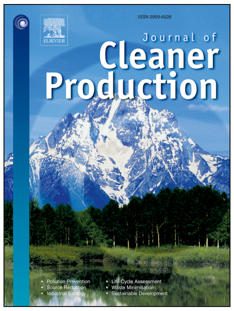

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An Advanced Micro-Bio-Loop to Produce Biogas

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Abstract: The authors report an advanced micro-bio-loop that involves recycling through four steps; namely: microalgae culture; de-oxygenation; anaerobic digestion; and aerobic decomposition. The advanced micro-bio-loop operates under sunlight to produce a continuous stream of biogas without requiring any additional external input or internal output to its surrounds. In comparison to conventional biogas production process, it achieves a net positive energy balance at remarkably different level of 0.0224 kWh MJ^{-1}, with less than 33% of environmental impacts, less than 0.57% of water demand, only 7.35% arable land-use and 0.041% of labor.

Highlights

- An advanced micro-bio-loop to produce biogas is proposed.
- The micro-bio-loop can break the bottlenecks of conventional biogas process.
- The overall performance is significantly improved by symbiotic coupling.

Keywords: biogas, microalga, biomass, biofuel, solar energy utilization

1. Introduction

Biogas has outstanding versatility and high energy content. As a result, biogas presents an opportunity to reduce fossil-fuel dependence while contributing significantly to the sustainable development of rural areas. However, conventional biogas production (Fig. 1(a)) is often limited by problems related to the procurement and pre-treatment of feedstock, the post-treatment of digestate, and the storage and transportation of both feedstock and digestate (Lukehurst et al., 2010).

To overcome these problems, the authors propose and patent an advanced micro-bio-loop (CN103290059A) that involves recycling through four steps; namely: microalgae culture; de-oxygenation; anaerobic digestion; and aerobic decomposition (Fig. 1(b)). The advanced micro-bio-loop operates under sunlight to produce a continuous stream of biogas without requiring any additional external input or internal output to its surrounds. Our analysis demonstrates that the micro-bio-loop is much more energy-efficient and more competitive technologically, environmentally, and economically than an equivalent conventional biogas production system. These advances imply that the micro-bio-loop has succeeded in breaking the conventional biogas production mode, altering it from “open” to “closed”, “complex” to “simple” and “sensitive” to “stable”, with the potential to underpin a burgeoning, future biogas industry.

2. Technological description of the advanced micro-bio-loop

2.1 Microalgae culture

Single-celled microalgae biomass, promoted as an ideal third-generation biofuel feedstock (Cuellar-Bermudez et al., 2015), is employed in the advanced micro-bio-loop. Its productivity offers 10~20 times more biomass yield than terrestrial crops — after all, the mass of microalgae can double in as little as 24 hours (Clarens et al., 2010; Luque, 2010). Microalgae culture production can take place almost everywhere, obviating pressure on arable land, and thus greatly reducing food versus fuel concerns (Ashokkumar et al., 2015; Monari et al., 2016). The micro-bio-loop circumvents the need for continuous feedstock procurement, storage, and transportation. Microalgae suspension (which generally contains 0.5 g L^{-1} dry microalgae biomass) can easily reach a COD value 3 times higher than the industrial design threshold of 500 mgCOD L^{-1} (Milieuhygiëne and Foundation, 1989), and so anaerobic digestion can be undertaken directly without energy-intensive de-watering and concentration pre-treatment steps.

2.2 De-oxygenation

The level of dissolved oxygen (DO) in microalgae suspension can easily reach up to five times the air saturation value (7 mgDO L^{-1}) (Jiménez et al., 2003; Mendoza et al., 2013), which is much higher than the methanogenic limit of 0.1 mgDO L^{-1} according to Deubling and Steinhauser (2011). For this reason, removal of dissolved oxygen is a critical procedure for the next stage of anaerobic digestion. Various liquid-phase de-oxygenation techniques have been employed in industry, including mechanical de-aeration, membrane-based de-oxygenation, heating and chemical reduction (using a deoxidizer), etc. Crucially, these technologies are too costly for the advanced micro-bio-loop and even can impede or halt its activity because of the invasion of foreign substances related to de-oxygenation. In the advanced micro-bio-loop, dissolved oxygen is progressively depleted by dark respiration of the microalgae without any addition of deoxidizer, thereby creating an environmentally-stable system. This de-oxygenation method can spontaneously and rapidly generate an oxygen-free microalgae suspension, provided the retention time lasts only 2~3 hours. This substantially reduces the capital and operational cost, the latter through a major gain in efficiency.

2.3 Anaerobic digestion

Conventional feedstock entering an anaerobic digester includes large organic polymers and recalcitrant materials that inevitably lower the conversion efficiency and generate inert residues of digestate (Chen et al., 2008). Owing to the absence of lignin, etc. (González-Fernández et al., 2012; Popper et al., 2011), microalgae are recognized to be an attractive substrate for anaerobic digestion, noting that microalgae produce 0.53～0.80 LCH_4 $g^{-1}VS$ (González-Fernández et al., 2012) (i.e. liters of methane per gram volatile solids). The resultant digestate does not contain inert residues, and so can achieve full recycling whereby fertilizer is created for the microalgae culture, accordingly reducing the disposal problem. The proportion of methane in the biogas produced lies in a similar range (i.e. 60%～75%) to that of the majority of other microalgae-based studies related to biogas applications, regardless of species and operating conditions (Ras et al., 2011).

2.4 Aerobic decomposition

Digestate is a highly valuable fertilizer which, if used effectively, can significantly offset inorganic fertilizer. However, conventional biogas production usually involves pumping digestate and then spreading it on nearby land or discharging into receiving waters without proper post-treatment. This practice greatly increases the risks of lake eutrophication arising from N and P outputs, the spread of pathogens from one farm to another, and the release of contaminants into the food chain. In the advanced micro-bio-loop, reuse of a digestate suspension to cultivate microalgae not only lowers the need for chemical fertilizer to promote microalgae production but also avoids the aforementioned risks. Moreover, water in the digestate suspension can also be re-used simultaneously in further microalgae cultivation. However, the digestate suspension contains some organically-bounded nutrients that are generally believed to be indigestible by or even toxic to the dominant microalgae species in nature (Uggetti et al., 2014). For direct feed back into the microalgae culture without pre-treatment, the resulting recycling ratio of partial nutrients will merely remain unaltered at about 50～80% (Brennan and Owende, 2010; Golueke and Oswald, 1959). In order to achieve a more optimal recycling ratio and keep microalgae at their best, advantage is taken of aerobic bacteria mineralization to convert organic nutrients in the digestate into inorganic forms that are readily digestible by microalgae. The nutrients and water in the advanced micro-bio-loop correspond to recycling ratios that are almost always 100%, achieving *in situ* quality management of the digestate. Consequently, the fertilizer cost substantially decreases from 0.012 \$ kg^{-1}algae $year^{-1}$ to 0 \$ kg^{-1}algae $year^{-1}$ (under 25 g algae m^{-2} d^{-1} productivity), which accounts for 30% cost and 45% effective energy of the microalgae culture (Clarens et al., 2010).

In the present study, the advanced micro-bio-loop employed naturally dominant species, i.e., aerobic and anaerobic bacteria taking from domestic sewage treatment plant, and microalgae taking from natural local lake. Tab.1 shows the mass and energy flows of the advanced micro-bio-loop with the considered functional unit of 890 MJ, produced by the combustion of CH_4 in an internal combustion engine.

3. Comparison of the advanced micro-bio-loop with conventional biogas production from the perspective of sustainability

Life Cycle Sustainability Assessment (LCSA) is performed to analyze potential impacts of the advanced micro-bio-loop and conventional biogas production process typically on natural resources, human society, economy and environment. The life time of processing infrastructures is assumed to be 15 years. The advanced micro-bio-loop considered herein is located in the middle of China. The relevant analysis on it is based on our experimental observation and material balance. The inventory of conventional biogas production process is derived from academic resources, engineering design standards, communications with industrial producers, and processes described in the Ecoinvent Database. (See Supplementary Table S1-S6)

Advanced micro-bio-loop and conventional biogas production process achieve a net positive energy balance at remarkably different levels, 0.0224 kWh MJ^{-1} and 0.0539 kWh MJ^{-1}. The C, N, P, K, and water balances in the micro-bio-loop corresponds to recycling ratios of 103.4 ± 0.5%, 99.8±1.9%, 102.7±1.1%, 104.2±0.9% and 99.97% respectively, achieving a free supply of fertilizer and water. Fig. 2 compares the impacts generated by producing 1 MJ biogas using these two systems from the perspective of Life Cycle Sustainability Assessment. Each impact is standardized according to the value of the worst scenario specific to the impact. The results indicate that the micro-bio-loop is vastly preferable to conventional biogas production in terms of energy use, acidification potential, global warming potential, ozone layer depletion, eutrophication, total investment cost, water demand, arable land use, and labor. All the preceding impacts are less than 33% of conventional biogas production. The water demand of the micro-bio-loop (3.66×10^{-5} m^3 MJ^{-1}) is less than 0.57% of conventional biogas production (6.42×10^{-5} m^3 MJ^{-1}) at the same functional unit. Due to the particular feedstock and simple infrastructure inherent to the micro-bio-loop system, its requirements for arable land-use and labor are only 7.35% and 0.041% of conventional biogas production. From the above insights into technological, environmental and economic dimensions, the advanced micro-bio-loop has much competitive performances beyond an equivalent conventional biogas production system.

In China, particularly in rural areas, the enthusiasm for household biogas production schemes has waned from an initial flourish of interest, partly because of a lack of scientific management by farmers of the inputs and outputs, along with a lack of inspection and maintenance of equipment. The advanced micro-bio-loop has more than

$40 billion market potential to revitalise household biogas production and could simultaneously mitigate at least 210 million tons CO_2 emission over the next 5 years, thereby making great contributions to China's Renewable Energy Development Plan and China's National Plan for Climate Change (2016-2020) (Committee, 2007, 2014).

4. A more efficient improvement for the advanced micro-bio-loop industrialization

Vigorous aeration is required to provide sufficient CO_2 for the microalgae culture and O_2 for aerobic decomposition (Grady Jr et al., 2011; Richmond, 2008). The associated energy consumption proves to be a millstone, resulting in an operational cost increase of 20%. In fact, only a coupled reactor can substitute for aerators in the advanced micro-bio-loop, without requiring any energy input, noting that both microalgae and aerobic bacteria exhibit a high degree of uniformity in the survival environment due to their symbiotic behavior. More precisely, microalgae produce the O_2 necessary for aerobic bacteria to mineralize organic matter, consuming in turn the CO_2 released by respiration of the aerobic bacteria (Praveen and Loh, 2015). According to the classical two-film theory, the CO_2/O_2 transfers involved in the microalgae culture and aerobic decomposition processes are all essentially controlled by liquid-films and gas-films (Fig. 3(a) and Fig. 3(b)). Use of a coupled reactor can completely eradicate the resistances of the four films created by microalgae culture and aerobic decomposition (Fig. 3(c)), thereby encouraging smoother exchange of CO_2 and O_2 and providing a mechanism for efficient mixing.

5. Conclusions

The advanced micro-bio-loop involves a completely independent, stable micro-ecosystem, which comprises a sustainable cycling eco-chain of producers, consumers, and decomposers (microalgae, anaerobic bacteria, and aerobic bacteria). The resulting micro-ecosystem differs to that of a conventional biogas production process in that the former simultaneously achieves full internal and external circulations of all substances. Technological simplicity combined with full circulation at steady-state operation make the advanced micro-bio-loop a particularly attractive option due to its large scale availability, tractable technology, ease of installation, safe operation, and overall economic efficiency. The advanced micro-bio-loop could progressively substitute for a significant proportion of biogas energy production facilities, with significant societal benefits.

Acknowledgements

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Figure captions

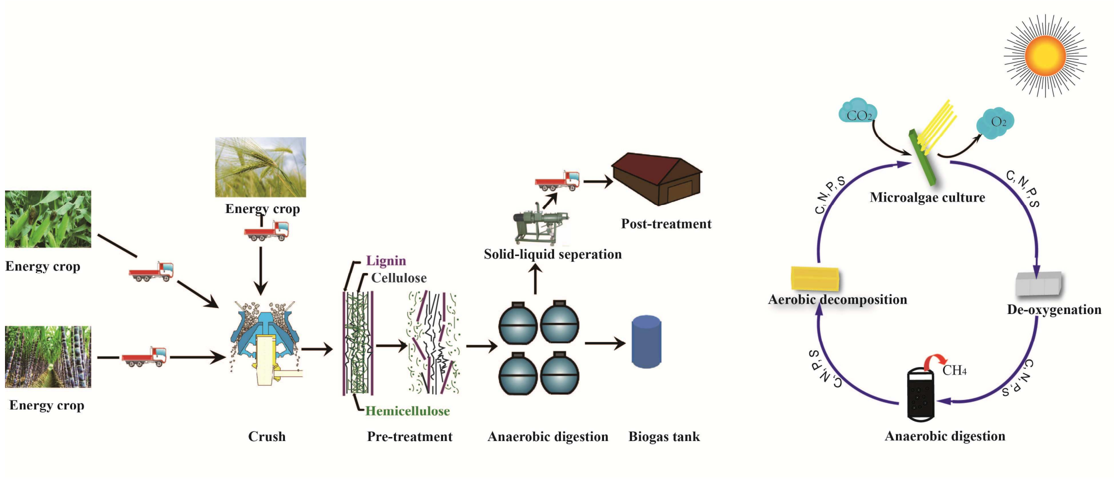
Fig. 1 Schematic diagrams of: (a) conventional biogas production process; and (b) advanced micro-bio-loop.

Fig. 2 Comparison of impacts generated by production of 1 MJ biogas using the conventional biogas production system and the advanced micro-bio-loop. The labels GWP, AP, EP, ODP, Arable land, Water, Labour, and Expense refer to global warming potential, acidification potential, eutrophication potential, ozone depletion, arable land use, water consumption, labour cost, and total investment.

Fig. 3 Two-film theory models of: (a) microalgae culture; (b) aerobic bacteria culture; and (c) microalgae coupled to aerobic bacteria culture.

Table 1 Mass and energy flows of the advanced micro-bio-loop with the functional unit of 890 MJ

Type	Description	Quantity	Units
Operation 1: microalgae culture			
Output	Flow out of the photo-bioreactor	310.288	m^3
Input	Mineralized digestate (contains inorganic N, P and K)	310.254	m^3
Input	N	0.000	kg
Input	P	0.000	kg
Input	K	0.000	kg
Input	Water	0.0325	m^3
Input	Electricity consumption (air pump)	1.310	kWh
Input	Electricity consumption (pumping)	0.873	kWh
Operation 2: de-oxygenation			
Output	Flow out of the de-oxygenation plant	310.288	m^3
Input	Flow out of the photo-bioreactor	310.288	m^3
Input	Electricity consumption (pumping)	3.939	kWh
Operation 3: anaerobic digestion			
Output	Biogas (70% CH_4)	32.250	m^3
Output	Digestate (contains organic N, P and K)	310.254	m^3
Input	Electricity consumption (pumping)	3.939	kWh
Input	Heat consumption (internal biogas)	2.047	kWh
Input	Flow out of the de-oxygenation plant	310.288	m^3
Operation 4: aerobic decomposition			
Output	Mineralized digestate (contains inorganic N, P and K)	310.254	m^3
Input	Digestate	310.254	m^3
Input	Electricity consumption (air pump)	1.310	kWh
Input	Electricity consumption (pumping)	0.873	kWh
Operation 5: purification			
Output	Methane, 96%	22.575	m^3
Input	Biogas (70%CH_4)	32.250	m^3
Input	Electricity consumption	4.291	kWh
Operation 6: combustion			
Output	Energy (from methane)	172.000	kWh
Input	Methane, 96%	22.575	m^3



(a) (b)

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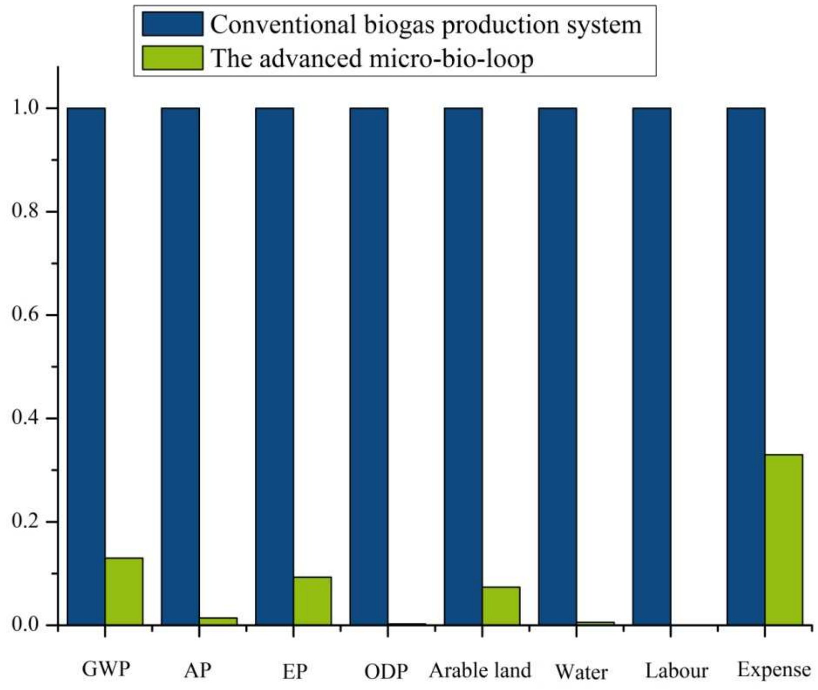

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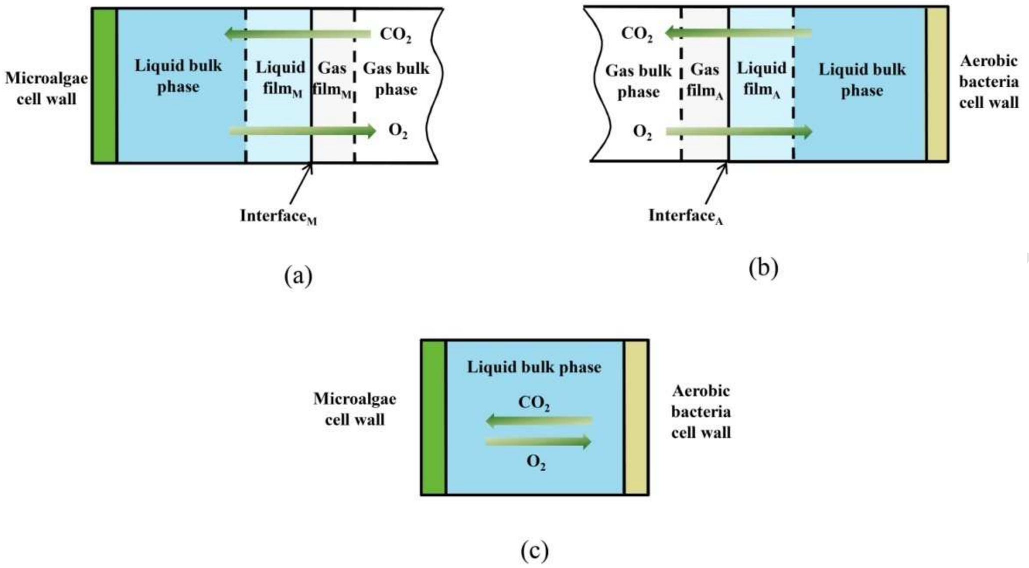

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