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Sustainability Assessment of Biodiesel Production by Monetary Indicators

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This paper introduces a monetary parameter (E-value), which can be used to compare the sustainability performance of design alternatives in a production system. The E-value summarizes the influence of three different sustainability aspects: economic, environmental and social. In this paper, we use biodiesel production from crops as an example to demonstrate the assessment methodology. Base on the result, the choice of indicators has been proven to be influential to the final result.

1. Introduction

Production process designs and decisions are traditionally made based on economic attractiveness. However, with increasing global concern on sustainable development, we also need to focus on the overall impact to the community. Sustainable development consists of three main aspects: economic, environmental and social. To strike for sustainable development, these three aspects have to be considered with the aid of different kinds of sustainability assessment methodologies. Energy consumption is a major environmental sustainability concern. The degree of energy usage can be measured in Global Warming Potential (kg CO_2-Equivalent). The social element is the most controversial one among the three aspects in the integrated sustainability assessment; it is likely due to the intangible nature of most social values. Examples of intangible social values include quality of life, social relations, education opportunities, etc. Not all of them directly relate to the design of production process. An important input to most production processes is labour, which is usually counted as environmental or economic expenditure. Yet, the social value of the labour input is seldom considered. In this paper, the job opportunities generated from a production process are perceived as benefits to society, which eases unemployment problem. We use the production of biodiesel from crops (jatropha, rapeseed and soybean) as an example to illustrate how sustainability can be mearsured and how it will affect design decisions.

2. Production Process of Biodiesel

Biodiesel production from crops involves several major steps: agricultural production, oil extraction and biodiesel conversion (Figure 1). Each step contains different inputs and outputs; some are having more than one alternative (Section 4.1). Each alternative

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carry different values in terms of the three sustainability aspects. To make a proper decision in the production design, we need to quantify those values with suitable indicators.

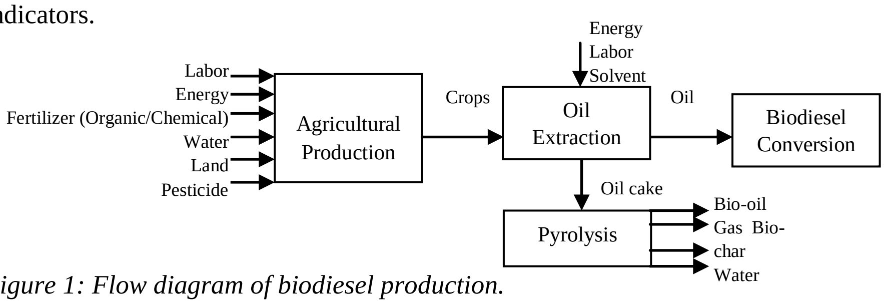

Figure 1: Flow diagram of biodiesel production.

3. Sustainability Indicators Definitions

To assess the sustainability performance of different process alternatives, indicators of the three sustainability aspects are defined and expressed in monetary unit. The economic indicator is based on the costs of purchasing material and energy, employing labors, and product prices. The environmental indicator is based on greenhouse gases emission (kg CO_2-Equivalent), which carries monetary value under carbon market operation. The social indicator is based on job opportunities generated from a process alternative. We consider jobs created to be beneficial to society. The beneficial effect is quantified by either (i) Gross Domestic Product (GDP) per capita or (ii) Unemployment Benefit paid by the government to the unemployed people. We consider the first value as the average ability of a labour to produce goods and services for a country, and the second value as the society's savings due to an increased employment rate.

3.1 Sustainability evaluation value (E-value)

We define a parameter E-value to compare the sustainability of process alternatives.

$$E\text{-value of alternative} = a \times Economic + b \times Environmental + c \times Social \quad (1)$$

$$Total\ E\text{-value} = \Sigma(E\text{-values of alternatives}) \quad (2)$$

The E-value of each process alternative is composed of the three sustainability indicators according to Equation (1). The coefficients a, b and c can either be One or Zero. 1 means a particular aspect being considered, and 0 means the opposite. The following case study will use the E-value to compare process alternatives.

4. Case Study

We use biodiesel production from jatropha, rapeseed and soybean as an example to illustrate how sustainability can be mearsured and how it will affect design decisions. Suppose our target production is 1 t biodiesel. We evaluate the production phases involved in production (Figure 1): agricultural production, oil extraction, biodiesel conversion and cake pyrolysis. In pyrolysis, the gas could be used to provide the energy requirements of the pyrolysis process (Murillo et al., 2006). Tab. 1-4 show the material and energy flows in the agricultural production, oil extraction, biodiesel conversion and cake pyrolysis respectively. The data are obtained from literatures (Achten et al., 2008; Reinhardt et al., 2008; Sheehan et al., 1998; Stephenson et al., 2008).

4.1 Process Alternatives

In agricultural production, we evaluate two alternatives for fertilizer input, organic and chemical. We assume the nutrient content (by weight) of chemical fertilizer to be approximately 4 times of the organic fertilizer. The organic fertilizer is produced from the oil cake by composting. Since composting process is the aerobic decomposition of organic materials by composting organisms, the energy input is considered insignificant. The diesel fuel consumption by the machines in cultivation is assumed to be replaceable by labour work, with the approximation of one labour hour in cultivation equivalent to 0.8 L diesel. In oil extraction, three alternatives, solvent (hexane) extraction, mechanical screw press and manual ram press, are evaluated (Tab. 2). The oil cake generated after oil extraction can be used as (i) fertilizer for crop production or (ii) go to pyrolysis. We therefore compare two scenarios: (i) all the cake goes to pyrolysis, (ii) the cake is used as fertilizer first, and it is found, based on calculations, to be in excess for the fertilizer use. The remaining cake therefore goes to pyrolysis.

Table 1 Inputs required in agricultural production (per t crop output and year).

Description of flow	Units	Jatropha	Soybean	Rapeseed
Chemical Fertilizer	kg	84.4	47.3	81.4
Pesticides	kg	0	1.73	0.65
Irrigation Water	t	139	1151	694
Diesel, Irrigation Pump	L	23.3	192.9	116
Diesel, Cultivation	L	23.1	26.4	15.3
Labor	hour	5	3	2
Land	ha	0.42	0.48	0.28
Oil Content	mass frac	0.34	0.18	0.41

Table 2 Inputs required in oil extraction (per t crop input).

Description of flow	Unit	Solvent	Mechanical	Manual
Hexane	kg	2.4	0	0
Electricity	kWh	8.8	150	0
Steam	MJ	802	172	0
% oil extracted	mass frac	0.98	0.77	0.62
Labour	hour	0.68	13	145

*Table 3 Products Yield of cake pyrolysis.**

Pyrolysis Products (Mass fractions)	Jatropha	Soybean	Rapeseed
Gas	0.2	0.2	0.1
Bio-oil	0.4	0.4	0.2
Water	0.1	0.2	0.4
Bio-char	0.3	0.2	0.3

* Yields & compositions of pyrolysis products are related to temperature, heating rate, gas residence and other variables. Data are approximated from the literature (Ucar and Ozkan, 2008; Raja et al., 2010; Uzun et al., 2006).

Table 4 Inputs required in biodiesel production (per t biodiesel output).

Description of flow	Units	Amount
Oil	t	1.04
Water	t	0.5
Methanol	kg	100
Diesel	L	65
Catalyst	kg	11

Table 5 Alternatives in different production phases.

Production phase	Alternatives (Abbreviations)
Agriculture	Organic fertilizer (Organic) vs. Chemical fertilizer (Chemical)
	Machine-farming (Machine) vs. Labour-farming (Labour)
Oil extraction	Solvent vs. Mechanical vs. Manual
Cake Pyrolysis	All cakes go to pyrolysis (All) vs. Cakes as fertilizer first and the remaining goes to pyrolysis (Partial)

4.2 Evaluation of Alternatives by E-value

To evaluate the alternatives using the E-value, we require a data list (Tab. 6) containing costs, CO_2-Equivalents and job opportunities of each alternative. We define positive values as expenditure and negative values as income. The objective is to minimize the Total E-value according to Equation (2). In this evaluation, four cases are studied and results are presented in Tab. 7. Case 1 is an economic evaluation. Case 2 evaluates both the economic and environmental aspects. Case 3 and 4 considers all the three sustainability aspects with different social indicator.

Table 6 Data list of alternatives (Costs in USD).

Items	Units	Economic cost	kg CO_2-Eq per unit[1]	Social cost
Chemical Fertilizer	kg	0.5	0.99	
Organic Fertilizer	kg	0	0	
Pesticides	kg	15	0.87	
Diesel	L	0.8	2.71	
Labou[r]	h	6.7, wage	0	-24
Labou[r]	h	6.7, wage	0	-2.7
Hexane	kg	0.47	negligible	
Electricity	kWh	0.07	0.78	
Steam	kWh	0.01	0.3	
Bio-oil	t	-130		
Bio-char	t	-150		
Methanol	kg	0.32	0.57	
Biodiesel	t	-690		

1. *Environmental cost = multiply kgCO_2-Eq by the carbon price (~19 USD/tCO_2-Eq in 2009).*
2. *US2009 GDP per capita (USD46400), assuming 240 working days/y and 8 working h/d.*
3. *Unemployment basic benefit in Cyprus 2007 (EURO 84 week), convert to USD per h assuming 40 working h/week and 1 USD = 0.78 EURO*

Table 7 Result Table of E-values, economic, environmental and social costs (in USD).

Crops	Case	Econ	Envir	Social	E-value	Chosen alternatives
Jatropha	1	-677	0	0	-677	Cake, Machine, Solvent, Partial
	2	-677	12	0	-665	Cake, Machine, Solvent, Partial
	3	155	11	-3861	-3695	Cake, Labour, Manual, Partial
	4	-672	16	-64	-720	Cake, Machine, Manual, Partial
Soybean	1	131	0	0	131	Cake, Machine, Solvent, Partial
	2	131	68	0	199	Cake, Machine, Solvent, Partial
	3	2361	93	-7561	-5107	Cake, Labour, Manual, Partial
	4	131	68	-43	157	Cake, Machine, Solvent, Partial
Rapeseed	1	-531	0	0	-531	Cake, Machine, Solvent, Partial
	2	-531	22	0	-508	Cake, Machine, Solvent, Partial
	3	17	29	-1965	-1920	Cake, Labour, Manual, Partial
	4	-531	22	-11	-520	Cake, Machine, Solvent, Partial

4.2.1 Case 1: a=1, b=0, c=0

Case 1 corresponds to economic evaluation. The resulting E-value consists of economic aspect only. According to data in Tab. 1-6, using oil cake as fertilizer, machine-farming and solvent extraction will result in the smallest E-value in all the three crops. Oil cake is free of charge compare with chemical fertilizer; machine-farming requires only small number of labours; solvent extraction requires small number of labours, consumes less electricity than mechanical screw press, and gives the highest oil yield. Among the three crops, jatropha has the smallest E-value, followed by rapeseed, soybean comes last. Soybean has the lowest oil content among the three crops and requires the largest amount of irrigation per tonne crop output, so it requires much more economic input in order to produce one tonne of biodiesel, making it not an economically sustainable (positive E-value) choice.

4.2.2 Case 2: a=1, b=1, c=0

Case 2 evaluates both the economic and environmental aspects. The results are similar to Case 1. The effect of environmental cost is insignificant comparing to the economic cost. We suggest that the market price of carbon may not be able to sufficiently reveal the environmental cost of energy consumptions.

4.2.3 Case 3: a=1, b=1, c=1 (with GDP per capita as social indicator)

Case 3 considers all the three sustainability aspects. According to the data, using oil cake as fertilizer, labour-farming and manual ram press will result in the smallest E-value in all the three crops. The E-value is dominated by the social component, because of the comparatively significant value in GDP per capita and the intensive labour requirement in the combination of labour-farming and manual ram press. Soybean has the smallest E-value in this case. Since soybean has the lowest oil content, it requires more inputs, including labour, to produce one tonne of biodiesel. This makes it create more job opportunities per tonne biodiesel production.

4.2.4 Case 4: a=1, b=1, c=1 (with Unemployment Benefit as social indicator)

Case 4 also considers all the three sustainability aspects, but using the Unemployment Benefit as the social indicator. According to the data, using oil cake as fertilizer, machine-farming and manual ram press will result in the smallest E-value in soybean and rapeseed. In jatropha's case, solvent extraction is employed. Since the magnitude of

Unemployment Benefit is much smaller than that of GDP per capita, the social component does not dominate the E-value, as compare with Case 3. This reveals that the choice of indicators can significantly affect the result of assessment.

5. Conclusions

A new methodology of sustainability study has been proposed, which combines the three aspects: economic, environmental and social. The influence of the three aspects are converted into monetary unit, and summarized as the E-value. Based on the E-values, different design alternatives can be directly compared. We found that the choice of indicators can affect the final result. This has been reflected in the choice of social indicator between the GDP per capita and the unemployment benefit. In this paper, although we have studied several factors involved in biodiesel production, there are other factors which can also affect the design decision. For example: the prices of labours, chemicals and utilities vary at different places, the land types and climatic conditions for agricultural production, etc. They should be studied in future works.

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References

Achten W. M. J., Verchot L., Franken Y. J., Mathijs E., Singh V. P., Aerts R. and Muys B., 2008, Jatropha bio-diesel production and use. Biomass & Bioenergy 32, 1063-1084.

Murillo R., Aranda A., Aylon E., Callen M. S. and Mastral A. M., 2006, Process for the separation of gas products from waste tire pyrolysis. Industrial & Engineering Chemistry Research 45, 1734-1738.

Raja S. A., Kennedy Z. R., Pillai B. C. and Lee C. L. R., 2010, Conventional Pyrolysis of Jatropha Oil Cake in a Fixed Bed Reactor. International Journal of Chemical Engineering Research 2, 85-96.

Reinhardt G., Ghosh P. and Becker K., 2008, Basic data for Jatropha production and use, Report, Institute for Energy and Environmental Research, Heidelberg; Central Salt & Marine Chemicals Research Institute, Bhavnagar; University of Hohenheim, Institute of Animal Production in the Tropics and Subtropics

Sheehan J., Camobreco V., Duffield J., Graboski M. and Shapouri H., 1998, Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus, report, Midwest Research Institute

Stephenson A. L., Dennis J. S. and Scott S. A., 2008, Improving the sustainability of the production of biodiesel from oilseed rape in the UK. Process Safety and Environmental Protection 86, 427-440.

Ucar S. and Ozkan A. R., 2008, Characterization of products from the pyrolysis of rapeseed oil cake. Bioresource Technology 99, 8771-8776.

Uzun B.B., Putun A.E. and Putun E., 2006, Fast pyrolysis of soybean cake: Product yields and compositions. Bioresource Technology 97, 569-576.