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Potential Impacts for Monitoring Sustainability: Case Study of Hollow Fiber Membrane

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Abstract: Sustainability level is a new indicator of quality and efficiency for product life cycle. Sustainability should be balanced among Triple Bottom Line (TBL) aspects namely environmental, economic and social elements. For monitoring the sustainability of product, a comprehensive framework considering potential impacts for sustainability assessment should be developed. Previously, several studies presented frameworks to assess the sustainability level. However, few studies relate their frameworks with the potential impact of all TBL. Determination of potential impacts with its parameter is important during framework development. Potential impacts for environmental such global warming, acidification and eutrophication should be taken seriously. In this study, potential impacts for each sustainability aspects are shown. For the case study of hollow fiber membrane the potential impacts were obtained from primary and secondary data such product specification, bill of materials, literature reviews and help of GaBi Software.

Key words: Sustainability assessment, potential impact, sustainability, life cycle assessment, economic and social elements

INTRODUCTION

The continuous increase in human population and social rates threaten sustainability worldwide. Sustainability is difficult to balance because it involves environmental, economic and social aspects. Sustainability is subjective what is sustainable for an environmentalist may not be sustainable for an economist and a socialist (Phillis and Andriantiatsaholiniaina, 2001). The increasing human population creates a high demand for mass production which consumes considerable amounts of raw materials and energy and depletes our natural resources. Sizeable waste and emission are generated during each stage of the product life cycle and should be balanced in terms of sustainability. Hazardous wastes from industries flow into natural water streams (e.g., rivers) and adversely affect human, animal and plant aquatic life (DOE, 2006).

Product and process development should begin at the earliest stage of design phase to achieve sustainability (Hemdi *et al*., 2013). The improvement option can focus on the stage that has the greatest influence on environmental, economic and social aspects. For example, the 6 R concepts (i.e., reuse, recover, recycle, redesign, reduce, remanufacture) can be applied at the stage involved and during product design and process development. However, the development of a sustainable product, process and system is quite complicated because the three aspects of sustainability should be balanced. That is why, determination of potential impacts and its parameter should be taken firstly before developing framework. In this study, potential impacts for each sustainability aspects for hollow fiber membrane were presented according to the primary and secondary data.

LITERATURE REVIEW

The potential impacts are determined using the Life Cycle Inventory (LCI) of input and output data that cross the system boundary. LCI involves data collection, measurement, calculation and estimation to quantify relevant parameters. Depending on the system boundaries, elementary flows are gathered and classified for evaluation. Input parameters include amount, type, price, material and consumed energy while output parameters include waste, emission and hazardous substances. Each parameter is classified according to impact categories and criteria. Users should categorize the parameters according to the potential impacts listed.

This study proposes to group the parameters into twelve potential impacts; global warming, acidification, eutrophication, waste for environmental. Then, human health, heavy metals, carcinogen and risk for social aspect. Next are resources, energy, price, fiber

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maintenance for economic. For the case study of hollow fiber membrane module the parameters are determined according to the elementary input and output flow that cross the system boundary. The selected system boundary is from cradle-to-grave which begins from material extraction, fabrication process, transportation and usage to end-of-life.

DATA COLLECTION

In this study, data were obtained for a case study of hollow fiber membrane. Table 1 shows the summarization of potential impacts with their parameters obtained from primary data, secondary data and the help of GaBi Software.

Table 1: Result of potential parameters

Sustainability aspects	Potential impacts	Parameters
Environment	Global Warming Potential (GWP): GWP relates to the measurement of heat and greenhouse gases in the atmosphere (Dincer, 2000). Greenhouse gases such carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH_4) contributes different amounts and characterization factors to GWP that describe and quantify the environmental impact CO, CO_2 and CH_4 emissions of the membrane system should be calculated at every life cycle phase to estimate their contribution to GWP	CO: CO is a poisonous, colorless and odorless gas that generates pollutants and impacts the environment (e.g., GWP effect) (Dincer, 2000). According to reference (Mahmood *et al*., 2014) even though CO contributes a smaller percentage to global warming than CO_2 and CH_4 it still increases GWP. CO is produced from the chemical oxidation of CH_4 and other hydrocarbons in the atmosphere. The characterization factor of CO is 3 compared to CO_2; 1 kg of CO equals 3 kg of CO_2-equivalent. CO is harmful when inhaled by humans CO_2: CO_2 is the primary greenhouse gas that contributes to GWP. Most CO_2 emissions are due to human activities (Dincer, 2000) and are emitted from electricity, transportation, industry, residential, commercial and non-fossil fuel combustion. Electricity is a significant energy source required by the combustion of fossil fuel. Combustion activities produce huge amounts of CO_2 that contribute to GWP. For the fabrication phase of the membrane system, CO_2 should be calculated because the electricity used is significant. CH_4: CH_4 also contributes to GWP. According to reference United Nations CH_4 is the second most prevalent global warming gas emitted. However the characterization factor of CH_4 is 25; 1 kg of CH_4 equals 25 kg of CO_2-equivalent. CH_4 is emitted from natural sources such as wetlands and human activities (e.g., industrial waste)
	Acidification Potential (AP): AP relates to the increase of hydrogen ions deposited to a medium. The increase alters the pH of the medium and damages the organic and inorganic materials. The parameters related to AP are sulfur dioxide (SO_2) and mononitrogen oxides (NO_X) (Seppala *et al*., 2006). SO_2 and NO_X emissions of membrane system should be calculated at every life cycle phase to estimate their contribution to AP	SO_2: SO_2 is a colorless gas that smells burnt and is the primary acidic gas that contributes to AP. SO_2 emission causes acidic deposition of sulfuric and nitric acid to the ecosystem which affects the nutrient cycle. SO_2 reacts with water in the atmosphere to form "acid rain" which impairs the ecosystem. The main source of SO_2 is industrial activities that involve sulfur NO_X: NO_X is a brownish gas that also contributes to AP. During the combustion process, NO_X is produced from the reaction of nitrogen and oxygen gases. The characterization of NO_X is 0.7; 1 kg of NO_X = 0.7 kg of SO_2-equivalent. The main source of NO_X is transportation and processes that involve the reaction of nitrogen and oxygen gases, especially at high temperatures
	Eutrophication Potential (EP): EP relates to the enrichment of aquatic or terrestrial nutrients. Wastewater without treatment and air pollution contribute to EP and decrease oxygen production. Phosphorus (PO_4), Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD) and ammonia (NH_3) contribute to Hemdi *et al*. (2013), Correll (1998), Kan-man and Jonsson (2001). PO_4, BOD, COD and NH_3 released from the membrane system should be measured at every life cycle phase to estimate their contribution to EP	PO_4: Phosphorus is an essential element of nucleic acids that often relates to Correll (1998). EP potential is calculated based on different amounts of characterization factors of PO_4-equivalent. Excessive loading of PO_4 to the ecosystem is usually caused by human activities (e.g., industrial activities near rivers and seas). PO_4 decreases the oxygen contained in water which in turn, decreases water quality and increases toxicity level, leading to EP BOD: BOD is the measurement of the oxygen consumed by microorganisms during decomposition which leads to the consideration of microorganisms in terms of oxidation susceptibility. BOD is used as an indicator of organic content because it provides information on the organic content of water. A high BOD value increases EP development which increases potential toxicity COD: COD is the measurement of chemicals (usually organic) that consume dissolved oxygen. According to reference (EPA, 1971) COD can measure the water quality by presenting the amount of oxygen necessary for oxidation. NH_3: NH_3 also contributes to EP. NH_3 readily reacts with strong types of acid to form ammonium salt (particulate matter) during combustion. The particulate matter is developed from rivers and increases the spread of EP The characterization factor of NH_3 is 0.33; 1 kg of NH_3 equals 0.03 kg of PO_4-equivalent
	Waste Potential (WP): WP relates to the solid and chemical wastes developed in the membrane system at each life cycle phase. Increasing solid and chemical wastes increases the development of WP. Different types of wastes require different types of end-of-life treatment methods (e.g., reused, remanufactured recycled, incinerated or dumped in a landfill) (EPA, 1971)	Solid waste: Solid waste is a useless product derived from human activities and then discarded. Solid waste is generated continuously from all human activities every single day. The disposal of large amounts of solid waste affects the environment Chemical waste: Chemical waste is hazardous only when the generated waste is ignitable, corrosive, reactive or toxic. Chemical waste that is harmful to the ecosystem should be managed properly. Most chemical waste comes from industrial activities. Disposed chemical waste should be monitored to decrease WP

Table 1: Result of potential parameters

Sustainability aspects	Potential impacts	Parameters
Social	Human health: Human health is a social problem caused by environmental contamination. Human health threatens population growth in terms of sustainability. CO, Non-Methane Volatile Organic Compound (NMVOC) and dust generally cause human health problems (USGS, 2012). CO, NMVOC and dust released from the membrane system should be measured at every life cycle phase to estimate their contribution to human health	CO: CO is a common industrial hazard that results from the incomplete burning of natural gases which is harmful to humans. CO inhaled by a human displaces oxygen in blood and deprives the heart and the brain of oxygen Inhalation of large amounts of CO results in unconsciousness and suffocation. CO poisoning includes symptoms such as headache, fatigue, dizziness, drowsiness and nausea and is harmful to human health related to social sustainability NMVOC: NMVOC is a colorless and odorless organic compound that is easily vaporized at room temperature. NMVOC is a group of chemicals that contain carbon elements (e.g., halogenated derivatives). When NMVOC is involved in a reaction, it can cause respiratory problems (Ness *et al*., 2007) Exposure to NMVOC can cause eyes and nose problems, headaches, attacks on the central nervous system and liver damage (DoE, 2006) Dust: Dust is a tiny solid particle scattered or suspended in the atmosphere. Excessive dust from industrial processes can endanger the lungs. Dust can cause problems to the respiratory system and result in disease. Various illnesses can occur when dust is inhaled
	Heavy metal: Heavy metals are metal compounds that cause human impairment. Four heavy metals (i.e., lead, mercury, chromium and copper) have the most effect on human health and should be explored further (Hemdi *et al*., 2013; Martins *et al*., 2007). Humans are exposed to these metals through drinking, eating or breathing Heavy metals should be measured at every life cycle of the membrane system to estimate their contribution to human health	Lead: Lead is a highly toxic metal commonly produced from the burning of leaded fuel. Lead is an extremely hazardous metal that can affect every organ and system in the human body. Excessive exposure to lead can cause severe brain and kidney damage. When exposed to lead for a long time, the functions of the nervous system decrease and organ damage occurs (Martins *et al*., 2007) Mercury: Mercury is a liquid metal at standard room temperature. It combines with other elements to form organic and inorganic mercury compounds. Mercury in soil and water is converted to methylmercury, a bioaccumulating toxin in microorganisms. Long-term exposure to mercury can cause permanent damage to the kidney, brain and lungs. Short-term exposure can cause nausea, vomiting, increase in blood pressure, skin rash and eye irritation (Martins *et al*., 2007) Chromium: Chromium compounds are toxins that can be in liquid, solid or gas state. Chromium is used in stainless steel, protective coating and pigment for paints. The inhalation of high levels of chromium can cause nose ulcers, runny nose and breathing problems. Long-term exposure to chromium can cause damage to the kidney, circulatory system and nerve tissues. When chromium comes into contacts with the skin, allergic reaction and skin irritation can occur Copper: Copper is a common substance in the atmosphere generated from industrial activities. Most copper compounds are bound with water sediments or soil particles. Soluble copper compounds are harmful to human health. Long-term exposure to copper can cause eye and nose irritation, headache, stomachache, dizziness, vomiting and diarrhea. High levels of exposure to copper can damage the kidney
	Carcinogen: Carcinogen can cause ionizing radiation. Arsenic and benzene are the most carcinogenic agents (Martins *et al*., 2007) commonExcessive exposure to carcinogenic agents can cause various health impairments Carcinogenic agents should be measured at every life cycle of the membrane system to estimate their contribution to human health	Arsenic: Arsenic is an odorless and tasteless carcinogen that can cause cancer of the lungs, skin, liver and bladder. Low levels of exposure to arsenic can cause nausea and vomiting. Long-term exposure to arsenic can cause skin darkening while high levels of exposure can result in death. Arsenic is released from industrial activities and should be monitored Benzene: Benzene is a sweet-smelling but highly toxic hydrocarbon. It evaporates quickly into the air and can dissolve in water. Long-term exposure to benzene can cause anemia and leukemia. Excessive inhalation of benzene can cause drowsiness and dizziness which can result in a rapid heart rate or death. The use of glue can cause exposure to benzene and should be monitored
	Risk: Risk is a qualitative measurement that includes the safety and ergonomics of the workplace. Risk that is related to social assessment should be measured in terms of sustainability. Safety and ergonomics of the membrane system should be considered at every stage of the life cycle	Safety: Safety of the workplace ensures the prevention of illness or injury to workers at the workstation. The safety level of the workplace is important and should acknowledge potential health and safety hazards. Risks in the workplace generally involve chemical toxins, electrical appliances, explosions, fire/heat, mechanical noise and radiation Ergonomics: Ergonomics provides comfort for workers in their interactions with a product, system or process. Ergonomics is usually related to musculoskeletal disorders that affect the muscles, nerves and tendons that can lead to workday injury and illness. Awkward human body posture during work and performing similar tasks repetitively can cause musculoskeletal disorders. Ergonomic designs prevent workers from experiencing musculoskeletal disorders

Table 1: Result of potential parameters

Sustainability aspects	Potential impacts	Parameters
Economic	Material: Two parameters are examined for material potential: renewable and non-renewable These parameters are calculated according to the GaBi database	Renewable materials: Renewable materials are materials or resources that can be produced and not depleted. These materials can be manufactured quickly to keep pace with how fast they are used up. Oxygen, carbon dioxide, water and oil from plants and seeds are renewable materials (May, 2013). Renewable materials are sustainable because they can replenish themselves at a sustainable rate. They also have economic advantages over fossil raw materials Non-renewable materials: Non-renewable materials are materials that cannot be produced and are eventually depleted. They cannot be readily replaced with natural resources. Non-renewable materials include fossil fuels such as petroleum, iron, antimony and clay (May, 2013). Non-renewable materials have negative economic and environmental impacts because they are scarce and expensive
	Energy: Two parameters are examined for energy potential: renewable and non-renewable. These parameters are also calculated according to the GaBi Database	Renewable energy: Renewable energy is generated from renewable resources. Solar energy, wind power, hydroelectricity and geothermal are renewable energy. The renewable energy used in Malaysia is hydroelectricity which generates electricity from the force of gravity and from water falling from high sources. Renewable energy has low economic and environmental impacts because it does not involve fossil materials and combustion processes Non-renewable energy: Non-renewable energy is produced from crude oil, natural gas, coal and uranium.The use of non-renewable energy has low sustainability impact because it increases the depletion of natural resources. The combustion of fossil fuel contributes to negative environmental impact because fossil fuel is made up of carbon which produces CO_2 when burned and can harm the ecosystem (Dincer, 2000)
	Price: Price is evaluated for the entire membrane system life cycle from material price, fabrication price and transportation price, to usage price and product end-of-life. Price assessment is normally done separately and is known as costing assessment. Evaluation of the membrane system life cycle price is essential to determining membrane system performance which is related to environmental burden. Low price equates to increased sustainability and membrane performance	-
	Fiber maintenance: Fiber maintenance is evaluated such that cleaning and replacement frequency are related to membrane system performance. High frequencies of cleaning and replacement indicate low sustainability because they relate to the economic aspect which requires a cleaning process and replacement of the membrane module. The frequencies depend on the usage of the membrane module (gallon per day)	Cleaning frequency: The cleaning process involves two processes: physical cleaning (backwashing) and chemical cleaning. When the membranes are clogged the cleaning process is performed to continue the filtering process. The cleaning frequency is normally once every 3-12 months. However, a high frequency of the cleaning process decreases membrane performance. High cleaning frequency required for one cycle of the membrane module has low sustainability because of economic and environmental impacts Replacement frequency: When membrane performance decreases, resulting in the lowest performance after the cleaning process the membrane module should be replaced. The used membrane module is moved to the end-of-life phase and dumped in a landfill

CONCLUSION

The study, proposes twelve potential impacts with its parameters should be considered for monitoring sustainability of hollow fiber membrane. Hence, a framework for sustainability assessment can be developed considering all TBL aspects. There are some future work improvement can be made to aggregate all potential impacts for monitoring sustainability for hollow fiber membrane.

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