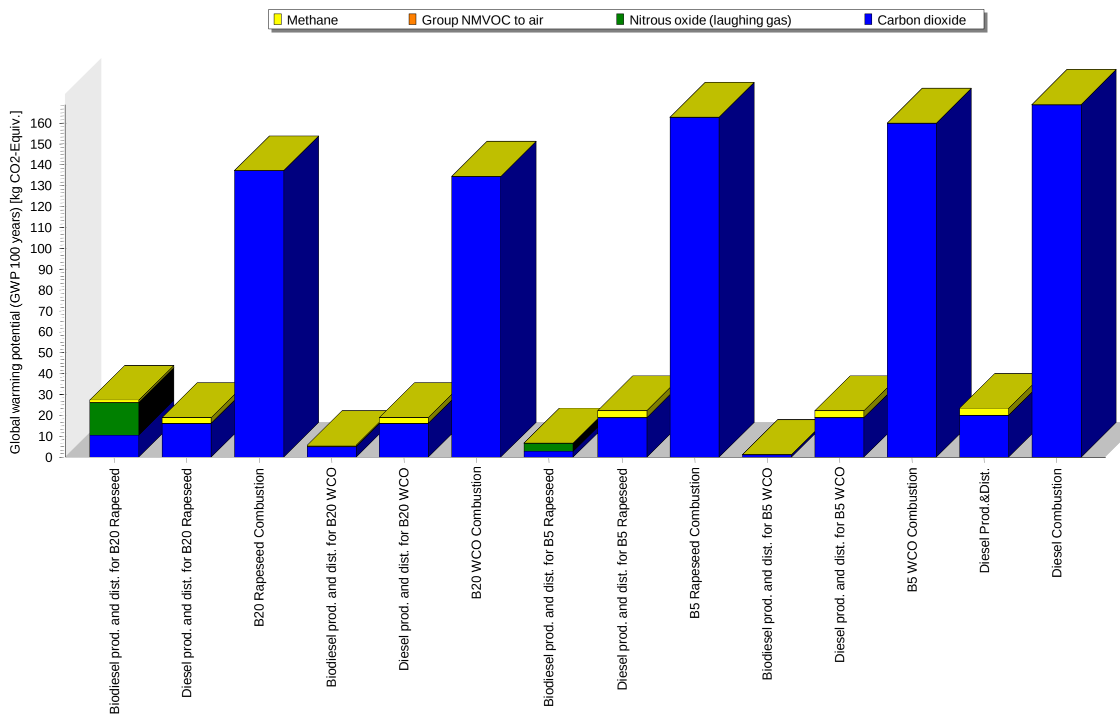

Figure 3. GHG emissions associated with biodiesel and diesel life cycle stages

Overall weighted results point out B20 and B5 rapeseed as least environmentally favorable options compared to WCO blends and petroleum-based diesel; high weighting factors placed on local acidification and eutrophication potentials combined with release of ammonia and nitrates as a result of rapeseed cultivation have lowered the total environmental performance of rapeseed biodiesel blends (Figure 4). The eutrophication potential of B20 rapeseed is 53% higher compared to B20 WCO and 45% higher compared to petroleum-based diesel. Weighted acidification potentials of the petroleum-based diesel, B20 rapeseed and B20 WCO are determined as 0.101, 0.115 and 0.094 Pt respectively.

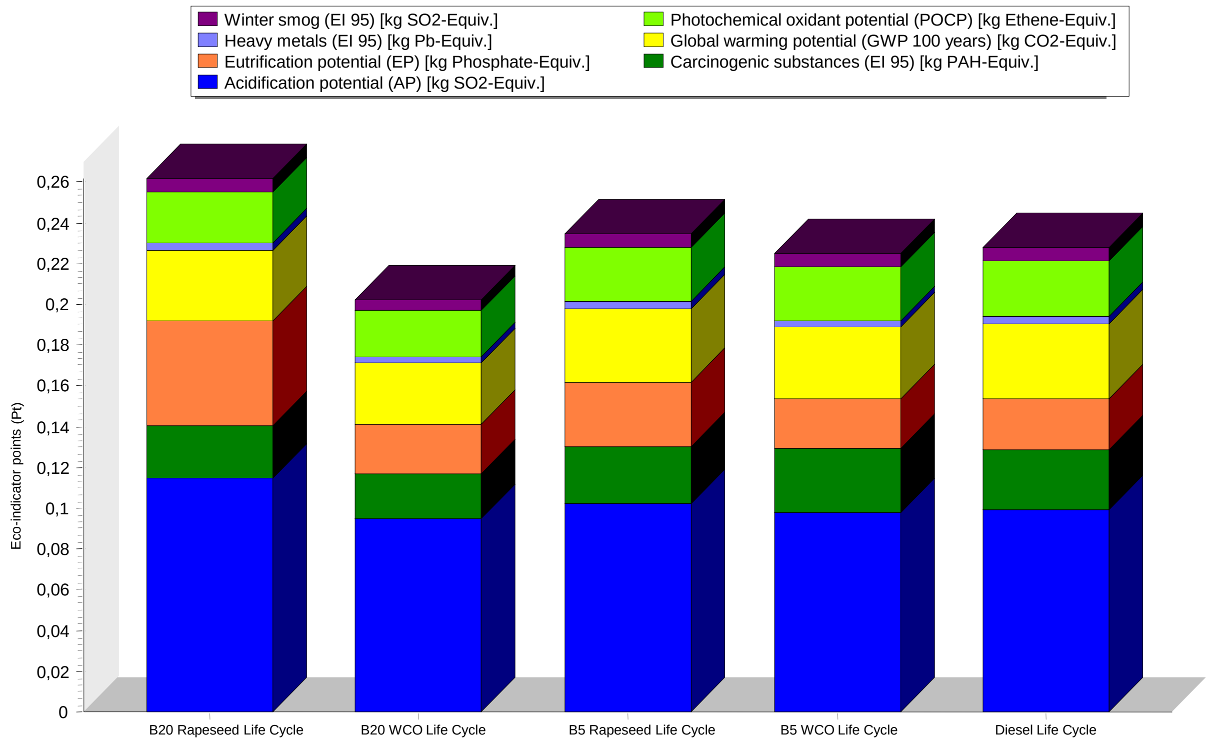

Figure 4. Weighted impact potentials of biodiesel and diesel fuels

The weighted carcinogenic potentials of B20 rapeseed, B20 WCO and petroleum-based diesel are 0.025, 0.022 and 0.026, Pt respectively. The carcinogenic potential is mainly associated with the combustion of fuel in the car engine and both biodiesel blends have been found to be applicable alternatives for decreasing the carcinogenic effects related to diesel fuel combustion. Heavy metal emissions from petroleum-based diesel life cycle

(0.004 Pt) are only slightly higher than those of B20 rapeseed (0.003 Pt) and B20 WCO (0.003 Pt). Photochemical oxidant formation potentials of the B20 rapeseed and B20 WCO are 7.5% and 18.5% lower compared to the petroleum-based diesel. The higher photochemical oxidant potential of the rapeseed biodiesel blend is explained by the hexane emission during the oil extraction phase of the rapeseed biodiesel life cycle. B20 WCO has lower winter smog potential (0.005 Pt) than the petroleum-based diesel (0.007 Pt) and B20 rapeseed (0.006 Pt).

4. Conclusions and Remarks

Considering the positive environmental performance of the WCO biodiesel in the global warming impact category along with the advantages of having lower acidification and eutrophication impacts (both below 0.005 Pt) due to lack of cultivation, harvesting and oil extraction phases, it is concluded that the replacement of petroleum-based diesel with B20 WCO biodiesel in public transport vehicles in Istanbul is a viable option for combating the climate change along with an array of other environmental challenges. In addition, WCO utilization for biodiesel production is an alternative way of waste vegetable oil minimization. On the other hand, while biodiesel made from WCO does not involve any changes in agricultural land use, it does require a well-developed infrastructure for efficient collection of waste vegetable oils from food factories, restaurants and fast food chains. Larger collection trucks can be used to minimize the total transportation distance.

Rapeseed biodiesel blends while effective in reducing the total GHG emissions associated with fuel life cycle, was found to have significant negative environmental impacts in the acidification and eutrophication categories and offers only slight advantages over petroleum based diesel in other categories. At the same time, producing biodiesel from edible oil feedstocks such as rapeseed oil, raises the fuel vs. food dilemma and it is of utmost important to ensure that the primary role of the agricultural industry is to provide food security for the population. Considering these circumstances, rapeseed biodiesel blends cannot be immediately recommended for replacing petroleum-based diesel but, efficient utilization of agricultural and industrial by-products such as rapeseed straw and glycerin can be a significant step towards increasing the sustainability of the rapeseed biodiesel blends.

Finally, a life cycle costing for assessment of the long term economic impacts of the WCO and rapeseed biodiesel utilization and a multi-stakeholder approach that will include the governmental policymakers, environmental institutions and organizations, community activists and biodiesel companies is needed in order to fully address the issue.

5. References

1. Official Gazette of Turkey. (2009). Pertaining to the Ratification of our Accession to the Kyoto Protocol to the United Nations Framework Convention on Climate Change, Issue: 27144, Ankara, Turkey, February 17, 2009
2. Energy Information Administration (EIA). International Energy Annual 2005. Available from: http://www.eia.doe.gov/oiaf/ieo/highlights.html (accessed on 15.04.09).
3. EIA/DOE. International Energy Outlook 2008. Available from: http://www.eia.doe.gov/oiaf/ieo/index.html (accessed on 15.04.09).
4. European Commission. General Directorate for energy and transport (DG TREN), Belgium. European Communities, 2009.
5. European Environmental Agency. Annual European Community Convention on Long-Range Transboundary Air Pollution, Emission inventory report 1990–2006 EEA Technical Report 7/2008.
6. European Environment Agency. Climate for a transport change. EEA Report 1/2008
7. European Environment Agency. Transport at a crossroads. EEA Report No 3/2009
8. Republic of Turkey, Prime Ministry, Turkish Statistical Institute (TURKSTAT). Available from: http://www.die.gov.tr (accessed on 17.04.09)
9. U.S. Environmental Protection Agency. A comprehensive analysis of biodiesel impacts on exhaust emissions, U.S. Environmental Protection Agency, 2002.

10. European Biodiesel Board, EU Biodiesel industry statistics. Available from: http://www.ebb-eu.org/stats.php (accessed on 20.04.09)
11. Pahl G. (2005) Biodiesel Growing a New Energy Economy. Chelsea Green Publishing.
12. International Energy Agency. Biofuels for transport, an international perspective. Available from: http://www.iea.org/textbase/nppdf/free/2004/biofuels2004.pdf (accessed on 20.04.09)
13. Turkish Vegetable Oils and Fats Industrialists Association. Available from: http://bysd.org.tr/en (accessed on 30.04.09).
14. Ministry of Environment and Forestry of Turkey. Used vegetable oils and animal fats. Ankara, 2004.
15. Official Gazette of Turkey. (2005). Regulation on Control of Waste Vegetable Oil, Issue: 25791, Ankara, Turkey, April 19, 2005
16. U.S. Environmental Protection Agency. Life cycle assessment: Principle and practice, Technical Report EPA/600/R-06/060, Cincinnati, USA, 2006.
17. European Environment Agency (EEA), 1997. Life cycle assessment, A guide to approaches, experiences and information sources, *Environmental Issues Series*, 6, pp.9-12, 51-72, Copenhagen.
18. GaBi 4 Software and database for Life Cycle Engineering, version 4.2.66.1, PE International GmBH and LBP University of Stuttgart, 2007.
19. Eco-indicator 95 Life Cycle Impact Assessment Methodology. Available from: http://www.pre.nl/eco-indicator95 (accessed on 30.04.09).
20. Prusty, B. Anjan Kumar, Chandra, Rachna, and Azeez, P. A. 2008. Biodiesel: Freedom from Dependence on Fossil Fuels? Nature Precedings. doi:10.1038/npre.2008.2658.1.
21. Biobus Project; 2003. Biobus Project Final Report, Biodiesel Demonstration and Assessment with the Montreal transport society, Montreal, Canada.
22. Camobreco, V., Duffield, J., Graboski, M., Shapouri, M. and Sheehan, J., 1998. Life cycle inventory of biodiesel and petroleum diesel for use in an urban bus, National Renewable

Energy Laboratory Report for U.S. Department of Energy's Office of Fuels Development and U.S. Department of Agriculture's Office of Energy, NREL/SR-580-24089, USA.

23. Elsayed M.A. and Mortimer N.D., 2006. North East biofuel supply chain carbon intensity assessment, *North Energy Associates Ltd. Report,* Sheffield, United Kingdom.
24. Armitage, D. M., Prickett, A. J., Norman, K. and Wildey, K. B. (2005). Survey of current harvesting, drying and storage practices with oilseed rape. UK: Home Grown Cereals Authority.
25. Chan, A., Fu, G. and Rollefson J., 2004. Assessment of the environmental performance and sustainability of biodiesel in Canada, National Research Council Canada Report for Ontario Ministry of Agriculture and Food, Agriculture and Agri-Food Canada, Environment Canada, Industry Canada, Natural Resources Canada.
26. Clements, D., Gerpen, J.V., Pruszko, R. and Shanks, B., 2004. Biodiesel production technology, National Renewable Energy Laboratory Report, NREL/SR-510-36244, USA.
27. Bakhshi N.N., Dalai, A.K., Issariyakul, T. and Kulkarni, M.G., 2007. Production of biodiesel from waste fryer grease using mixed methanol/ethanol system, Fuel Processing Technology, 88, 429-436.
28. Canakci., M., 2006. The potential of restaurant waste lipids as biodiesel feedstocks; Bioresource Technology, 98, 183–190.
29. Collignon, M., Demmers, M. and Goedkop, M., 1996. Eco-Indicator95 manual for designers, National Reuse of Waste Research Programme (NOH) Report, Updated version, 9524, Utrecht.