

Small-Scale Household Biogas Digesters as a Viable Option for Energy Recovery and Global Warming Mitigation—Vietnam Case Study

Thanh Ba Ho¹, Timothy Kilgour Roberts² and Steven Lucas²

1. Faculty of Environment and Natural Resources, Nong Lam University, Ho Chi Minh City, Vietnam

2. The Tom Farrell Institute for the Environment, University of Newcastle, NSW 2308, Australia

Abstract: Biogas from livestock waste is considered as clean and renewable energy in Vietnam. In the last 20 years, in rural and remote areas of Vietnam, there has been a significant increase of small-scale household biogas digesters. Biogas digesters create the benefits of replacing energy and mitigation of climate change caused by greenhouse gas (GHG) emission and deforestation for firewood and charcoal. Livestock waste produces approximately 85 million tonnes every year and continues to increase, meaning there are huge feedstocks for biogas digesters to meet the energy demands in households. However, there are also many constraints on the development programme for small-scale household biogas digester. In Vietnam, the socio-economic situation and the lack of a sustainable energy policy for biogas from livestock sector are hindering the growth of the biogas digester industry. Government subsidies are needed to encourage farmers to participate. This paper will be helpful not only for the sustainable development of household biogas in Vietnam, but also for the developing program of biogas generation in developing countries with similar agricultural economies to Vietnam.

Key words: Small-scale household biogas, renewable energy, biogas digester, Vietnam.

1. Introduction

Approximately 70% of Vietnam's 90 million people rely on agriculture. The quickly rising population and demand for meat have led to the rapid development of the livestock sector [1]. Like other developing countries, the scale of the livestock farm in Vietnam is small-scale (household scale). With the growth of these small-scale farms, Vietnam is facing many problems associated with animal waste management, such as environmental pollution by odour, greenhouse gas (GHG) emission and human pathogenic organisms. Livestock waste, as manure or urine, is not usually treated due to lack of money and government regulation and also lack of recognition of the problem by the farmers themselves. Binding regulations to the handling of livestock waste in

household scale is not strict and it is accepted as a habit of traditional small-scale livestock breeding in Vietnam. Therefore, it is difficult to apply modern technology of waste treatment on a small-scale due to lack of available finance for farmers.

In the past, manure from small-scale household farms was used for composting, used for fish feed and/or was discharged into rivers and lakes causing spread of pathogenic microorganisms into watersheds. There are some bacteria that cause human disease being found in livestock manure, such as *E. coli*, *Salmonella* sp., *Staphylococcus* sp. or parasite [2, 3].

In recent decades, the popular application of bio-digestion for treatment of livestock waste in Vietnam has brought many benefits in terms of the environment and energy. Bio-digesters overcome environmental pollution caused by pathogenic microorganism or odour. Methane from bio-digestion can be used for home cooking, boiling water and

Corresponding author: Thanh Ba Ho, M.Sc., research field: microbiology.

lighting, reducing the dependence on fossil fuels and reducing emission of methane to the atmosphere.

This paper reviews the deployment of small-scale biogas digesters with a special focus on the conditions in Vietnam, highlighting the benefits of biogas digesters at a household scale for improving the environment and producing energy. The current status of the livestock sector and popular biogas digesters used in Vietnam are also discussed.

2. Current State of Livestock Sector in Vietnam

Livestock at household scale supports the livelihoods of millions of people. According to General Statistics Office of Vietnam (GSO) from 1990 to 2013, the numbers of livestock have increased with time, especially poultry and pigs [4].

Along with the rapid increase in numbers of livestock, there has been a concomitant expansion of the numbers of households with livestock. Indeed, most households are small-scale farmers with less than 19 fattening pigs or fewer than five sows [3]. Therefore, biogas technology offers the best management for waste treatment of manure and for energy collection in household.

Currently, there are no official statistics on the volume of waste from livestock sector in Vietnam. However, based on estimated data of Ministry of Natural Resource and Environment, Vietnam, and using the average manure production per head per day

at about 1.5-2.0 kg/pig, 15 kg/cattle and 0.2 kg/poultry, it can be estimated that there are about 85 million tonnes of livestock wastes discharged every year.

In the past, livestock waste was discharged into the environment, or used as feed for fish or as an organic fertilizer. From 1970, due to the increasing prices of fossil fuels, anaerobic digestion to collect biogas as an energy source for cooking became economically feasible. It was noted that cooking food accounts for 90% of energy consumption in the households of developing countries [5]. For the last 20 years, as shown in Fig. 1, there has been a strong growth of biogas technology through the support of both finance and technology transfer from foreign organizations, such as Netherland Development Organization, Asian Development Bank and the World Bank in an effort to reduce environmental pollution and also provide biogas as a clean energy source.

Currently, there are about 500,000 biogas digesters in Vietnam, mainly smaller than 10 m³ in size [6]. One of the most important biogas project funded by foreign organization is the Vietnam Biogas Programme. This project has been supported by the SNV, Netherlands, a non-profit, international development organization, established in the Netherlands in 1965. By the end of 2012, 152,349 biogas plants were built by the organization [7]. The project has won international recognition as a winner of the Energy Global Awards in the years of 2006, Ashden Award in 2010 and Humanitarian Award in

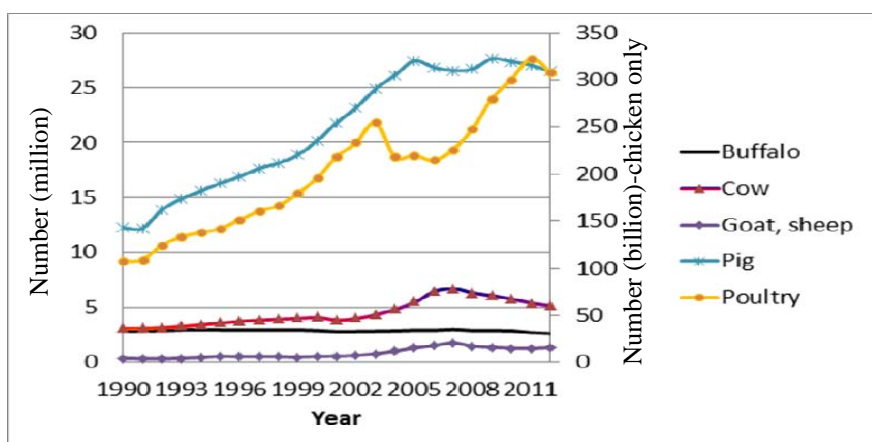


Fig. 1 Statistic of main livestock from 1990 to 2013 in Vietnam [4].

2012 [8, 9]. Increased awareness of the importance of environmental protection and the reuse of livestock waste as a renewable energy is occurring in Vietnam. The Vietnam government, together with technology transfer of biogas technology and financial support from foreign organizations, will be aiming for a sustainable target of biogas digester uptake in most Vietnam households.

3. Small-Scale Household Biogas Digester Types Used in Vietnam

There are many types of well-known biogas digesters used around the world, such as the fixed dome digester (Chinese model), the floating drum digester (India model), the plastic tubular bio-digester (Taiwan model) [5, 10]; however, in Vietnam, the research and application of biogas technology have been given considerable attention in the last 30 years and focused on three main models of biogas digester for small-scale applications, each with its own advantages and disadvantages.

3.1 Fixed Dome Bio-digester (Chinese Model)

The fixed dome digester is the original and is most popular type of biogas digester in Vietnam. The shape of the fixed dome bio-digester is similar to a sphere and is built below ground by blocks and/or bricks, cement and steel (Fig. 2). However, there are some slight modifications on later models regarding the location of inlet and outlet. These modifications also include use of different materials, such as fiberglass

reinforced plastics, to improve their efficiency, increase operational life, lower maintenance costs and lower time of installation [11]. The size of fixed dome digesters ranges from 5 m³ to 30 m³.

3.2 VACVINA (Vietnamese Design)

This model (Fig. 3) was designed in 2000 by the Centre for Rural Communities Research and Development (CCRD)—a non-governmental and non-profit organization belonging to the Vietnam Gardening Association [12].

VACVINA biogas digesters have many advantages over some other models of biogas digesters, such as simple design suitable to rural areas with stable and long-term operation. The model combines a toilet on surface, where the biogas digester is used a septic tank to save on costs and construction area. In addition, human excrement is used as an organic feedstock for bio-digestion, and the concentration of pathogenic bacteria, such as *E. coli*, is reduced [13]. This model has been popular in Vietnam and is also used in other countries, such as Cambodia and Tanzania [12].

3.3 Plastic Bladder with Continuous Flow (Taiwan Type)

The plastic tubular bio-digester (Fig. 4) consists of an elongated polyethylene bladder and is often placed in a trench to avoid damage [14]. The gas is stored at the upper section of the bladder, and the length of the bladder depends the volume of waste to be treated. The inlet and the outlet are attached directly to the



(a) Brick



(b) Prefabricated concrete

Fig. 2 Illustrative models of fixed dome digesters.

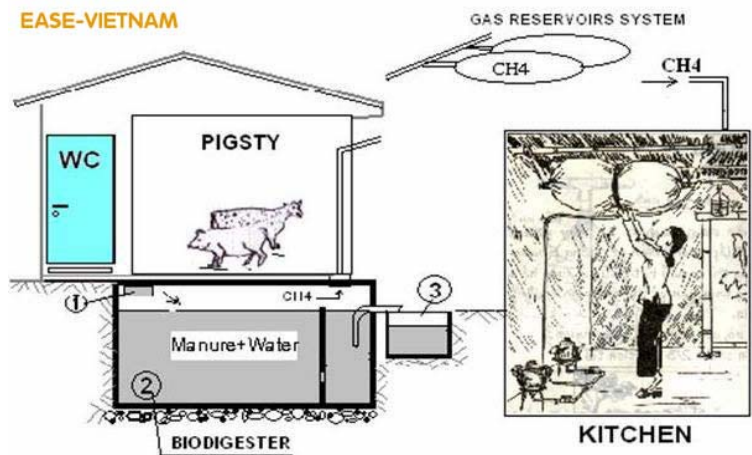


Fig. 3 The diagram of VACVINA model of biogas digester [12].



Fig. 4 A plastic bladder type biogas digester [15].

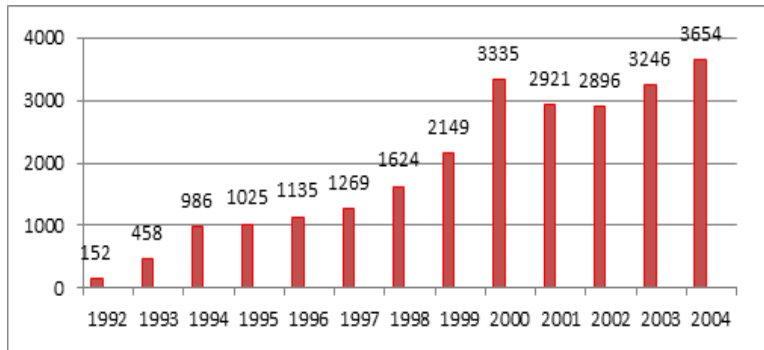


Fig. 5 The number of plastic film biogas digesters in Vietnam [16].

membrane of the bladder.

This bio-digester is much less costly than the fixed dome bio-digester, but has a lower useful life (less than 25% of the life of the fixed dome bio-digester). However, it suits the household scale with changeable plan of livestock. On the basis of low investment, fast payback, simple technology, simplicity of installation,

positive effects on the environment and women's lives in rural areas, this model (Fig. 5) has been rapidly adopted and disseminated to farmers [17]. More than 40,000 plastic bladder biogas plants (8% of total biogas digesters in Vietnam) have now been installed in these provinces, especially in Dong Nai, Binh Duong, Tay Ninh, Long An, Binh Thuan and Ninh Thuan.

Plastic bladder digesters do not provide much insulation, so they are most suitable in regions, where the climate is warm all year, such as the South of Vietnam [18, 19].

4. Benefits of Energy Recovery and Global Warming Mitigation

Biogas is a renewable and clean energy that can be used to meet basic energy demands for cooking, heating and lighting. In Vietnam, biogas is mainly used for cooking of human food, animal feed and in other businesses, such as wine, tofu, egg hatcher and so on [20]. A small portion of biogas is used for heating, lighting and electricity production. Replacing traditional energy sources, such as wood, dried dung, charcoal and liquefied petroleum gas (LPG), with biogas from human and livestock wastes, will reduce deforestation [21]. According to Surendra et al. [7] and Khoiyangbam [22], firewood is estimated to account for approximately 54% of deforestation in developing countries. Using biogas also mitigates indoor pollution (less dust, soot and smoke), improves the working environment for women and reduces odour, pathogens and flies. The use of biogas will also reduce the workload for farmers, who would otherwise have to collect firewood [7, 23]. Therefore, biogas technology can help reduce poverty and support sustainable development [24]. The approach is also particularly suitable for rural or remote areas, where there is no energy infrastructure. Surendra et al. [7] also reported that energy content in 1 m³ of biogas at average of 60% CH₄ has a heating value of about 21.5 MJ. A comparison of the energy potential of 1 m³ of biogas with other energy sources is showed in Table 1.

Another application for biogas digesters is the collection of high quality organic fertilizer generated from the slurry of anaerobic digesters [10]. Due to limited access to chemical fertilizers (availability and cost), this bi-product from biogas digesters is important for mountain or remote areas in Vietnam. Instead of discharge to the ambient environment or lost in the form of CO₂ during traditional methods of

open pit composting, about 60% organic matter content of manure containing plant nutrient, such as nitrogen, phosphorus and potassium, are well preserved in slurry [7, 25]. The slurry helps maintain soil structure and supply organic matter lost during plant harvesting. Using fermented manure as a source of organic material and nutrients for crops also helps to reduce NO₂ emissions (another GHG), which is known to occur when using chemical fertilizers [26, 27].

In recent decades, biogas digester has been mentioned as one way of mitigating GHG. The United States Environmental Protection Agency (EPA) states that methane is a GHG of 20 times more heat-absorbing than CO₂ when in the atmosphere [28]. The impact of methane in GHG is 25 times higher than impact of CO₂ based on an observation period of 100 years [29-31]. However, using biogas as a renewable energy to replace other energy sources will mitigate potential of GHGs contributing to global warming [32]. Besides CO₂, small quantities of CH₄, N₂O and CO are released during combustion. A comparison of potential emissions of these gases in Table 2 shows that biogas is the cleanest energy by GHG emissions.

Table 1 Energy equivalence of different energy sources with respect to biogas [7].

Energy source	Equivalent to 1 m ³ of biogas
Gasoline	0.53-0.73 L
Ethanol	0.81-1.10 L
Petroleum gas	0.48-0.65 L
Natural gas	0.45-0.61 m ³
Wood coal	0.91-1.24 kg
Electric energy	4.6-6.2 kWh
Mineral coal	0.60-0.82 kg

Table 2 A comparison of GHG emissions during combustion of different types of fuels [30].

Fuels	Gas emission/1 MJ of delivered energy			
	CO ₂ (g)	CH ₄ (mg)	CO (g)	N ₂ O (mg)
Biogas	81.50	57	0.11	5.40
Coal	682	1,300	26.20	1.40
LPG	139	8.90	0.82	6.00
Wood	532	600	14	4.30
Dung	885	7,100	39	270

Vietnam can receive benefits from selling credits (by CO₂ reduction) through the clean development mechanism (CDM) Project and this is an important factor for increasing the uptake of biogas digesters. CDM is an arrangement under the Kyoto protocol allowing industrialized countries with a GHG reduction commitment to invest in projects which reduce emissions in countries producing less GHG. As a consequence, the development of CDM biogas technology projects and the sale of carbon credits have opened up new channels of finance for biogas programs in Vietnam. The Vietnam Biogas Program has achieved registration under the gold standard and the stringent certification standard for projects reducing carbon emissions [33]. Some CDM projects of biogas have been developed in Vietnam with the support from foreign organizations, such as the cooperation between Can Tho University, Vietnam and Japan International Research Centre for Agricultural Sciences (JIRCAS). Under the CDM, JIRCAS will invest capital to farmers for building biogas digesters for methane collection and minimizing CO₂ emissions to the environment [34]. The reduction of this gas will be measured and converted into carbon credits. One carbon credit is equivalent to 1 tonne of CO₂ emission. On average, every 1,000 households in the province of Can Tho in the program with 1,000 biogas digesters are deployed each year, and this could create about 3,000 carbon credits. When carbon credits have been stabilized over time (target uptake of biogas digesters), JIRCAS will sell these credits to another country. Until the end of 2012, the Vietnam Biogas Program has produced 510,952 carbon credits, equivalent to reducing 510,952 tonnes CO₂ emission [35]. The total potential dollars calculated for all of Vietnam, based on 20 million biogas digesters using 85 million tonnes of livestock waste and at an average price per one credit about 5-20 US dollars, would be \$300 million to \$1.2 billion US dollars. Vietnam can gain financially from biogas program.

5. Potential and Challenge of Development of Biogas Digesters

Vietnam has a huge feedstock for biogas digesters to meet the energy demands in households due to about 85 million tonnes of livestock waste every year, which continues to increase over time. Biogas digesters are suitable for management of livestock waste in Vietnam at a household scale. Livestock waste can be combined with human excreta and food wastes from household or plant, such as water hyacinth [34], to increase treatment efficiency and methane rate. Different waste source will produce different amount of biogas, as shown in Table 3 [7]. However, if averaged just 0.4 kg dry weight of livestock waste to form 1 m³ biogas, 85 million tonnes of livestock waste will make more than 212 billion m³ of biogas every year without mention of other feedstock, such as human excreta or food waste.

Vietnam has a tropical and humid climate all year with high temperature, which suits biogas digesters. Annual average temperature in Vietnam ranges from 23 °C to 27 °C and provides good conditions for microbial activity, which contributes to high percentage of methane in biogas component.

Although there are such potential of development of biogas digester in household scale, biogas energy has not yet received significant attention of farmers. The first and the biggest challenge is that farmers do not have enough money for investment of biogas digester at their home, because most of them live in rural area and are poor farmers. According Thu et al. [24] in their

Table 3 Biogas yield potential of different organic substrates [7].

Source	Specific biogas production (m ³ /kg dry weight)
Cattle manure	0.20-0.30
Pigs manure	0.25-0.50
Chicken manure	0.31
Sheep manure	0.30-0.40
Human excreta	0.38
Vegetable waste	0.40
Water hyacinth	0.40

survey, 90% of farmers lack sufficient funds for biogas installation.

The second barrier for development of biogas programme is the lack of information about biogas technology and biogas technology transfer at the rural areas. This results in almost all livestock waste discharging freely into the open environment without treatment. This causes contamination of water sources in the local areas, which are used by most of the local people, especially the poor for their living. Therefore, it is necessary to generate more communication programs on biogas technology, water and sanitation, etc., for rural residential communities in the process of improvement of the environment and livelihoods of the local people.

Farmers need more advice and technical support to optimise biogas production. Thu et al. [24] reported in their survey that most farmers learn about technology of biogas digester from neighbor, although they do not have much technical knowledge. Many farmers give up using their biogas plant after some years when gas flow decreases, because they do not know how to maintain biogas digester, such as, knowing the ratio of water to manure input or a loading rate to increase gas volume and so on.

Another concern is gas leaking in the operational process. Very little information is available about methane losses from small-scale biogas digester, but Sander et al. [30] reported approximately 40% CH₄ losses from small-scale digesters by emission from inlet and outlet, leaking from cracked/broken cap of digester or non-airtight gas valves and intentional releases. It was estimated that about 2 m³ of gas emission per year from inlet and outlet occurred from a fixed dome biogas digester [36]. Regarding the emissions from intentional release of excess biogas, Bruuna et al. [30] reported that up to 15% of gas produced in Thailand was released. This is possibly higher in Vietnam, especially in summer when high temperatures leads to gas forming faster due to strong growth of bacteria. Most excess biogas was directly

released into atmosphere or burnt, and only a small amount was shared with neighbours [24, 30, 37].

6. Conclusions

Small-scale biogas digesters have become a suitable solution for management of livestock waste in Vietnam, and have significantly helped Vietnam to solve the energy shortages and environmental pollution in remote areas. It converts waste to useful energy, reduces GHG emissions and reduces the need for solid fuels, thereby reducing indoor air pollution and providing health gains. Further progress will be dependent on more efforts, as educating the public and the farmers about the benefits of biogas, development of biogas technology and legislative reforms about renewable policies. When educating the public to the benefits of biogas derived from manure, emphasis should also be placed on the potential health risks of the post-fermented waste due to pathogen survival.

At the moment, energy recovery from biogas might not be a priority for the energy development program in developed countries around the world, but it is extremely useful for a developing country, such as Vietnam with its value both to the environment and the energy economy.

Acknowledgments

This work has been financed by the scholarship of University of Newcastle and Ministry of Education and Training of Vietnam.

References

- [1] Vu, Q. D., Tran, T. M., Nguyen, P. D., Vu, C. C., Vu, V. T. K., and Jensen, L. S. 2012. "Effect of Biogas Technology on Nutrient Flows for Small and Medium Scale Pig Farms in Vietnam." *Nutr. Cycl. Agroecosyst* 94 (1): 1-13.
- [2] Yen-Phi, V. T., Clemens, J., Rechenburg, A., Vinneras, B., Lenßen, C., and Kistemann, T. 2009. "Hygienic Effects and Gas Production of Plastic Bio-digesters under Tropical Conditions." *J. Water and Health* 7 (4): 590-6.
- [3] Vu, T. K. V., Tran, M. T., and Dang, T. T. S. 2007. "A Survey of Manure Management on Pig Farms in Northern Vietnam." *Livestock Science* 112 (3): 288-97.

- [4] General Statistic Office of Vietnam. 2014. "The Number of Cattle and Poultry." Accessed December 2, 2014. <http://www.gso.gov.vn/default.aspx?tabid=390&idmid=3&ItemID=15270>.
- [5] Rajendran, K., Aslanzadeh, S., and Taherzadeh, M. J. 2012. "Household Biogas Digesters—A Review." *Energies* 5: 2911-42.
- [6] Union of Science and Technology of Quangngai Province. 2012. "Biogas: The Solution to the Problem of Searching for New Energy." Accessed December 12, 2014. <http://lienhiephoi.quangngai.gov.vn/mnews.aspx?id=185>. (in Vietnamese)
- [7] Surendra, K. C., Takara, D., Jasinski, J., and Khanal, S. K. 2013. "Household Anaerobic Digester for Bioenergy Production in Developing Countries: Opportunities and Challenges." *Environ. Technol.* 34: 1671-89.
- [8] Biogas Project Management Unit. 2014. "Biogas Program for the Animal Husbandry Sector in Vietnam: Project Overview." Accessed November 15, 2014. <http://www.biogas.org.vn/english/Introduction/Project-Overview.aspx>.
- [9] SNV World. 2014. "Renewable Energy." Accessed December 7, 2014. <http://www.snvworld.org/en/countries/vietnam/our-work/programmes/renewable-energy>.
- [10] Cepero, L., Savran, V., Blanco, D., Diaz-Pinon, M. R., Suarez, J., and Palacios, A. 2012. "Production of Biogas and Biofertilizers from Biodigester Effluents." *Pastos y Forrajes* 35 (2): 219-26.
- [11] Chen, Y., Yang, G. H., Sweeney, S., and Feng, Y. Z. 2010. "Household Biogas Use in Rural China: A Study of Opportunities and Constraints." *Renew. Sustain. Energy Rev.* 14 (1): 545-9.
- [12] The Center for Rural Communities Research & Development. "The Biogas Technology." Accessed December 20, 2014. <http://ccrd.com.vn/NewsDetail.asp?m=1&IDMain=1&ID=533&IDdetail=663>.
- [13] Luu, Q. H., Henry, M., Le, X. A., Pham, T. N., and Anders, D. 2014. "Hygienic Aspects of Livestock Manure Management and Biogas Systems Operated by Small-Scale Pig Farmers in Vietnam." *Science of the Total Environment* 470-471: 53-7.
- [14] Frederiks, B. 2011. "Biogas Bag Installation Manual for Small Bag-Type Plug Flow Digesters, in FACT Foundation, Eindhoven, Netherlands." FACT Foundation, Eindhoven, Netherlands. Accessed October 2, 2011. <http://www.fact-foundation.com>.
- [15] Phuong Nam Clean Technology Co, Ltd. 2013. "Technical Installation, Operation and Storage Biogas PE Bags." Accessed November 20, 2014. <http://www.safuna.com/detail.php?id=92&lg=1>. (in Vietnamese)
- [16] Lam, V., Watanabe, T., Phan, T. T., and Khai, L. T. L. 2010. *Low-Cost Plastic Biogas Digester in Integrated Farming Systems in Vietnam*.
- [17] Bui, X. A., Thomas, R. P., and Frands, D. 1997. "The Introduction of Low-Cost Polyethylene Tube Bio-digesters on Small-Scale Farms in Vietnam." *Livestock Research for Rural Development* 9 (2).
- [18] Nguyen, V. C. N., Phan, T. H., and Vo, H. N. 2012. "Review on the Most Popular Anaerobic Digester Models in the Mekong Delta." *Journal of Vietnamese Environment* 2 (1): 8-19.
- [19] Thy, S., Buntha, P., Vanvuth, T., Preston, T. R., Khang, D. N., Soukanh, K., Phouthone, B., Mikled, C., and Sopharoek, N. 2005. "Effect of Length: Diameter Ratio in Polyethylene Bio-digesters on Gas Production and Effluent Composition." *Livestock Research for Rural Development* 17 (11).
- [20] EPRO Consulting JSC. 2014. *Biogas User Survey 2013 & Voluntary Gold Standard Monitoring*. Biogas User Survey Report.
- [21] Tauseef, S. M., Premalatha, M., Abbasi, T., and Abbasi, S. A. 2013. "Methane Capture from Livestock Manure." *J. Environ. Manag.* 117: 187-207.
- [22] Khoiyangbam, R. S. 2011. "Environmental Implications of Biomethanation in Conventional Biogas Plants." *Iranica J. Energy Environ.* 2 (2): 181-7.
- [23] Liu, Y., Kuang, Y. Q., Huang, N. S., Wu, Z. F., and Xu, L. Z. 2008. "Popularizing Household-Scale Biogas Digesters for Rural Sustainable Energy Development and Greenhouse Gas Mitigation." *Renew. Energy* 33 (9): 2027-35.
- [24] Thu, C. T. T., Cuong, P. H., Hang, L. T., Chao, N. V., Anh, L. X., Trach, N. X., and Sommer, S. G. 2012. "Manure Management Practices on Biogas and Non-biogas Pig Farms in Developing Countries—Using Livestock Farms in Vietnam as an Example." *J. Cleaner Prod.* 27: 64-71.
- [25] Fan, M., Zhu, H. G., and Ma, J. Q. 2014. "Measurement and Analysis of Biogas Fertilizer Use Efficiency, Nutrient Distribution and Influencing Factors of Biogas Residues and Slurry on Pig Farms." *Int. J. Agric. Biol. Eng.* 7 (1): 60-9.
- [26] Bonten, L. T. C., Zwart, K. B., Rietra, R. P. J. J., Postma, R., De Haas, M. J. G., and Nysingh, S. L. 2014. "Bio-slurry as Fertilizer: Is Bio-slurry from Household Digesters a Better Fertilizer than Manure?: A Literature Review." Wageningen, Alterra Wageningen UR, University & Research Centre. Accessed November 28, 2014. <https://www.wageningenur.nl/en/Publication-details.htm?publicationId=publication-way-343534383833>.
- [27] Jarvis, S. C., Stockdale, E. A., Sepherd, M. A., and Powlson, D. S. 1996. "Nitrogen Mineralization in Temperate Agricultural Soils: Processes and

- Measurement.” *Advances in Agronomy* 57: 187-235.
- [28] United States Environmental Protection Agency (EPA). 2013. “The U.S. Government’s Global Methane Initiative Accomplishment.” Accessed October 28 2014. http://www.epa.gov/globalmethane/pdf/2013-accomplish-report/GMI_USG2013_Sector-Highlights.pdf.
- [29] Intergovernmental Panel on Climate Change (IPCC). 2007. “Climate Change 2007: The Physical Science Basis.” In *Contribution of Working Group I to the Fourth Assessment Report of the IPCC*. New York: Cambridge University Press.
- [30] Bruuna, S., Jensena, L. S., Khanh Vu, T. K., and Sommer, S. 2014. “Small-Scale Household Biogas Digesters: An Option for Global Warming Mitigation or a Potential Climate Bomb?” *Renew. Sustain. Energy Rev.* 33: 736-41.
- [31] Wellinger, A., Murphy, J., and Baxter, D., ed.. 2013. *The Biogas Handbook: Science, Production and Application*. Oxford: Woodhead Publishing Limited.
- [32] Zhang, L. X., Wang, C. B., and Song, B. 2013. “Carbon Emission Reduction Potential of a Typical Household Biogas System in Rural China.” *J. Cleaner Prod.* 47: 415-21.
- [33] SNV World. 2012. “Vietnam Biogas Programme Joins Global Carbon Market.” Accessed October 3, 2014. <http://www.snvworld.org/en/regions/asia/news/vietnam-biogas-programme-joins-global-carbon-market>.
- [34] Bui, V. C., Ho, T. L. H., Do, N. Q., Nguyen, N. T., Duong, N. K., and Nguyen, N. E. 2013. *Handbook on Quality Guidelines for Some Kinds of Small-Scale Biogas Plants in Vietnam*. Vietnam: Vietnam Biogas Association.
- [35] Viet, L. 2013. “Sale Carbon Credits.” *The Dan Viet Magazine*. Accessed October 10, 2014. <http://danviet.vn/nha-nong/ban-tin-chi-phat-thai-co2-36114.html>. (in Vietnamese)
- [36] Khoiyangbam, R. S., Kumar, S., Jain, M. C., Gupta, N., Kumar, A., and Kumar, V. 2004. “Methane Emission from Fixed Dome Biogas Plants in Hilly and Plain Regions of Northern India.” *Biores. Technol.* 95 (1): 35-9.
- [37] Prapasongsa, T., Christensen, P., Schmidt J. H., and Thrane, M. 2010. “LCA of Comprehensive Pig Manure Management Incorporating Integrated Technology Systems.” *J. Cleaner Prod.* 18 (14): 1413-22.