WHAT DO WE WANT TO SUSTAIN AND HOW DO WE DECIDE?

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For bio-fuel to be a suitable substitute for fossil fuels, its sustainability as a fuel has to be established. This translates to establishing that bio-fuels have superior environmental benefits while being economically competitive with fossil fuel, and that they can be produced in sufficient quantities to satisfy the existing energy demand while providing a net energy gain over the energy sources used in producing them. As an integrated systems approach, sustainable development (SD) framework methodology has been proposed and employed to address these issues. Most sustainability studies have been concerned only with the environmental impact, while this methodology ensures SD of a process not with respect to just environmental impact, resource consumption but also with respect to societal and economic impacts. Moreover, it allows the user to decide what should be sustained and how to make such a decision. This methodology starts with the prioritization of the sustainability metrics (health and safety, economic, ecological and social components). Then the alternatives are subjected to a pair-wise comparison with respect to each SD indicator and prioritized depending on their performance. The SD indicator priority score and each individual alternative's performance score together are used to determine the most sustainable alternative. The feasibility and effectiveness of this methodology has been demonstrated by identifying the most sustainable bio-diesel process system from a set of alternatives.

1 INTRODUCTION

Most sustainability studies have been concerned only with the environment. In fact, sustainability is an integration of three issues which are the economic, environmental and social implications, thus it is a property of the entire system. For an engineering process, an optimal balance has to be achieved between all these implications. Hence in order to ensure a high degree of effectiveness in reducing the negative implications of a process, a broader concept of designing the process is necessary and the most suitable methodology for addressing this issue is sustainable development (SD), which is well defined by the Brundtland Commission of 1987 as the "*Development that meets the needs of the present generation without compromising the ability of the future generations to meet their own needs*". It aims at striking a balance between various impacts the process has on the environment, economy, society and safety while satisfying the requirements of all the generations of decision makers. Hence chemical companies have begun to assign strategic importance to SD by incorporating them into their decision making. In order to ensure a complete SD, appropriate tools and techniques are required for evaluating available choices and identifying the most sustainable alternative.

The definition of SD makes clear that the development of new technologies has to take into account economic and social issues (present generations) and long-term and large-scale environmental issues (future generations). Bio-fuels, an alternative fuel made from renewable biological sources, have gained more and more interest recently due to high energy costs, increasing demands, concerns about petroleum reserves and greater realization of the environmental impacts of fossil fuels. For bio-fuel to be a suitable substitute for fossil fuels, its sustainability as a fuel has to be established. This translates to establishing that bio-fuels have superior environmental benefits while being economically competitive with fossil fuels, and that they can be produced in sufficient quantities to satisfy the existing energy demand while providing a net energy gain over the energy sources used in producing them.

Currently, bio-diesel studies have been focusing on raw materials (Freedman et al., 1986; Ma and Hanna, 1999, Canakci and Gerpen, 2001), catalysts (Ma et al., 1998; Zhang et al., 2003), alcohols used (Zhang, 2002), and chemical reactions, such as transesterification (Wimmer, 1992; Ali, 1995; Ma et al., 1998) and thermal cracking or pyrolysis (Sonntag, 1979; Weisz et al., 1979). However, its sustainability as a fuel has not been studied widely.

In this paper, SD is performed on the life cycle of a bio-fuel system. The bio-fuel considered here for the SD is bio-diesel. Using proposed methodology the system boundaries for the bio-diesel system is defined, which includes a complete cradle-to-grave analysis of bio-diesel inclusive of the raw materials, the chemical reactants, the process conditions, the by-products, the waste treatment options as well as the disposal of the wastes, excess reactants and the used end product. Then SD indicators are used to quantify the impact bio-diesel has on the environment, economy, society and safety of the surroundings over its lifetime. The analytical comparison tool, Analytical Hierarchical Process (AHP) is used to prioritize the available alternatives depending on their degree of sustainability. Finally the end result of the analysis is a complete bio-diesel system that is sustainable from its cradle to its grave.

2 PROPOSED METHODOLOGY

A SD framework methodology has been proposed to identify the most sustainable design for a given chemical process from a set of alternatives. The proposed methodology has already been reported in detail (Narayanan, 2007). Thus, the principle and procedure of this methodology are briefly introduced in this section.

The SD framework consists of three major steps. Each of these three steps consists of a number of intermediate stages where certain analytical calculations and quantifications are performed. The three steps of the SD decision making framework are as follows

1. System definition and alternatives identification

System definition is the first step in the proposed methodology, which aims at defining the boundaries of the system and identifying the subsystems within the existing system. To enable a complete cradle-to-grave SD, a Life Cycle Analysis (LCA) of the system under consideration is performed. Slight modifications have been done to the process in order to customize it for the problem of SD. Once the system boundary has been established, the succeeding step is to divide the system into a number of subsystems to make the decision making process more robust. The main criterion for identifying the subsystems is to determine the decisions that need to be taken at each stage within the chemical process under development. This step is process dependent and has to be performed for each process for which the decision framework is being used to do sustainability development.

Once the system boundary and the subsystems have been identified, it is the time to recognize all the decisions that need to be made regarding the most sustainable process method or design for each subsystem. In order to proceed with this step, all practicable alternatives must be identified for each process or object under consideration. These alternatives were identified by performing literature survey on various studies performed on bio-diesel production. (Zhang et al., 2003; Tapasvi et al., 2005; Xun and High, 2004; Rudolph and He, 2004; Roszkowski, 2003; Demirbas and Karslioglu, 2007; Besnainou and Sheehan, 1997). The alternatives identified have been proven to be practicable though not sustainable, hence the main objective of the framework is to identify the most sustainable option from a list of practicable alternatives within each subsystem.

2. SD indicators/impact assessment

Once the alternatives have been identified, in order to do the comparison to identify the most sustainable option, the implication of each alternative on the economy, environment, society and safety must be quantified. This quantification is done by the calculation of certain SD indicators, safety indices and by performing a cost-benefit analysis. In this research work, four indicators are analyzed and applied in the SD of bio-diesel production, including the environmental indicators such as emissions, resource depletion, land and water usage, economic indicators such as expenditure, tax incentives, profit margins, safety indicators such as inherent safety of the entire process, hazards associated with the materials used and certain societal implications such as impact on the local economy and employment generation. For each subsystem, a set of indicators are identified. Most of the indicators are common to all subsystems, except for a few subsystem specific indicators.

3. Alternatives comparison and SD decision making

The final step is the decision making, where the most sustainable alternative is identified for each subsystem based on previously defined SD criteria which includes economic, environmental and social feasibility and other performance and safety criteria. Analytical Hierarchical Process (AHP), which is a multi-criteria decision making method was chosen for decision making. This method was subjected to minor modification to customize it to meet the requirements of SD.

3 CASE STUDY – BIO-DIESEL PROCESS

The proposed methodology for SD of a process has been applied to the bio-diesel system. The final product of the proposed methodology is a completely sustainable bio-diesel system. A step-by-step description of the entire SD method is illustrated with supporting tables and visualizations for the bio-diesel system in this section, but the detailed calculations for this process are not provided.

The entire life cycle of the bio-diesel plant has been taken into account in this work, which is inclusive of raw material manufacturing, transportation and storage, the actual process energy requirements, storage and transportation of the final product, treatment of effluents, disposal or reuse of excess reactants and raw materials and finally disposal of the final product after its usage. Within this system, subsystems are identified and suitable alternatives for each of these subsystems are subsequently identified and listed in Table 1.

3.1 RAW MATERIAL SUBSYSTEM

The raw material subsystem within the bio-diesel lifecycle system; is the first subsystem subjected to SD using the developed framework. In this case study the raw materials considered are soybean, rape seed, sunflower and beef tallow. Since these are widely cultivated, available and economically viable they are the most commonly used feedstock for bio-diesel production. The SD indicators used are environmental indicator including Environment Performance Indicators (EPI), land usage, and water usage; economic indicators including total capital costs, manufacturing costs, after tax rate of return, bio-diesel break even price; safety indicators, such as risk assessment matrix (RAM) index, and certain system specific indicators including fuel cetane number and fuel carbon %.

Table 1. The subsystems and the corresponding alternatives

Subsystem	Alternatives
Bio mass	Soybean Rape Seed Oil Sunflower Oil Beef Tallow
Catalyst	Basic Acidic Enzymatic
Alcohol	Methanol Ethanol
Production Process	Thermal Cracking Transesterification
Glycerol Extraction	Gravitational Settling Centrifuging
Bio-diesel Purification	Hexane Extraction Water Washing
Bio-diesel Mix Ratio	Direct Use Blending

Table 2. Priority scoring for SD indicators

Level	Score	AHP score	Definition-diff in level of priority
HIGH	3	1	Same
MEDIUM	2	2 or 0.5	1 Level
LOW	1	3 or o.33	2 Levels

The prioritization of these indicators was based on their degree of importance with respect to that particular subsystem. The scale is defined in Table 2 and used in AHP comparison to obtain the priority scores for the different SD indicators. The number scores are allotted to the SD indicators depending on their degree of importance to be used while performing the pair-wise comparison in AHP. The scoring scale varies from 1 to 3, with 1 representing equal importance or performance, 2 representing moderate difference and 3 signifies well marked difference between the two alternatives with one being strongly preferred over the other. The indicator with the higher level of priority is given the higher score and the other indicator is given the reciprocal of the score. The scaling used is qualitative for all the three SD indicators and based on historic data and expert opinion.

Table 3(a) indicates the priority levels assigned to the SD indicators for the raw material subsystem. As raw material is the highest contributor to the bio-diesel price, economic indicators are given the highest priority. Since feed-stock is used in the largest quantity among all the raw materials for bio-diesel production, its impact on the environment must be given high priority when considering the life cycle environmental impact of bio-diesel. There are no major safety-issues associated with raw materials manufacturing or use, thus safety indicators are given medium priority. Certain fuel properties such as cetane number and percentage of carbon depend largely on the raw material used and are hence used as indicators which are given high priority like the environmental and economic indicators. Table 3(a) also lists the numerical scores corresponding to the priority level for each of the SD indicators.

The calculated final priority score for each SD indicator with respect to the raw materials subsystem is illustrated in Table 3(b), which involves the neutralization of the pair-wise comparison scores.

An AHP template is used to compare the alternatives with respect to each of the SD indicators and prioritize them based on their performance using the pre-defined AHP

Table 3 (a). SD Indicator priority level assignment for raw materials subsystem

Indicator	Priority level	Number score
Environmental	HIGH	3
Economic	HIGH	3
Safety	MEDIUM	2
Fuel Performance	HIGH	3

Table 3 (b). Final priority score evaluation for raw materials subsystem

	Environmental	Economic	Safety	Fuel performance	Priority score
Environmental	0.286	0.286	0.286	0.286	0.286
Economic	0.286	0.286	0.286	0.286	0.286
Safety	0.143	0.143	0.143	0.143	0.143
Fuel Performance	0.286	0.286	0.286	0.286	0.286

scoring scales. The first SD indicator used for the comparison of the raw-material alternatives is the environmental indicator, EPI, which directly depends on the environmental impact of the pesticides and other chemicals used in the cultivation and other raw material related processes. The values for the EPI for each raw-material are given in terms of CO_2 weight equivalent emission, shown in Table 3(c). These values are based on the amount of green house gases emitted during fertilizer manufacturing, cultivation, harvesting and oil recovery as well as the amount of N_2O released during cultivation of the feedstock which is converted into CO_2 weight equivalents (Jungmeier, Hausberger et al., 2003). It was observed that soybean required much less fertilizer than both rape seed and sunflower. Rape seed cultivation requires large amounts of nitrogen fertilizers and hence its impact on the environment is higher in comparison to sunflower and soybean. Beef tallow was given the highest EPI score since more energy is input into the pre-processing of this raw material to be used as a feedstock for bio-diesel production.

Other than EPI, land and water usage are also used as environmental impact indicators. The land and water usage for the alternatives are qualitatively assessed as high, medium or low and are assigned corresponding numerical scores. Table 3(c) lists all three environmental indicators for all the raw material alternatives.

Once the environmental indicators are quantified, the next step is to perform the pair wise comparison of the alternatives using an AHP template, with respect to each of these

Table 3 (c). Environmental Indicators for raw materials subsystem

	Environmental				
		Land usage		Water usage	
Alternatives	EPI	Usage level	Number score	Usage Level	Number score
Soybean	40	MEDIUM	2	MEDIUM	2
Rape Seed	110	LOW	1	MEDIUM	2
Sunflower	70	HIGH	3	HIGH	3
Beef Tallow	140	MEDIUM	2	MEDIUM	2

Table 3 (d). Net Environmental Impact score for each raw material alternative

	Soybean	Rape seed	Sunflower	Beef tallow	EPI score	Land usage score	Water usage score	Environmental indicator score
Soybean	0.50	0.47	0.62	0.30	0.47	0.26	0.23	0.289
Rape Seed	0.17	0.16	0.10	0.30	0.18	0.14	0.42	0.224
Sunflower	0.17	0.32	0.21	0.30	0.25	0.14	0.12	0.153
Beef Tallow	0.17	0.05	0.07	0.10	0.10	0.45	0.23	0.234

indicators and obtain individual performance scores. The final indicator scores for all three environmental indicators for each of the raw material alternative are shown in Table 3(d).

Using the scores obtained with respect to EPI, land usage and water usage, the final environmental indicator score for each alternative is calculated by the following formula, and the results are listed in Table 3(d).

$$\text{Final Score} = \sum(0.33 * A_i)$$

Where, A_i = AHP score allotted to alternative with respect to environmental indicator i (i can be EPI, land usage or water usage); *0.33* = Score of importance given to environmental indicator i with respect to the other indicators (all indicators are given equal importance hence the score of 0.33).

The calculation results have shown that the most sustainable option with respect to environmental impact within the raw materials would be soybean as it has the highest environmental indicator score. AHP templates are also developed to quantify the other SD indicators and prioritize the raw materials with respect to economic (Zhang, Dube et al., 2003), safety and system specific indicators (NREL, 1994), shown in Table 3(e).

Table 3 (e). SD indicator quantification for raw materials

	Economic		Safety		Fuel performance	
Alternatives	Total costs($/kg)	Total manufacturing cost of biodiesel $/L	RAM index	Oxidation stability (rancimat induction period h)	Cetane number	Carbon %
Soybean	0.52	0.3	LOW	5.9	51.34	0.94
Rape Seed	0.67	0.69	LOW	9.1	54.4	0.044
Sunflower	0.48	0.56	LOW	3.4	49	
Beef Tallow	0.3	0.85	MEDIUM	1.2	58	0.92

Table 3 (f). SD score for raw materials subsystem

	Environmental	Economic	Safety	Fuel performance	SD score
Soybean	0.289	0.368	0.28	0.33	0.32
Rape Seed	0.224	0.145	0.37	0.23	0.22
Sunflower	0.153	0.24	0.24	0.31	0.23
Beef Tallow	0.234	0.247	0.12	0.13	0.19

The net SD score is determined for each alternative by taking an aggregate of the product of the alternative's indicator score and the corresponding indicator's prioritization score for each SD indicator. Table 3(f) lists all the indicator scores for the raw material alternatives with respect to each SD indicator and the final SD score which is used to determine the most sustainable option. It is found that soybean is the most sustainable raw material for bio-diesel production as it has an overall good performance in all the fields of SD, which is evident from its high SD score.

3.2 CATALYST SELECTION

Transesterification, which is treatment of triglycerides (present in the feedstock) with an alcohol in the presence of a catalyst to produce fatty acid alkyl ester (bio-diesel) and glycerine, is the most common method of producing bio-diesel. The transesterification process can be catalyzed by homogenous catalysts which can be alkalis, acids or enzymes (Vicente, Martinez et al., 2004). The first two types have received the greatest attention as they are more economically viable than enzyme catalyzed transesterification. For this subsystem, the SD indicators include certain system specific indicators such as reaction time in minutes and percentage of yield, besides environmental, economic indicators and safety indicators. The quantification of these indicators is shown in Table 4(a).

For the catalyst subsystem, environmental and safety indicators are given high priority and the economic and system specific indicators are given medium priority. The prioritization scores obtained for each of SD indicators by AHP is displayed in Table 4(b).

The catalyst alternatives are compared with respect to each of the SD indicators. For environmental indicators the EPI values are determined for sodium hydroxide (NaOH) for alkaline catalyst (Vicente, Martinez et al., 2004) and sulfuric acid (H_2SO_4) for acidic catalysts (Canakci and Van Gerpen, 1999). For economic indicators the percentage of difference in total manufacturing cost of bio-diesel and the bio-diesel break-even price are used as comparison parameters (Zhang, Dube et al., 2003). Certain system-specific indicators such as reaction time (min) and percentage of yield are used to compare the alternatives.

The score for each SD indicator with respect to each catalyst alternative is listed in Table 4(c). The final SD score is calculated for each alternative and from these scores basic catalyst was identified to be the most sustainable as it had the highest SD score. Basic catalysts have the best performance in both the environmental and safety implications and

Table 4 (a). SD indicators quantification for catalysts

	Environmental	Economic			Safety		Specific indicators	
Alternatives	EPI (for 100 units of release)	Total costs ($ $\times 10^{-6}$)	Total manufacturing cost of bio-diesel ($ $\times 10^{-6}$)	Break even price ($/ton)	RAM index	Number score	Reaction time(min) for 90% conv	Yield %
Base (NaOH)	70	0.32	6.86	857	MEDIUM	2	90	95
Acidic(H_2SO_4)	114.4	1.41	7.08	884	HIGH	3	4140	97
Enzyme	20	3.5	10.5	900	LOW	1	480	71

Table 4 (b). SD indicators prioritization score

Indicator	Prioritization score
Environmental	0.333
Economic	0.167
Safety	0.333
System specific	0.167

at the same time have favorable economic performance and also result in lesser reaction time and higher yield (Vicente et al., 2004). Acidic catalysts such as sulfuric acid have more impact on the environment as they result in acid rain; have higher human- and eco-toxicity levels than the alkaline catalyst. The Environmental Protection Agency (EPA) of USA gives sodium hydroxide a score of 3 and sulfuric acid a score of 7 on a scale of 10 for environmental impact and toxicity levels. Since basic catalysts have an overall good performance in comparison to acidic and enzymatic catalysts they are considered to be the most sustainable. This is evident from the highest SD score of 0.51.

3.3 REACTANT ALCOHOL SELECTION

The alcohols that can be used in the transesterification process are methanol, ethanol, propanol, butanol and amyl alcohol. Methanol and ethanol are used most frequently and hence are considered as the alternatives that are subjected to comparison for the identification of the more sustainable alcohol reactant. The SD indicators used are quantified and listed in Table 5(a) for methanol and ethanol.

The prioritization of the SD indicators for the alcohol subsystem is shown in Table 5(b). In the transesterification reaction, the alcohol to triglyceride ratio is 6 : 1 for alkali catalyzed reaction and 30 : 1 for acid catalyzed. Due to the large amount of alcohol required, it affects the price of bio-diesel; hence economic indicator is given high priority. Environmental, safety and system specific indicators are given medium priority.

Bio-diesel produced from ethanol and methanol have comparable chemical and physical fuel properties and engine performances (Peterson et al., 1995), but for economic reasons, only methanol is currently used for producing bio-diesel on an industrial scale due to the much lower price compared to ethanol. Methanol, however, is currently mainly

Table 4 (c). SD scores for the catalyst alternatives

	Environmental	Economic	Safety	System specific	SD score
Base	0.478	0.549	0.54	0.48	0.51
Acidic	0.172	0.310	0.16	0.17	0.19
Enzyme	0.350	0.141	0.30	0.35	0.30

Table 5 (a). SD indicator quantification for alcohol reactants

	Environmental	Economic		Safety		Fuel performance
Alternatives	EPI (for 100 units of release)	Total manufacturing cost of biodiesel ($\$ \times 10^{-6}$)	Break even price (\$/ton)	RAM index	Number score	Cetane number
Ethanol	70	10	900	MEDIUM	2	48.12
Methanol	14	6.86	857	HIGH	3	51.34

produced from natural gas. Thus, methanol-based bio-diesel is not a truly renewable product since the alcohol component is of fossil origin. Furthermore, methanol is highly toxic and hazardous, and its use requires special precautions. Use of ethanol for production of bio-diesel would result in a fully sustainable fuel, but only at the expense of much higher production costs. Table 5(c) illustrates the AHP scores obtained for the alcohol alternatives with respect to each of the SD indicators as well as the net SD score for each alternative. As can be seen in the table both the alternatives have the same SD score, but due to the above stated reasons, it is environmentally favorable and safer to use ethanol in the place of methanol though it is not a very economically favorable option.

3.4 BIO-DIESEL PRODUCTION PROCESS SELECTION

There are three most widely technologies to produce bio-diesel from plant oils or animal fats and they are pyrolysis, transesterification and microemulsification. Pyrolysis is the conversion of one substance into another by means of heat or by heat with the aid of a catalyst. It involves heating in the absence of air or oxygen and cleavage of chemical bonds to yield small molecules. The pyrolysis of vegetable oils, animal fats and natural fatty acids can result in the production of bio-diesel. Transesterification (also called alcoholysis) is the reaction of a fat or oil with an alcohol in the presence of a catalyst to form esters (bio-diesel) and glycerol. Micro-emulsion is the formation of thermodynamically stable

Table 5 (b). Prioritization of SD indicators for alcohol reactant

Indicator	Prioritization score
Environmental	0.333
Economic	0.333
Safety	0.167
System Specific	0.167

Table 5 (c). SD score for alcohol alternatives

	Environmental	Economic	Safety	System specific	SD score
Ethanol	0.750	0.250	0.667	0.333	0.50
Methanol	0.250	0.750	0.333	0.667	0.50

dispersions of two usually immiscible liquids, brought about by one or more surfactants. But micro-emulsions of vegetable oils and alcohols cannot be recommended for long-term use in engines as they are prone to incomplete combustion, formation of carbon deposits and an increase in the viscosity of the lubricating oil. Due to these drawbacks micro-emulsions are not usually used in large-scale production of bio-diesel. In this study, only pyrolysis and transesterification processes are compared for the production of bio-diesel. The SD indicators quantified for the production processes are the environmental (Impact degree), economic (total capital cost), safety (RAM index) and fuel performance (yield %) indicators, shown in Table 6(a).

As the system under study is a chemical process, economic and safety indicators are given high priority. As the environmental impact of the reactants involved in the process has already been included while selecting the sustainable alternatives, environmental indicators are given only medium priority. System specific indicator (yield %) is given the least priority while comparing the different bio-diesel production techniques. Table 6(b) illustrates the AHP prioritization score for the SD indicators for the production process subsystem.

Transesterification has much better environmental and safety performance than thermal cracking as thermal cracking requires bio-diesel to be produced in an oxygen-free environment and this requires more complex systems which increases the environmental impact as well as making the process more hazardous (Ma and Hanna, 1999). Moreover the bio-diesel obtained from transesterification has better emission performance than the bio-diesel obtained by thermal cracking. Transesterification is more economically favorable than thermal cracking due to lesser number of complex equipments. Due to all these favorable factors, transesterification is considered to be more sustainable than thermal cracking for producing bio-diesel. The AHP scores for each of the SD indicators as well as the final SD score for each alternative is shown in Table 6(c).

Table 6 (a). SD indicators for the production process alternatives

	Environmental	Economic	Safety	Fuel performance
Alternatives	Impact degree	Total capital costs	RAM index	Yield %
Thermal Cracking	HIGH	HIGH	HIGH	84
Transesterification	LOW	LOW	MEDIUM	98

Table 6 (b). Prioritization of SD indicators for production process

Indicator	Prioritization score
Environmental	0.189
Economic	0.351
Safety	0.351
System Specific	0.109

3.5 BIO-DIESEL PURIFICATION PROCESS SELECTION

Bio-diesel purification method is the final subsystem considered in this case study. Water washing and hexane extraction are considered as alternatives. Due to the evident impact of this subsystem on the total cost of bio-diesel, the economic implications are given the highest priority followed by safety issues. The reasoning for the priority scores allotted for environmental and system-specific indicators is similar to that offered for the bio-diesel production process subsystem. Table 7(a) and (b) show the SD indicator prioritization scores and the final SD scores respectively. It is found that the water washing has a much higher environmental score than hexane extraction, which is due to the avoidance of use of hexane thereby making the process inherently safer (Zhang, Dube et al., 2003). Water washing is also more economically favorable than hexane extraction due to simpler equipment and more readily available materials (water is cheaper and readily available than hexane). Due to these favorable features, water washing is usually preferred to hexane extraction and this was the result obtained from the decision framework developed.

In summary, using proposed SD methodology to analyze bio-diesel process, it is found that soybean is the most sustainable alternative over other raw materials, such as rape seed oil, sunflower oil and beef tallow. Basic catalyst is more sustainable than acidic and enzymatic catalysts. The optimal production process for bio-diesel is transesterification and the sustainable option for alcohol used in this process is ethanol. Water washing is considered to be the sustainable purification method used in the bio-diesel process, due to its good environmental and economic performance. All these identified sustainable alternatives for each subsystem are illustrated in Table 8.

4 CONCLUSION

The proposed methodology in this paper is an integrated systematic approach to sustainable engineering decision making, which has so far been treated only qualitatively. It elucidates

Table 6 (c). SD scores for the production process alternatives

	Environmental	Economic	Safety	System specific	SD score
Thermal Cracking	0.33	0.33	0.33	0.18	0.32
Transesterification	0.67	0.67	0.67	0.83	0.68

Table 7 (a). Prioritization of SD indicators for bio-diesel purification

Indicator	Prioritization score
Environmental	0.189
Economic	0.351
Safety	0.351
System Specific	0.109

Table 7 (b). SD scores for the bio-diesel purification process alternatives

	Environmental	Economic	Safety	System specific	SD score
Water washing	0.75	0.75	0.33	0.24	0.55
Hexane Extraction	0.25	0.25	0.67	0.76	0.45

Table 8. Sustainable bio-diesel process

Subsystem	Sustainable alternative
Bio mass	Soybean
Catalyst	Basic
Alcohol	Ethanol
Production process	Transesterification
Bio-diesel Purification	Water Washing

not only what we want to sustain but also how we do so based on environmental, economic and safety impacts. The feasibility and effectiveness of this methodology has been demonstrated by applying to identify the most sustainable bio-diesel process system from a set of alternatives, since the analysis results of the proposed methodology are in excellent agreement with the generic system accepted to be the most optimal and environmentally favorable by most researchers and commercial bio-diesel plant designers (Zhang et al., 2002; Haas et al., 2005; NREL). Therefore, the proposed methodology is useful in identifying sustainable options from a given set of alternatives and assessing new technologies in term of current generation and future generation.

In summary, this methodology is simple, flexible and user friendly, since the scoring scales for the SD indicators and alternatives comparison are not very system-specific. Thus, this methodology can also be customized to be applied to other engineering processes, such as, SD of fuel cell technology, solar cells, wind power, and other alternative energy sources.

ABBREVIATIONS

AHP	Analytical Hierarchical Process
EPI	Environment Performance Indicators
EPA	Environmental Protection Agency
LCA	Life Cycle Analysis
RAM	Risk Assessment Matrix
SD	Sustainable Development

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