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Faculty of Tropical AgriSciences

Small-scale biogas technology in Southeast Asian countries: current state, bottlenecks and perspectives

Dissertation thesis

PhD Candidate:	Hynek Roubík
Department:	Department of Sustainable Technologies
Supervisor:	Associate professor Jan Banout, PhD
Co-supervisor:	Jana Mazancová, PhD

In Prague, August 6th, 2018

“Science is built up of facts, as a house is built of stones;

but an accumulation of facts is no more a science than a heap of stones is a house“

~ Henri Poincaré

“Live as if you were to die tomorrow.

Learn as if you were to live forever.”

~ Mahatma Gandhi

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- Dissertation thesis

Declaration

I declare that this dissertation thesis titled: “**Small-scale biogas technology in Southeast Asian countries: current state, bottlenecks and perspectives”** has been composed by myself and that the work has not be submitted for any other degree or professional qualification.

I confirm that the work submitted is my own, except where work which has formed part of jointly-authored publications has been included. My contribution at each of the publications have been explicitly indicated at the beginning of each such chapter. I confirm that appropriate credit has been given within this thesis where reference has been made to the work of others.

In Prague, August 6th, 2018

Hynek Roubík

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Abstract

Development of biogas technology in Southeast Asia has a relatively long history, but its main expansion has been recognized in recent decades. The benefits of small-scale biogas plants, providing an opportunity to solve manure management problems and simultaneously providing energy in the form of biogas has brought this technology to many small-scale farmers. This dissertation intends to provide in-depth understanding regarding small-scale biogas plants in Southeast Asia by taking into account the potential risks. Investigating such a topic is within the context of continuing concern regarding small-scale biogas technology in rural areas of developing countries. For this reason, technical, social, economic and environmental assessment of small-scale biogas technology was carried out. Methods of data collection comprised questionnaire surveys and focus group discussions among randomly selected owners of biogas plants, semi-structured personal interviews with local authorities and facilitators and observation. Sample collection of biogas to analyze its composition was performed with both multifunctional portable gas and flue gas analyzers at small-scale biogas plants. Furthermore, prediction of future development of this technology was provided using a system dynamic approach, which will serve as a decision support and policy-making tool. One third of researched biogas plants have experienced problems with biogas technology, and therefore an innovative problem analysis of biogas technology is presented in this research. Furthermore, average daily biogas production in the area equates to 0.499 m^3, not covering the demand of a typical rural household with the content of CH_4 and CO_2 in biogas from small-scale biogas plants being 64.34% and 30.36%, respectively. However, biogas quality is stable during the life-span of small-scale biogas plants. It should be noted that households use biogas mainly for cooking and not for lightening or electricity. The management of digestate is a fundamental issue and requires an immediate solution, with excessive water use for washing pigpens being reported. Finally, this research presents an innovative approach that uses system dynamics which proposes a complex model according to the motivation of farmers to well-functioning biogas plants, and the causal loop diagrams will serve as a decision support and policy-making tool for influencing assessments of various measures and decisions.

Keywords: small-scale biogas plant; biogas technology; Southeast Asia; developing countries; small-scale farmers; system dynamics

Abstrakt

Rozvoj bioplynové technologie v Jihovýchodní Asii má poměrně dlouhou historii, nicméně k expanzi došlo až v posledních desetiletích. Díky výhodám malých bioplynových stanic, které poskytují možnosti k řešení problémů s nakládáním s hnojem a zároveň tvorbu energie ve formě bioplynu, se tato technologie dostala k mnoha malým zemědělcům. Cílem této disertační práce je poskytnout dostatečný vhled do problematiky malých bioplynových stanic v Jihovýchodní Asii s přihlédnutím k možným problémům a rizikům. Zkoumání tohoto tématu je v rámci dlouhodobého zájmu o malotonážní technologii na produkci bioplynu ve venkovských oblastech rozvojových zemí. Z tohoto důvodu bylo provedeno technické, sociální, ekonomické a environmentální zhodnocení malotonážní bioplynové technologie. Metody sběru dat zahrnovaly dotazníková šetření a ohniskové diskuzní skupiny mezi náhodně vybranými vlastníky bioplynových stanic, semi-strukturované osobní rozhovory se zástupci místních úřadů a místními facilitátory a pozorování. Odběr vzorků bioplynu a spalin za účelem analýzy složení bioplynu byl proveden pomocí multifunkčního přenosného analyzátoru plynů a analyzátoru spalin na náhodně vybraných malotonážních bioplynových stanicích. Predikce budoucího vývoje této technologie byla vytvořena pomocí systémového dynamického přístupu, který bude sloužit jako nástroj na podporu rozhodování a tvorbu politik. Třetina bioplynových stanic zaznamenala problémy s touto technologií, a proto je v tomto výzkumu prezentována inovativní problémová analýza této technologie. Průměrná denní produkce bioplynu se rovná 0,499 m^3, což nepokrývá potřeby typické venkovské domácnosti s obsahem CH_4 a CO_2 v bioplynu 64.34 %, respektive 30.36 %. Avšak kvalita bioplynu je stabilní po dobu životnosti této malotonážní technologie. Je třeba také poznamenat, že domácnosti využívají bioplyn hlavně pro vaření, nikoliv pro osvětlení nebo elektrickou energii. Nakládání s digestátem zůstává problémem, který si žádá okamžité řešení, zejména kvůli nadměrnému používání vody při čištění prasečích chlívků. Závěrem tento výzkum předkládá inovativní přístup, který využívá systémové dynamiky, jež navrhuje komplexní model podle motivace malých zemědělců k dobře fungujícím zařízením na výrobu bioplynu, a schémata kauzálních smyček budou sloužit jako nástroj na podporu rozhodování a tvorbu politik pro ovlivňování hodnocení různých opatření a rozhodnutí.

Klíčová slova: malotonážní bioplynové stanice; technologie na výrobu bioplynu; Jihovýchodní Asie; rozvojové země; drobní zemědělci; systémová dynamika

Zusammenfassung

Die Entwicklung der Biogastechnologie in Südostasien hat eine relativ lange Geschichte, obwohl diese Technologie verbreitete sich erst in den letzten Jahrzehnten. Die Vorteile der Biogas-Anlagen bieten Möglichkeiten zur Lösung der Probleme, die mit der Benutzung von Düngemittel zusammenhängen, und zugleich eine Erzeugung der Energie in Form von Biogas ermöglichen. Dank erwähnten Vorteile steht diese Technologie vielen kleinen Landwirten offen. Das Ziel dieser Dissertationsarbeit ist es, einen hinreichenden Einblick in die Problematik der kleinen Biogas-Anlagen in Südostasien darzustellen und dabei mögliche Probleme und Risiken zu berücksichtigen. Die Erforschung dieses Themas ist erforderlich im Rahmen eines langfristigen Interesses an kleiner Technologie zur Erzeugung von Biogas auf den Landgebieten der Entwicklungsländer. Aus diesem Grund wurde technische, soziale, ökonomische und environmentale Bewertung der kleinen Biogastechnologie durchgeführt. Die Methode der Datensammlung fasste sowohl Fragebogenuntersuchungen, Focusgruppen unter den zufällig ausgewählten Besitzern von Biogas-Anlagen, semistrukturierte persönliche Interviews mit den Vertretern der örtlichen Behörden und mit den lokalen Fazilitatoren, als auch Beobachtung um. Die Entnahme der Probe von Biogas und Abgasen zum Zwecke der Analyse von Zusammensetzung des Biogases wurde mithilfe des multifunktionalen mobilen Gasanalysators und Abgasanalysators auf den beiläufig ausgewählten kleinen Biogas-Anlagen durchgeführt. Die Prognose der zukünftigen Entwicklung dieser Technologie wurde mithilfe der Systemdynamik-Methode (*System Dynamics*) geschafft, die zur Unterstützung der Entscheidungen und Durchführung der Politik beiträgt. Ein Drittel der Biogas-Anlagen registrierte Probleme mit dieser Technologie und daher ist in dieser Forschung eine innovative Problemanalyse dieser Technologie dargestellt. Eine durchschnittliche Produktion von Biogas liegt bei 0,499 m^3, was deckt Bedürfnisse, die typisch für ländliche Haushalte sind (d. h. CH_4 und CO_2 in Biogas 64,34 % bzw. 30,36 %), nicht. Die Qualität des Biogases ist jedoch stabil während der Nutzungsdauer dieser kleinen Technologie. Es ist noch zu bemerken, dass die Haushalte das Biogas hauptsächlich zum Kochen, und nicht als Beleuchtung oder als elektrische Energie nutzen. Die Nutzung von Gärresten ist noch immer problematisch und fordert eine sofortige Lösung, vor allem wegen der übermäßigen Wassernutzung zur Reinigung der Schweineställe. Zum Schluss legt diese Forschung eine innovative Einstellung vor, die Systemdynamik nutzt, die ein komplexes Modell darstellt, das von der Motivation der kleinen Landwirte zu den gut funktionierenden Anlagen für Erzeugung von Biogas ausgeht. Und die Causal Loop Schemas werden als Instrument dienen, das die Entscheidungen und Durchführung der Politik, die Bewertung der verschiedenen Maßnahmen und Entscheidungen beeinflusst.

Schlüsselwörter: kleine Biogas-Anlagen; Technologie zur Erzeugung von Biogas; Südostasien; Entwicklungsländer; kleine Landwirte; Systemdynamik

Аннотация

Развитие биогазовых технологий в Юго-Восточной Азии (ЮВА) не является ничем новым, однако более широкое распространение они получили в течение последних нескольких десятилетий. Благодаря преимуществам малотоннажных биогазовых станций, которые предоставляют возможность решения проблем, связанных с использованием помета, и одновременно возможность продукции энергии в виде биогаза, данная технология попала к многим малым фермерам. Целью этой диссертации является приближение проблематики малых биогазовых станций в ЮВА с учетом всех возможнх проблем и рисков. Причина исследования данной темы исходит из долгосрочного интереса к малотоннажным технологиям для разработки биогаза в сельских областях развивающихся стран. По этой причине была проведена оценка малотоннажных биогазовых технологий по технической, социальной и энвайронментальной сторонам. В методы сбора данных было включено анкетное обследование, дискуссионные фокус-группы среди случайно выбранных владельцев биогазовых станций, полоструктурированные интервью с представителями местных учреждений, местными фасилитаторами, а также наблюдение. Взятие пробы биогаза и продуктов сгорания с целью проведения анализа состава биогаза было сделано при помощи многофункционального переносного анализатора продуктов сгорания на случайно взятых малотоннажных биогазовых станциях. Прогноз дальнейшего развития данной технологии был создан при использовании системного динамического подхода, который будет служить иструментом для принятия решений и создания политики. Одна треть биогазовых станций имела проблемы с этой технологией, и поэтому в данном исследовании представлен иновационный анализ проблемы данной технологии. Средняя дневная продукция биогаза равняется 0,499 m^3, что не покрывает потребность типичного сельского домашнего хозяйства с содержанием CH_4 и CO_2 в биогазе 64,34 % или же 30,36 %. Однако качество биогаза является стабильным на протяжении срока эксплуатации этой малотоннажной технологии. Следует подчеркнуть, что домашние хозяйства используют биогаз прежде всего для приготовления пищи, а не для освещения или в качестве источника электроэнергии. Использование дигестата остается проблемой, которая требует срочного решения особенно из-за чрезмерного использования воды при очистке свинарников. В заключение данное исследование представляет иновационный подход, применяющий системную динамику, которая предлагает комплексную модель исходя из мотивации малых фермеров к хорошо работающим устройствам для продукции биогаза. В исследовании также применяются схемы т.н. *causal loop diagram*, которые будут служить в качестве инструмента, способствующего принятию решений, а также формированию политики, влияющей на оценку различных мер и решений.

Ключевые слова: малотоннажные биогазовые станции; технологии для разработки газа; Юго-Восточная Азия; развивающиеся страны; малые фермеры; системная динамика

Content

1. FOREWORD

The resource limitations of fossil fuels and problems arising from their combustion have led to the widespread utilisation of renewable energy sources. Energy and environmental issues have become one of the first problems to be solved by humankind to further sustainable development (Amigun et al., 2008; Zhou et al., 2011). Biogas produced via the anaerobic digestion (AD) of organic waste materials is considered as an important technology in improving the environment. As it solves waste management problems and simultaneously produces biogas as a main product and digestate as a by-product, which can also be used as a fertilizer (Gautam and Herat, 2000; Muller, 2007; Amigun et al., 2008; Adu-Gyamfi et al., 2012; Molino et al., 2013).

Within the rising expectations for the substitution of fossil energy with renewable energy as one of the solutions to cope with climate change, the environmental aspects of small-scale biogas plants, as widely used method for energy creation, should be evaluated in a holistic and systematic way (Zhang et al., 2013). In Southeast Asia it is mostly common to use small-scale biogas plants for energy creation from organic waste. This source of energy is mainly lauded for its low costs, clean production and high fertilization effects of digested matter for crops (Zhang et al., 2013). There are a number of advantages of small-scale biogas production on farms, including also savings on firewood or fossil fuels and reduction in odour and greenhouse gas emissions from using other fuels (Shu-Guang et al., 2006; Raposo et al., 2011; Pérez et al., 2014). However, biogas plants are often poorly managed and there is lack of proper distribution systems for biogas (Roubík et al., 2016). That results in inadvertent release of methane through leaks in digesters and tubing, and intentional one when production exceeds demand (Bruun et al., 2014). As methane has a global warming potential 25 times higher than that of carbon dioxide, environmental advantages of small-scale biogas plants might be compromised (Bruun et al., 2014; Hrad et al., 2015).

This dissertation intends to provide in-depth understanding about the issue with taking into accounts possible risks. Investigating of such a topic is within continuing concern about small-scale biogas technology in rural areas of developing countries. For this reason, technical, social, economic and environmental assessment of small-scale biogas technology should be done. Furthermore, prediction of future development of this technology will be created.

2. STRUCTURE OF THE DISSERTATION

This dissertation is based on the results presented in the scientific papers which were prepared by the author and are already published, or are currently under review in the scientific journal. This form of dissertation is allowed by the Faculty of Tropical AgriSciences, Czech University of Life Sciences Prague Deans´ decision No 2/2017.

The results are presented in the following articles:

I. **Roubík, H.,** Mazancová, J., Banout, J., Verner, V., 2016. Addressing problems at small-scale biogas plants: a case study from central Vietnam. Journal of Cleaner Production 112(4), 2784-2792. https://doi.org/10.1016/j.jclepro.2015.09.114
   a. *Author was responsible for the idea, conceptualization, data collection, performed all experimental work, analysed the data, wrote the original manuscript, and executed its revision.*

II. **Roubík, H.,** Mazancová, J., Phung, L.D., Dung, D.V., Banout, J., 2018. Biogas Quality across Small-Scale Biogas Plants: A Case of Central Vietnam. Energies 11(7), https://doi.org/10.3390/en11071794
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III. **Roubík, H.,** Mazancová, J., 2018. Small-scale biogas plants in central Vietnam and biogas appliances with a focus on a flue gas analysis of biogas cook stoves. Submitted to Renewable Energy (11/08/2017).
   a. *Author was responsible for the idea, conceptualization, methodology, data collection, performed all experimental work, analysed the data, wrote the original manuscript, and executed its revision.*

IV. **Roubík H.,** Mazancová J., Phung L.D., Banout J., 2018. Current approach to manure management for small-scale Southeast Asian farmers - Using Vietnamese biogas and non-biogas farms as an example. Renewable Energy 115(C), 362-370. https://doi.org/10.1016/j.renene.2017.08.068
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V. **Roubík, H.,** Mazancová, J., Rydval, J., Kvasnička, R., 2018. Uncovering the dynamic complexity of the development of small-scale biogas technology through causal loops. Submitted to Energy (10/07/2018).

   a. *Author was responsible for the idea, conceptualization, data collection, co-wrote the original manuscript.*

VI. **Roubík, H.,** Mazancová, J., 2016. Small-and medium-scale biogas plants in Sri Lanka: Case study on flue gas analysis of biogas cookers. Agronomy Research 14(3), 907-916.

   a. *Author was responsible for the idea, conceptualization, methodology, data collection, performed all experimental work, analysed the data, wrote the original manuscript, and executed its revision.*

VII. **Roubík, H.,** Mazancová, J., 2018. Suitability of small-scale biogas system for the rural areas in northern Sumatra. Submitted to Renewable Energy (20/06/2018).

   a. *Author was responsible for the idea, conceptualization, methodology, data collection, performed all experimental work, analysed the data, wrote the original manuscript.*

VIII. **Roubík, H.,** Mazancová, J., 2018. Identification of Context Specific Knowledge as tool for facilitators and their quality involvement – using Vietnamese practice as an example. Submitted to NJAS - Wageningen Journal of Life Sciences (29/08/2016).

   a. *Author was responsible for the idea, conceptualization, methodology, data collection, performed all experimental work, analysed the data, wrote the original manuscript.*

IX. **Roubík, H.,** Mazancová, J., 2016. Small-scale biogas sector in central Vietnam: ways of financing of the technology. Agrarian Perspectives XXV., 312-318.

   a. *Author was responsible for the idea, conceptualization, methodology, data collection, performed all experimental work, analysed the data, wrote the original manuscript, and executed its revision.*

X. **Roubík, H.,** Mazancová, J., Situmeang, R.C., Brunerová, A., Simatupang, T.M., 2017. Livestock manure management practices in rural households in Tapanuli Utara regency of North Sumatra. Agronomy Research 15(4), 1782-1794. http://dx.doi.org/10.15159/ar.17.055

   a. *Author was responsible for the idea, conceptualization, methodology, data collection, performed all experimental work, analysed the data, wrote the original manuscript, and executed its revision.*

XI. **Roubík, H.,** Mazancová, J., Phung, L.D., Dung, D.V., 2017. Quantification of biogas potential from livestock waste in Vietnam. Agronomy Research 15(2), 540-552.

   a. *Author was responsible for the idea, conceptualization, methodology, data collection, performed all experimental work, analysed the data, wrote the original manuscript, and executed its revision.*

3. OBJECTIVE OF THE THESIS

The major objective of this dissertation is to provide in-depth understanding about the small-scale biogas technology and all its aspects. Investigating of such a topic is within continuing concern about small-scale biogas technology in rural areas of developing countries. For this reason technical, social, economic and environmental assessment of small-scale biogas technology should be done. Therefore, technical, social, economic and environmental assessments is provided as well as prediction of future development of this technology.

3.1. Technical Assessment

The use of biogas plants has been spread in many developing countries, bringing various operational problems with their widening use. The technical part of this dissertation attempts to identify challenges with biogas technology at three levels, such are technology, products (biogas and by-product digestate), and owners and facilitators. Furthermore, results of flue gas analysis of this technology as well as biogas quality assessment.

3.2. Social Assessment

This dissertation attempts to cover social aspects of the technology, bringing the identification of Context Specific Knowledge for facilitators and their quality involvement and bringing improvement and policy recommendations for further quality involvement in the facilitating this technology.

3.3. Economic Assessment

The dissertation also covers the calculation of the payback period of biogas plants and the analyses of financing of biogas technology and purchasing decision-making process. One of the fundamental questions from economic perspective is if biogas technology is really an appropriate solution for the poor.

3.4. Environmental Assessment

One of the specific objectives of this dissertation is to evaluate a manure management practices with all its aspects. Objective of this dissertation is also to determine environmental aspects of small-scale biogas plants in selected Southeast Asia regions. It is essential to uncover impacts of this technology on environment, because of its wide use and popularity.

3.5. Future development

Prediction of future development of this technology is created based on uncovering dynamic complexity of development of biogas technology through causal loops.

The perspective and objectives are shown on the case country of Vietnam for clarity and contextuality, however, further examined countries can be found in the appendix (especially Sri Lanka, Indonesia and others).

4. RESULTS IN FORM OF CHAPTERS

CHAPTER I. - Addressing problems at small-scale biogas plants: a case study from central Vietnam

Adopted from: **Roubík, H.,** Mazancová, J., Banout, J., Verner, V., 2016. Addressing problems at small-scale biogas plants: a case study from central Vietnam. Journal of Cleaner Production 112(4), 2784-2792. https://doi.org/10.1016/j.jclepro.2015.09.114

Author was responsible for the idea, conceptualization, data collection, performed all experimental work, analysed the data, wrote the original manuscript, and executed its revision

Abstract

The anaerobic digestion process is an important technology in improving the environment because it solves organic waste management problems and simultaneously produces both biogas and fertilizer. The use of biogas plants has been spreading in many developing countries, bringing various operational problems with their widening use. This study attempts to identify the problems with this technology at the level of owners of biogas plants (n=141) and local facilitators (n=9) in central Vietnam. A survey was conducted from July to September 2012. The methods of data collection included focus group discussions, semi-structured personal interviews and a questionnaire survey. The survey revealed that 29% of biogas plant owners have experienced at least one problem with this technology. The most frequently encountered problem is linked to leakages from reactors leading to undesired CH_4 emissions, which sometimes stopped the biogas plants from functioning. Other problems concern the failure of biogas cookers to properly function with solid digestate incrustation floating in the main tank, resulting in decreased biogas production. The respondents call for better-trained builders and facilitators, who are often unable to solve difficulties encountered with BGPs. The importance of a working information flow between actors is demonstrated. The study also involves the calculation of the payback period of biogas plants. The findings show a linear relationship between the payback period and biogas plant-owners' satisfaction with biogas technology, biogas production and the biogas programme. In addition, the study recommends improvements in the skills of facilitators because they have a direct impact on the quality of training of BGP owners and builders¬. In conclusion, this study provided an innovative problem analysis of biogas technology along with appropriate recommendations. It demonstrated the need for further research on the eradication of problems associated with biogas technology.

Keywords: anaerobic digestion, biogas, Thu Thien Hue, facilitators, payback period, technology difficulties

Introduction

The resource limitations of fossil fuels and problems arising from their combustion have led to the widespread utilisation of renewable energy resources. Energy and environmental issues have become one of the most important problems of common concern and one of the first problems needing to be solved by mankind to further sustainable development (Zhou et al., 2011; Amigun et al., 2008). Biogas produced via the anaerobic digestion (AD) of organic waste materials is considered an important technology in improving the environment because it solves waste management problems and simultaneously produces biogas as a main product and digestate as a by-product, which can also be used as fertiliser (Gautam and Herat, 2000; Muller, 2007; Amigun et al., 2008; Molino et al., 2013; Adu-Gyamfí et al., 2012). A biogas plant (BGP) is a piece of equipment that uses an AD process for biodegradable waste treatment. The utilisation of AD represents an appropriate solution to health, hygiene and environmental problems (Katakiza, et al., 2012; Jha et al., 2011; Jingura and Matengaifa, 2007). The production of biogas through the AD process provides significant advantages over other forms of renewable energies (Zhang et al., 2013; Lu Shu-Guang et al., 2006). It has been demonstrated to be one of the most energy-efficient and environmentally friendly forms of energy and of technologies for renewable energy production (Pérez et al., 2014; Raposo et al., 2011). Economic prosperity and quality of life in rural areas are closely linked to per capita energy consumption, and the adopted strategy is to use energy as a fundamental tool to achieve both (Singh and Sooch, 2004). Energy consumption in the rural areas of central Vietnam can be met by the use of household-sized biogas plants and can provide a healthier and more sustainable way of living. One can expect that a higher number of BGPs in developing countries will also produce a significant number of problems and complications regarding their operation, thereby reducing the benefits of this technology. The objective of this paper is to analyse current problems with BGPs in the target area and outline possible easily applicable solutions in line with local conditions. This paper will also have value for other developing countries in the region.

Biogas plants in developing countries

In 1984, more than 7 million BGPs were in operation worldwide, mostly in Asian countries (Steinar and Kandler, 1984). Currently, millions of BGPs can be found in developing countries (Mwakaje, 2008). There are approximately 38 million BGPs (Chen et al., 2012) in China, more than 3.7 million in India (Rao et al., 2010), over 80,000 BGPs in Vietnam (Ghmire, 2013), 60,000 in Bangladesh and an increasing number in Peru and African countries (Thu et al., 2012). The most common BGP type is the so-called Chinese type (Maithel, 2009; Pérez et al., 2014).

The Chinese-type biogas plant was originally based on a septic tank (Fulford, 2015), but the original rectangular tank was rapidly replaced by a design based on a fixed dome shape that provided better performance. There are many varieties of fixed domes such as the KT model (described in this paper and widely used in Southeast Asia), the Janata model (the first fixed dome design in 1978 in India) (Singh and Sooch, 2004; Kalia and Kanwar, 1998), the Camartac model (developed in the 80s in Tanzania) (Pérez et al., 2014; Nzila et al., 2012), and the Deenabandu model (developed in the 90s in India) (Singh and Sooch, 2004). Different NGOs and private companies manufacture these and other designs, which is leading to increased variations in quality.

The increasing number of BGPs in developing countries also means an increase in the number of problems and complications associated with BGPs (Aburas et al., 1995). Generally, there are many advantages to biogas production but also many disadvantages. If these cons outweigh the pros, small-scale farmers abandon BGPs, as shown in China (Zhou et al., 2011). One of the most important problems hindering any biogas technology in developing countries is cost, which can create difficulties for the installation of such plants, together with sourcing spare parts (An et al., 2006; Mwakaje, 2008). It has been widely reported that the development of BGPs was greatly facilitated because of substantial support from governments, development projects and aid agencies (Mwakaje, 2008; Kristoferson and Bokhalders, 1991); however, when the subsidies were later reduced, the number of BGPs built each year fell dramatically (Desai, 1992). Technical and operational problems are common in the case of small-scale BGPs, yet suitable solutions are often found (Aburas et al., 1995). Further political measures, including training and capacity building programmes, flexible financing mechanisms and dissemination strategies, may be needed to encourage adoption (Karekezi, 2002; Greben and Oelofse, 2009; Zhou et al., 2011). System failures of small-scale BGPs can be divided into six main subsystems, as adopted from Cheng et al. (2014): structural components, biogas utilisation equipment, piping systems, biogas production, digestate disposal systems and knowledge-related problems. Problems with structural components were found in studies conducted by Chang et al. (2011) in Inner Mongolia and by Lam and Heegde (2012) in Asia and Africa. Problems with biogas utilisation equipment in Vietnam, such as biogas cookers and lamps, are described by Pipatmanomai et al. (2009) and Thu et al. (2012). Problems with piping systems, such as leakages or blockages, were found in Sovacool et al. (2015) and Cheng et al. (2014), and problems with biogas production, such as leakages in biogas digesters, were found by Chang et al. (2011) and Thu et al. (2012). Solid digestate incrustation floating in the main tank prevents biogas from escaping, as found in the studies from China conducted by Chen et al. (2012, 2010). Digestate disposal systems are important to the sustainability of BGPs because without appropriate disposal and operating procedures, there can be no long-term sustainability (Alburquerque et al., 2012). A call has been made for quality supervision, inspection, maintenance, quality controls, effectiveness evaluations and technical guidance (Chen et al., 2012; Suzuki, 2015). To ensure that BGPs continue to function properly, there is a need for improvements in knowledge (Cheng et al., 2014; Thu et al., 2012; Vu et al., 2007; Suzuki, 2015), which should be transferred from local facilitators to small-scale biogas owners (Jha et al., 2011; Maithel, 2009).

There is also a promising alternative in the form of biohydrogen production via an AD process (Lee, 2013), which is an emerging candidate among other alternative energy carriers (Bakonyi et al., 2014). This method may provide future competition to the conventional anaerobic digestion process (Ravina and Genon, 2015). Biohydrogen may also be a viable option for developing countries; however, its development in Asia is expected to be much slower than in other regions (Lee, 2013). Therefore, this study does not move towards its further recognition. Biomethane production refers to the separation of the methane fraction from other gaseous components via a treatment process commonly referred to as biogas upgrading (Ravina and Genon, 2015; Bauer et al., 2013). In the study of Bauer et al. (2013), emerging technologies for small-scale upgrading and the future application of upgraded biogas are discussed; however, these shifts into the future are expected to be introduced slowly in developing countries, especially in rural areas.

Current situation with BGPs in Vietnam

Since 2003, Vietnam has implemented a national program for the use of biogas in the animal sector – The Biogas Programme for the Animal Husbandry Sector in Vietnam (BPAHS). The BPAHS has been placed into practice by the Biogas Project Division of the Ministry of Agriculture and Rural Development in collaboration with the Dutch development organisation SNV. Since 2003, more than 100,000 household biogas plants have been built under this programme, including 2,900 family biogas plants in the Thua Thien Hue province, central Vietnam. In addition, builders, facilitators and technical teams have been trained to control the quality and viability of BGPs and provide training to users.

Methods

Target area

The survey was conducted in the province of Thua Thien Hue in central Vietnam. Its population consists of 1,045,134 inhabitants (Thua Thien Hue, 2000), which represent 1.13% of the population of Vietnam. One third of this population lives in and around Hue City. The population density is lower than the national average (219 and 265 persons per km2, respectively) and varies across the province (General statistics of Vietnam, 2013). Our survey was conducted in the districts of Huong Tra and Phong Dien. The climate in the region is tropical humid (Cong Vinh, 2007), the average temperature is approximately 25 °C, and the average rainfall is in the range of 1,600 - 4,000 mm per year (Thi Mui, 2006). These rains can be very sudden and heavy, causing not only possible decreases in agricultural activity and school attendance but also losses of property and human lives as well as damage to the environment. These limitations (floods, storms, drought and coastal erosion) need to be considered. For example, coastal erosion is widespread and causes losses of life, prevents socio-economic development (Ngoc Ca et al., 2005) and leads to economic weaknesses in the area.

Data collection

The survey was conducted from July to September 2012 using randomly selected owners of BGPs (n=141) and local authorities and facilitators (n=9) in the districts of Huong Tra and Phong Dien. The methods of data collection included focus group discussions (n=41), semi-structured personal interviews and a questionnaire survey (n=100) and observation. BGP owners and facilitators were interviewed using a semi-structured interview (Figure 1 and 2); each interview took approximately one hour. To increase the scope of the study, four focus groups were conducted with farmers. The results of these participatory methods were compared with the results of observations of the target groups. The questionnaire was designed to determine the reality of the current situation about the issue. The questionnaire included different types of questions such as open, closed, semi-open, evaluation and multiple choice questions. The questionnaire included two main categories: a socio-economic part and a part related to biogas technology (Table 1). The questionnaire was subject to pilot testing and was subsequently adjusted and approved by experts from the Agricultural Forestry Fishery Extension Centre in Hue City (AFFEC) before final distribution.

Table 1 Main categories of the questionnaire.

Category	Focus of the questions
Socio-economical part	District, villages, sex, role in household, size of family, amount of members living in farm, education, occupation, income, farm size, crops, equipment in household
Biogas technology related part	Motivation, technology related costs, main benefits of using BGP, saved money related to using BGP, use of human excreta to BGP, time for fuel wood picking, satisfaction with technology, trainings about BGP, problems with biogas technology, attitude to the technology, currently used solutions to the difficulties, knowledge about related topics

Data analysis

The collected data were categorised, coded and analysed using the statistical software package Statistica 10. Due to the nature of the data, Spearmen´s correlation coefficient (R) was used to detect possible relationships between Payback Period (PB) and the satisfaction of BGP owners with BGP technology, satisfaction with biogas production (amount and quality) and satisfaction with the biogas programme.

Figure 1 Data collection in cetral Vietnam.

Conceptual framework of problem analysis

This paper uses a problem analysis (PA) approach to identify and describe major problems and potential risks, with the intent to facilitate the adoption of various improvements and prevent failures. The PA is structured based on the following main problematic subsystems (Table 2): structural components, piping systems, equipment utilising biogas, digestate disposal systems, AD processes and biogas utilisation, and knowledge-related problems. This results in subsystem and failure criteria descriptions and allows us to provide recommendations (Table 3). Subsystems and a description of their failure criteria and relevant recommendations were assembled with respect to problematic subsystems and based on technical problems recognised during field research and based on further secondary data from various studies. The six subsystems combined address the entire small-scale biogas system and all main aspects essential to its proper functioning. When a failure occurs, it is usually due to events occurring in one or more of these subsystems. The average occurrence of all problems for each subsystem is individually calculated for these problematic subsystems.

Table 2 Main problematic subsystems of the small-scale biogas plants (N=141).

Main subsystems	Average diameter of problems (%)
AD process and biogas production	37.2
Biogas utilization equipment	25.2
Digestate disposal system	17.1
Knowledge related problems	9.1
Piping system	6.2
Structural components	5.0

Figure 2 Meeting with local facilitators of small-scale biogas plants.

Payback Period calculation

Equation (1) was used to calculate the Payback Period (BP), where D is the payback time [years], I is the biogas installation cost [USD], Pr is the annual benefit [USD] and Npr is the annual operating cost [USD]. The installation costs of a BGP represent the total construction expenses that the owners paid. They were calculated both with and without subsidies. The data collected from the respondents on savings obtained through the use of BGPs were used to determine the annual economic benefits. To determine the annual operating costs, a figure of 5% of the costs of the BGPs was used as the value of the average costs of repairs and operation. For BGPs, where problems arose, an amount of 23.5 USD was included (= the modus of the most common amount paid for their repair for any given complication).

$$D = \frac{I}{P_r - N_{pr}}\ (years) \qquad (1)$$

Results and discussion

Socioeconomic characterisation of biogas plant owners in the target area

The average size of a rural family in central Vietnam is four to five people, which is in agreement with the findings of Thu et al. (2012), with 2.2 people on average actively working. These numbers are comparable with the official population statistics of Vietnam, which show 3.9 people per family in rural areas of central Vietnam (General Statistics Office of Vietnam, 2009). However, the respondents report their families to consist of five to six members. This means that there are on average two members of each family who do not reside on the farm but who are mostly studying or working in another city, in our case, in DaNang or Ho Chi Minh City. The education of the respondents, taken as the highest educational attainment in a household, was tertiary (34%), secondary (55%), primary (10%) and without education (1%). There is an expectation that the greater the education, the greater the ease of adaptation to new opportunities (Behrman and King, 1999), which can in turn be connected to the better maintenance of BGPs and better digestate management. It must be said that in terms of education and accessibility to education, Vietnam has made noticeable achievements (Ahn et al., 1995), mainly due to long-term government policy. The rate of educational achievement in Vietnam is high, as also evidenced in the study by Bélanger and Lui (2004). The respondents (BGP owners) in our survey attended training (related to BGPs) in 79% of cases, and on average, they attended 1.9 training sessions, with reported satisfaction in 61 cases (48.2%). The importance of focusing on this topic is linked to the view that education is one of the principal routes for poverty alleviation in developing countries (Glewwe and Jacoby, 2004), and the willingness to pursue new possibilities increases with increased education (Behrman and King, 2001). Therefore, a connection between training and satisfaction with training and the management of technology and the attitude of BGP owners is assumed.

Biogas plants in the target area

The KT1- and KT2-type BGPs are predominant in the target area. These types, based on the Chinese fixed dome model, include the following main components: a mixing inlet tank, a digester, a compensation tank with an overflow outlet, and a gas pipe (Figure 3 for scheme, Figure 4 for working biogas plant and Figure 5 for malfunction). The outer wall of the digester and compensation tank is constructed of brick. The digester is dome shaped. The bottom is concreted or constructed of brick. The mixing tank has a rectangular shape. The compensation tank can be constructed either as dome shaped or as rectangular in shape. All three tanks are connected together by inlet and outlet pipes. The KT1 type is appropriate when using a quality substrate with a good soil structure to provide easy excavation. The KT2 type is used in places where it is harder to dig into the soil or where there is a high groundwater level; this type has a shallower or flatter shape. However, both types operate on the same principles, and there are no significant differences affecting the process or problem rates.

The working principle of biogas plants in the target area is as follows: mainly pig manure is sluiced with water directly into the biogas inlet, where gravity guides it into the digester. In addition, households' toilets connected to the digester are flushed with a bucket of water. In the anaerobic processes, bacteria decompose the organic matter and produce biogas, which is collected under the dome and pushes the digested slurry into the outlet tank. The biogas then travels through the pipeline to the end user. There is no significant seasonal variability in the input materials; however, variations were recognised in the watering volumes – being higher during the summer season when water is also used for cooling pigs.

The most common volume of biogas digesters in the target area is 6 m^3 (52.7%); the other volumes are 12 m^3 (7.5%), 9 m^3 (17.2%), 8 m^3 (16.1%) and 7 m^3 (6.5%). The average size is 7.5 (±2.2) m3. Most BGPs are 2 years old (54.0%).

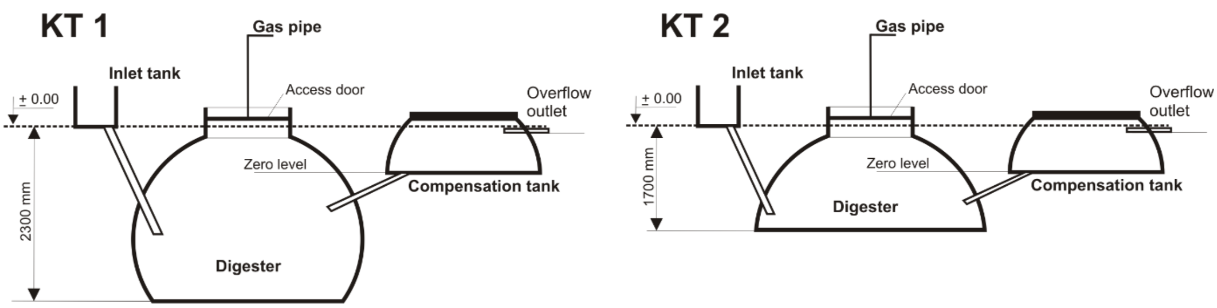

Figure 3 Scheme of KT1 and KT2 biogas plants.

Figure 4 Small-scale biogas plant in Vietnam.

Problem analysis for biogas technology in the target area

The survey revealed that 29% of BGP owners have experienced a problem with this biogas technology. Two populations of the districts were considered statistically directly comparable. Failures were recognised in all six main subsystems, with the highest average occurrence of problems in AD process and biogas production subsystems, biogas utilisation equipment subsystems and digestate disposal systems (further information on the average occurrence of problems and descriptions of their failure criteria and relevant recommendations are given in Table 2 and Table 3, respectively). Certain key failures and their frequency are present in Table 4.

Figure 5 Small-scale biogas plant in Vietnam with leakages.

Table 3 Subsystems and failure criteria description and recommendations for the biogas technology.

Subsystem	Failure description	Further studies describing similar problems and country of study	Recommendation, possible solutions and notes
Structural components			
	Problems with the inlet pipe	Cheng et al. (2014) Nepal	Clean the inlet pipe with stream of water or with a long stick
	Unstable BGP in rainy season	N/A	Appropriately selected BGP and higher skills from masons
	Inconvenient position of BGP components	Cheng et al. (2014) Nepal	The BGP is too far from animal sheds, the inlet pipe is at an inappropriate slope, the outlet tank is too remote to be reached. These are in the competence of skilled masons and facilitators
Piping system			
	Leakage in piping system	Sovacool et al. (2015) Kenya, Cheng et al. (2014) Nepal	When the pipe is not connected adequately. The connections between the valve and the pipe or between pipe and nipple are not working properly. The gas pipe is corroded. When necessary, the pipe line should be replaced or repaired by facilitators/masons.
	Blockage of piping system	Cheng et al. (2014) Nepal	When the pipe line is overhanging for long time, and if no water filter is available water may be condensed within the pipe. Use of a water filter and regular use
Biogas utilization equipment			
	Malfunction of biogas cooker	Pipatmanomai et al. (2009) Thailand, Thu et al. (2012) Vietnam, Cheng et al. (2014) Nepal	Malfunctions of biogas cooker are diverse in origin such as corrosion, a broken gas tap, and a broken flame pedestal or ablocked air injection hole. Corrosion can be reduced with a H2S filter, other problems solved by appropriate use of fire and higher quality cookers, which should be recommended by facilitators
	Malfunction of biogas lamp	Cheng et al. (2014) Nepal	Biogas lamps are rarely used due to the low price of electricity and its accessibility

Digestate disposal system			
	Poorly accessible reservoir for digestate	N/A	When the reservoir is inappropriately located, it creates difficulties with further digestate management. It is the responsibility of masons and facilitators to think it through
	Lack of organic matter in digestate	Thu et al. (2012) Vietnam	High water levels: manure ratios cause a lack of OM in the digestate. The ratio should be around 3-6:1. Knowledge should be transmitted via local facilitators
AD process and biogas production			
	Leakage in reactor	Chang et al. (2011) China, Lam and Heegde (2012) Asia and Africa	When the digester is not made properly, the pressure from inside the digester pushes the gas out. It can lead to the elimination of the functionality of the BGP. Masons must be skilled enough to avoid problems with digester. In cases of significant leakages, the BGP must be fully rebuilt.
	Solid digestate incrustation floating in the main tank	Cheng et al. (2014) Nepal	A scum layer on the surface preventing biogas from going through it. The BGP must be opened and cleaned
	Lack of biogas	Thu et al. (2012) Vietnam	Can be caused by the poor quality of biogas (a slow concentration of methane), or by a lack of organic matter. Can also be caused by process breakdowns. BGP owners should be sufficiently informed by facilitators
	Poor quality of biogas	Pipatmanomai et al. (2009) Thailand	The quality of biogas depends on the individual components and its methane concentration. This is affected by temperature, the presence of oxygen, feedstocks, hydraulic retention time etc.
	Smell of biogas	Pipatmanomai et al. (2009) Thailand, Thu et al. (2012) Vietnam	Any bad smell from biogas can be removed by the use of a H2S absorbent. In the case of a simple carbon filter, it must be cleaned every two months
	Lack of feedstock/Over-size of BGP	Singh and Sooch (2004) India, Chen et al. (2012) China, Thu et al. (2012) Vietnam, Cheng et al. (2014) Nepal	When farmers reduce the number of animals, there are no longer appropriate amounts of manure, animals are not feed regularly or manure is not moved to the inlet tank. Also over-size a BGPs are a problem, partly due to the reasons mentioned above (can also be caused by the under-sizing of the BGP leading to an oversupply of biogas. Facilitators and masons should be aware of importance of proper BGP sizing
	Breakdown of AD process	Thu et al. (2012) Vietnam, Cheng et al. (2014) Nepal, Chang et al. (2011) China, Sovacool et al. (2015) Kenya	There are many parameters affecting the AD process, such as: an inappropriate pH, an unbalanced C:N ratio, low temperature and large temperature fluctuations, and the existence of inhibitors. Inhibitors can originate from inappropriate cleaning chemicals in pig-pens, feeding additives like growth hormones, antibiotics and heavy metals. There is a need to consider all of aspects and BGP owners must receive sufficient information concerning them.

	Oversupply of biogas	Limmeechokchai and Chawana (2007) Thailand	Consequences are because of farmers releasing biogas into the atmosphere: making a contribution to the GHG due to the presence of methane.
Knowledge related problems			
	Lack of knowledge by respondents Unsatisfactory knowledge of masons Unsatisfactory knowledge of facilitators	Zhou et al. (2011) China, Zurbrugg et al. (2012) Indonesia, Uddin et al. (2012) Banghladesh, Amjid et al. (2011) Pakistan, Agyenim and Gupta (2012) Ghana	There is need for a functioning transmission of information from the large-scale level via local facilitators to the target group of BGP owners
Further non-technical problems			
	Proliferation of mosquitoes (*Anopheles sp.*) on the outer surface of BGP	N/A	The solution may be to cover the surface of the BGP, even if we lose direct access to its surface and risk possible leakages.
	Lack of finance Cultural and social obstacles Political restrictions Lack of land	Singh et al. (1996) Himachal Pradesh, Chen et al. (2012) China, Zhou et al. (2008) China, Zhou et al. (2011) China, Thu et al. (2012) Vietnam	Solving non-technical problems should be within the competence of local facilitators, local authorities and national level authorities

Problem analysis: Structural components

The most frequent problems with structural components were related to the inlet pipe (6 cases), the inconvenient location of BGP components (3 cases) and instability of the BGP during the rainy season (1 case). In this category, the most serious identified fault concerns problems with the inlet pipe; similar results were found in Nepal in the study by Cheng et al. (2014). This problem is mainly associated with an inappropriate angle of the inlet pipe leading to problems with organic matter reaching the digester. Any blockage of the inlet pipe can usually be fixed by using a stream of water or a long stick. The next identified problem concerns the inconvenient location of the BGP, such as in terms of the distance from pig sheds or toilets or from the farm, resulting in poor accessibility and additional difficulties in the operation of the BGP and maintenance. The third problem described centred on the unstable construction of BGPs, especially during the rainy season. This problem can be associated with low-quality workmanship. It is important to realise that skilled builders are a prerequisite for avoiding failures associated with improperly conducted construction.

Problem analysis: Piping systems

The average occurrence of problems in the subsystem of the piping system was 6%. Two problems described in this subsystem were leakages in the piping system and its blockage. The leakages in the piping system (6 cases) were described in the study by Cheng et al. (2014). The second problem described was blockage of the piping system (3 cases), which was also mentioned in a study from Nepal. This problem occurs when the pipe line is left unused for a long time and if no water filter is available. This can result in a build-up of water within the pipe line. Therefore, constant use of the BGP and the use of a water filter are recommended.

Table 4 Main failures in central Vietnam associated with small-scale biogas plants.

Main failures at BGPs	Frequency of appearance (N=141)
Leakage in a reactor	49
Malfunction of a biogas cooker	22
Solid digestate incrustation in the main tank	19
Breakdown of anaerobic digestion process	19
Lack of feedstock/Over-size of BGP	16
Lack of organic matter in digestate	14
Smell of biogas	13
Lack of biogas	11
Lack of knowledge of the owner of BGP	11
Malfunction of biogas lamp	7
Leakage in piping system	6
Poorly accessible reservoir for digestate	6
Problems with the inlet pipe	6
Blockage of the outlet pipe	3
Inconvenient position of BGP components	3
Unsatisfactory skills of masons	3
Unstable BGP construction in rainy season	1
Blockage of piping system	1
Unsatisfactory knowledge of facilitators	1

Problem analysis: Equipment Utilising Biogas

The second highest average occurrence of problems was reported in the biogas utilisation equipment subsystem (25%). The main failure in this subsystem was a failure of biogas cookers to correctly function (22 cases), which was also the second-most common failure in our survey (Table 3). Malfunctions of biogas cookers are diverse in nature and include being the result of corrosion, a broken gas tap, a broken flame pedestal or a blocked air injection hole. Corrosion can be reduced using a H_2S filter (desulfuriser). Other problems can be prevented by appropriate treatment (the use of a suitable level of fire and better maintenance of the cooker) or through the use of better quality cookers. Similar conclusions and problems were found in other studies from Thailand, Vietnam and Nepal (Pipatmanomai et al., 2009; Thu et al., 2012; Cheng et al., 2014). The second problem mentioned by the respondents was linked to malfunctions in biogas lamps (7 cases). However, it is important to note that the use of biogas lamps is declining due to the very favourable price and accessibility of electricity in rural areas.

Problem analysis: Digestate disposal systems

The average occurrence of problems with the digestate disposal system was 17%. This system encounters problems associated with a lack of organic matter (OM) in the digestate (14 cases) and with poorly accessible reservoirs (6 cases). The lack of OM in the digestate is usually caused by the use excessively high water/manure ratios. Knowledge about the use of adequate amounts of water during watering should be conveyed to BGP owners through local facilitators. The lack of OM and nutrients decreases the added value of the digestate, which can be used as an efficient fertiliser (Li et al., 2012; Mwakaje, 2008). When used as a fertiliser, the digestate can improve soil fertility (Alburquerque et al., 2012). This provides advantages over raw manure (Thy et al., 2003), and when used instead of chemical fertiliser, it can reduce the use of non-renewable energy and carbon dioxide emissions (Li et al., 2012). Second, poorly accessible reservoirs contribute to the underuse of digestate. This occurs when a reservoir is inappropriately located and results in further complications with digestate management.

Problem analysis: Anaerobic digestion process and biogas production

The AD process and biogas production subsystem is the main problematic subsystem, producing the highest average occurrence of problems (37%). This subsystem is associated with the main goal of BGPs - to produce biogas. The AD process is a process based on the microbial conversion of organic matter without access to air and is assisted by mixed cultures of microorganisms and the formation of biogas and stabilised biomass called digestate (Molino et al., 2013; Yu et al., 2008). The production of biogas depends on multiple requirements that must be adhered to, including those concerning temperature, pH, nutrients, microorganism concentration, and the absence of oxygen and process inhibitors. When not fulfilled, the process and its effectiveness are threatened. In this category, leakages in the reactor were found and represent the most common problem with small-scale biogas systems. This problem occurred in 49 cases. Leakage in a reactor can be the result of several issues, e.g., unskilled builders and poor construction, high pressures in the digester and the use of inappropriate materials. Problems with leakage in reactors were mentioned in other studies from China (Chang et al., 2011), Nepal (Cheng et al., 2014) and Asia and Africa (Laam and Heegde, 2012). A further problem occurs with solid digestate incrustation floating in the main tank (19 cases), which is the third-most common problem associated with small-scale BGPs (Table 3). This occurs when a solid scum layer is formed on the surface, preventing biogas from passing through and leading the system to stop functioning. When such a problem occurs, the BGP must be opened, and the solid surface must be removed. Another problem was associated with the collapse of the AD process (19 cases). This can be divided into various sub-problems in the subsystem where the cause was known. Another problem described was the lack of feedstock (associated with an over-sized BGP); this was reported in 16 cases. This usually occurs when farmers reduce the number of animals on the farm, and they are no longer able to provide sufficient amounts of organic manure for the BGP. This problem can also occur when animals are not fed regularly, leading to irregular excretion. This is closely associated with the over-sizing of BGPs (or the under-sizing of BGPs). Similar problems were found in India, China, Nepal and other parts of Vietnam (Singh and Sooh, 2004; Chen et al., 2012; Cheng et al., 2014; Thu et al., 2012). The under-sizing of BGPs is associated with the oversupply of biogas, which can also be considered a problem. A common practice when there is an oversupply of biogas is to release some of the biogas into the atmosphere; however, methane is a fundamental greenhouse gas, which contributes to global warming. Similar conclusions were reached in the study from Thailand (Limmeechokchai and Chawana, 2007). Facilitators and builders should be highly familiar with the current situation of prospective BGP owners and be able to calculate a suitable size of a BGP that fits their needs. The smell of biogas was mentioned (13 cases) as another problem and was identified in households without a desulfurisation unit or that did not perform proper maintenance of that unit. This problem was also described in Thailand and other parts of Vietnam (Pipatmanomai et al., 2009; Thu et al., 2012). A simple solution is to use a properly maintained desulfurisation unit. Knowledge about this solution should be provided via facilitators. The last problem found in the target area was insufficient biogas production (11 cases), which can be linked to poor-quality biogas (low concentration of methane), to an insufficient OM supply, or to process collapse. The quality of biogas relies on several factors and is affected by temperature, the presence of oxygen, feedstock, and hydraulic retention time.

Problem analysis: Other non-technical problems

Other non-technical problems are not included in the main subsystems as listed, but naturally, they must be included in our analysis. One of the problems is the proliferation of mosquitoes (Anopheles sp.) on the outer surfaces of BGPs. Respondents reported fears of the possibility of a higher risk of malaria transmission. Other problems were diverse in nature and stemmed from a variety of sources, including a lack of finance for maintenance and repair of BGPs, cultural and social obstacles (use of human excreta as feedstock for BGPs), and certain political restrictions. Further, institutional barriers must also be considered. Non-technical problems with small-scale biogas plants were mentioned in other studies from different countries such as India, China, Thailand and Vietnam (Singh et al., 1996; Chen et al., 2012; Zhou et al., 2008; Suzuki et al., 2015; Thu et al., 2012). The ability to solve non-technical problems should be featured among the competences of local facilitators, local authorities, and authorities at the national level.

Problem analysis: Knowledge-related problems

The importance of proper and adequate knowledge was mentioned several times above, and it is an essential aspect of the implementation of any technology. The average occurrence of problems in this subsystem was 9.1%, but there is a substantial overlap with other subsystems. The most common occurrence was a lack of knowledge of the BGP owners (11 cases), followed by the unsatisfactory skills of builders (3 cases) and the unsatisfactory state of knowledge of facilitators (1 case), the last two as reported by BGP owners. Additional relationships and consequences are listed in Table 5 and in subsequent chapters (variables across small-scale biogas technology). Problems concerning a lack of knowledge were recognised and described in other studies from China, Indonesia, Bangladesh, Pakistan, Vietnam and Ghana (Zhou et al., 2011; Zurbrugg et al., 2012; Uddin and Mezbah-ul-Islam, 2012; Amjid et al., 2011; Roubik and Mazancova, 2014; Agyenim and Gupta, 2012). These studies also highlighted the importance of knowledge and its transmission. There is a need for the efficient transmission of information from the large-scale (national) level to the target group of BGP owners via local facilitators. A proper information flow is essential to the proper functioning of the system and its long-term sustainability.

Payback Period

Based on information from respondents, the payback period was calculated using the PB formula (1). The average installation cost of a BGP was 336.2 (± 94.1) USD, the average donation from the BPAHS programme was 163.6 (± 94.9) USD, and the average financial contribution by the BGP owners was 175.1 (± 99.2) USD. The average PB for a BGP with a subsidy was 2.25 (± 2.04) years; alternatively, it was 4.46 (± 3.22) years without any subsidy. This indicates a 2.26-year change in PB caused by the subsidy programme. This funding is essential to the rapid development of the technology because the main increase in take-up always results from the introduction of financial compensation. Large variances are found in cases where BGPs provide minimal benefits due to the inappropriate maintenance of the BGPs, collapses in the functioning of the BGPs or due to the decision of the BGP owners to reduce the use of this technology (Table 5).

Table 5 Payback Period (PB) of small-scale biogas plants.

PB [comparison between payback time (D) with subsidy and without subsidy] in years	**Mean**	Standard deviation	Minimum	Maximum
D with subsidy (n=98)	**2.25**	2.03	0.26	15.43
D without subsidy (n=98)	**4.46**	3.22	0.53	17.14

Variables across the small-scale biogas technology

Based on our statistical analysis, correlations across the small-scale biogas technology and relevant factors were calculated. Our findings revealed several significant linear relationships, which are present in Table 6. Satisfaction with small-scale biogas technology is mainly influenced by satisfaction with the BPAHS programme, satisfaction with the biogas (quality and amount) and satisfaction with the cooker. Variables affecting biogas cookers and their malfunctions (Table 4) are fundamentally expressed by satisfaction with the technology. Satisfaction with the BPAHS programme is mainly influenced by satisfaction with the technology, with the biogas (amount and quality), and with the biogas cooker; the level and quality of support from facilitators showed the strongest relationship with satisfaction with the BPAHS programme. This demonstrates the importance of a proper information flow between BGP owners and local facilitators. Respondents' satisfaction with biogas is influenced by the level of functionality of the technology and by satisfaction with the BPAHS programme and obviously with the effectiveness of the biogas cookers. Surprisingly, a correlation between the owners' satisfaction with the facilitators and their satisfaction with the biogas cookers was found. This could be caused by the influence of facilitators on the choice of biogas cooker; facilitators often recommend better cookers based on their experience. Therefore, the study recommends improvements in the skills of facilitators, the principle mediators between BGP owners and implementers, because such skills have a direct impact on the quality of training of BGP owners as well as of builders. Facilitators play an important role in addition to purely technical extension work; they become designers of learning scenarios, therein encouraging BGP owners to participate and learn, according to their social and psychological characteristics. This contributes to higher satisfaction among the end users of this technology and their higher involvement in the proper maintenance of the BGPs (Roubik and Mazancova, 2014).

Table 6 Correlation of the various examined variables.

	Problems with BGP	Satisfaction with BGP	Satisfaction with BPAHS	Satisfaction with Biogas	Support from facilitators	Satisfaction with Digestate
ROI in years	-0.125	0.089	0.204	0.149	0.056	0.007
Problems with BGP†	1.000	-0.373	-0.375	-0.369	-0.401	-0.172
Satisfaction with BGP††	-0.373	1.000	**0.569***	**0.671***	0.483	0.224
Satisfaction with BPAHS††	-0.375	**0.569***	1.000	**0.669***	**0.809***	0.247
Satisfaction with Biogas††	-0.369	**0.671***	**0.669***	1.000	0,489	0.141
Support from facilitator ††	-0.379	0.490	**0.809***	0.489	1.000	0.344
Satisfaction with Biogas cooker††	-0.301	**0.636***	**0.622***	**0.660***	**0.525***	0.254
Satisfaction with Digestate††	-0.172	0.224	0.247	0.141	0.344	1.000

Correlation: Marked correlations (*) are significant at level p < 0.05000, N=95
†Questions were coded as Yes/No ††Satisfaction of each case coded with the five point scale: 1-very good, 2-good, 3-moderate, 4-low, 5-very low

Conclusion

Small-scale biogas plants can play a vital role in farming systems and add value to agricultural waste and livestock excreta. This technology offers significant advantages, especially in regard to energy, the environmental and economic development. To provide a more in-depth examination, small-scale biogas technology was divided into six main subsystems: structural components, equipment utilising biogas, piping systems, biogas production, digestate disposal systems, and knowledge. The survey revealed that 29% of surveyed BGP owners had experienced problems with this technology, mainly with the biogas production process and biogas utilisation subsystems. The satisfaction of the respondents is linked to the support received from facilitators and the national programme promoting biogas technology. The programme also produces a decrease in payback period of 2.26 years compared to with no subsidy.

In conclusion, this study provided an innovative problem analysis with respect to the current situation surrounding problems with biogas plants in Thua Thien Hue province in central Vietnam. The study showed the need for further research into the eradication of problems with this technology. There is also a need for additional studies to shed light on the health-threatening components of the use of BGPs to promote alternative ways of using BGPs in developing countries. Furthermore, it is important to facilitate the use of this technology and to make this technology more effective for end users. There is also a need for further education and on-going training regarding the technology and should be supported by a higher frequency of technical visits. The final results of this study will be useful mainly for local authorities, especially for facilitators at the local level, as well as for programme designers and policy makers. Systematic empirical studies of this topic are a high priority for further research activities.

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CHAPTER II. - Biogas Quality across Small-Scale Biogas Plants: A Case of Central Vietnam

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Abstract

Production of bioenergy by the fermentation reaction is gaining attraction due to its easy operation and the wide feedstock selection. Anaerobic fermentation of organic waste materials is generally considered a cost-effective and proven technology, allowing simultaneous waste management and energy production. Small-scale biogas plants are widely and increasingly used to transform waste into gas through anaerobic fermentation of organic materials in the developing world. In this research, the quality of biogas produced in small-scale biogas plants was evaluated, as it has a direct effect on its use (as fuel for biogas cookers), as well as being able to influence a decision making process over purchasing such technology. Biogas composition was measured with a multifunctional portable gas analyser at 107 small-scale biogas plants. Complementary data at household level were collected via the questionnaire survey with the owners of biogas plants (n = 107). The average daily biogas production equals 0.499 m3, not covering the demand of rural households which are using other sources of energy as well. Related to the biogas composition, the mean content of methane (CH_4) was 65.44% and carbon dioxide (CO_2) was 29.31% in the case of biogas plants younger than five years; and CH_4 was 64.57% and CO_2 was 29.93% for biogas plants older than five years. Focusing on the age of small-scale biogas plants there are no, or only minor, differences among tested values. In conclusion, the small-scale biogas plants are sustaining a stable level of biogas quality during their life-span.

Keywords: anaerobic digestion; methane; carbon dioxide; small-scale biogas plants; developing countries

Introduction

In developing countries, environmental pollution and access to energy sources still represent challenges, especially in relation to human and environmental health and economic development (Ahuja and Tatsutani, 2009). Energy influences the status and pace of development; hence, a current challenge for the developing world lies in the available supply of affordable and sustainable eco-friendly renewable energy (SDG 7) (Mengistu et al., 2016a). Energy poverty is exhibited by a lack of access to electricity and clean cooking facilities, which are two elements that are essential to meeting basic human needs (Rahman et al., 2014). Therefore, bioenergy production by fermentation reaction is gaining attraction due to its easy operation and a wide selection of organic wastes feedstock (Thi et al., 2016). Anaerobic fermentation of organic materials is generally considered as a major cost-effective and matured technology (Kinyua et al., 2016) with its dual benefits as a waste management tool and simultaneous energy production (Roubík et al., 2016). Small-scale biogas plants are widely and increasingly used to transform waste into valuable gas in the developing world (Huong et al., 2014; Mushtaq et al., 2016) and may represent an economically feasible technology (Cu et al., 2012; Rodolfo et al., 2016), which is producing biogas as a main product and simultaneously producing digestate (which may be used as fertilizer) as a by-product through waste degradation (Cu et al., 2012; Chiumenti et al., 2015). There are many factors affecting household energy consumption (as well as CO_2 emissions), such as socio-economic factors, household characteristics and geographic factors (Zhang et al., 2015).

The small-scale biogas plants also create a number of indirect environmental, economic, and societal benefits, such as a reduction in deforestation, fewer hours devoted to fuelwood collection or savings on fuelwood/fossil fuels purchasing, decreasing the need to purchase propane for cooking, the creation of jobs, the decrease of organic matter in effluent waters, the decrease of odour, the production of less indoor smoke than other fuels, the production of digestate as a fertilizer and a reduction in greenhouse gas emissions into the atmosphere, if used appropriately (Bruun et al., 2014; Huong et al., 2014; Neupane et al., 2015; Mengistu et al., 2016b; Roubík et al., 2016). According to Zhang et al. (2015) biogas households indicate having over 50% lower greenhouse gas emissions than non-biogas households. Due to above-mentioned benefits, small-scale biogas technology has been widely promoted and financially supported by governments and development aid donors in Asia, including Vietnam (Bruun et al., 2014). Long-term, stable running and maintenance are key points to maximize the benefits of small-scale biogas plant (Zhang et al., 2013; Bruun et al., 2014). However, if these key points are not met, the benefits of this technology may be compromised (Bruun et al., 2014; Kinyua et al., 2016; Truc et al., 2017).

In comparison to other forms of renewable energy (solar energy, biodiesel, bioethanol, wind energy, etc.) biogas production through small-scale biogas plants is relatively simple, decentralised, and can operate under various conditions in tropical regions, such as Southeast Asia, particularly Vietnam. The most common feedstock material is animal dung or human faeces, as it is usually the most problematic waste material in terms of waste management for rural households (Rajendran et al., 2012). An important advantage of small-scale biogas technology and one of the main reasons for the government support is that the technology is a cost-effective method of reducing greenhouse gas emissions and odours from animal manure, if used properly (Chiumenti et al., 2009; Bruun et al., 2014). The biogas produced is mainly used for cooking, heating and lighting, therefore replacing energy sources such as fuelwood, dried dung, coal, or liquid petroleum gas (LPG), commonly used for these purposes in rural households (Cu et al., 2012; Bruun et al., 2014; Kinyua et al., 2016). It is always difficult to adopt new and unknown digester technology within households. Therefore, recommendations for various models implemented within the country are needed. The design of the biogas plants varies based on geographical locations, availability of feedstock and climatic conditions. The most common types of feedstock for chosen Asian countries can be seen in Table 1. In Asia, the fixed dome model is the most commonly used (Kinyua et al., 2016; Zhang et al., 2013). However, there are two exceptions— Indonesia, where various models were applied according to the regions and islands, and India with a prevailing number of the floating drum model followed by the fixed dome (Bhattacharya and Jana, 2009).

Table 1 Most common feedstock for small-scale biogas plants in selected Asian countries.

Country	Most Common Feedstock	Reference
Vietnam	Pig manure	Huong et al., 2014; Roubík et al., 2016
Cambodia	Combination of pig manure and cow manure	Thy et al., 2003
Bangladesh	Cow and buffaloes manure	Khan and Martin, 2015; Kinyua et al., 2016
Laos	Cow manure	Phanthavongs and Saikia, 2013
Nepal	Cow manure	Katuwal and Bohara, 2009
India	Livestock manure	Kaur et al., 2017
Indonesia	Cow manure	Usack et al., 2014; Abdeshahian et al., 2016

In Vietnam, anaerobic digestion of animal manure has already been practiced since the 1960s (Huong et al., 2014; Rodolfo et al., 2016). Since then its popularity has grown, mainly due to the promotion of this technology by the government and international organizations, e.g., SNV (Netherland Development Organization). The Ministry of Agriculture and Rural Development of Vietnam (MARD), together with SNV (using 10% government subsidy for support of capital costs of small-scale biogas technology), installed between 2003 and 2013 over 200,000 small-scale biogas plants (Ghmire, 2013; Kinyua et al., 2016). The follow-up biogas programme by SNV and MARD aimed to build 140,000 biogas digesters between 2006 and 2011. The current number of small-scale biogas plants in Vietnam is more than 500,000 (Khan and Martin, 2016). The target was reached, and digesters serve over 600,000 people with cooking fuel with CO_2 savings of around 260,000 tons per year (SNV, 2014). However, in Vietnam, the biogas technology is still far below its potential for utilizing available livestock and agricultural wastes (Khan and Martin, 2016).

As the small-scale biogas technology is one of the fastest growing and highly promising renewable energy sources, mainly for rural households, the main objective of this paper is to evaluate the quality of biogas produced in the small-scale biogas plants installed in central Vietnam in terms of chemical and physical parameters in relation to the age of installed biogas plants. The quality of biogas has a direct effect on its use (as fuel for biogas cookers), which may, in return, influence an individual decision of purchasing such a technology. Furthermore, biogas quality evaluation is needed to provide sufficient information for authorities to have their future policy decisions well supported.

Materials and Methods

The research was carried out in two districts, Huong Tra and Phong Dien, Thua Thien Hue Province, in Central Vietnam (Figure 1). Huong Tra is a rural district in the northern part of the central coast of Vietnam with a population of over 115,000 inhabitants covering an area of 521 km2. The district is located on the northern outskirts of Hue (provincial city of Thua Thien Hue province) and can, therefore, be considered as a peri-urban area. Phong Dien has a population over 105,000 inhabitants and covers an area of 954 km2. The district has a varied topography with mountains, plains, and coastline.

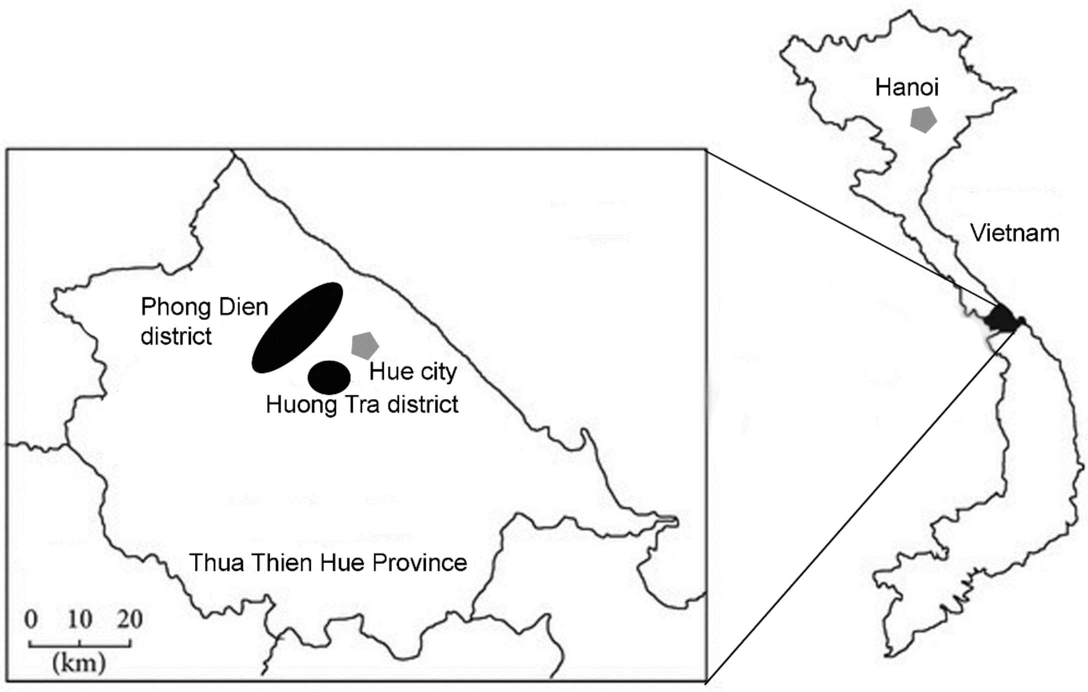
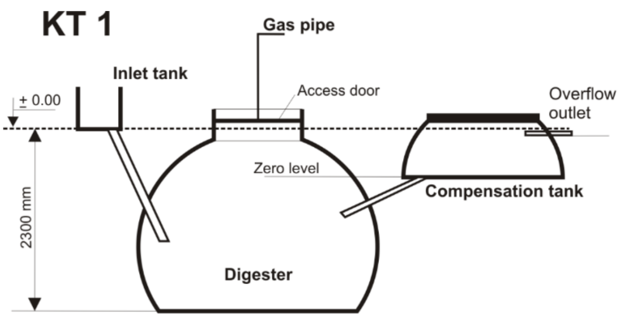


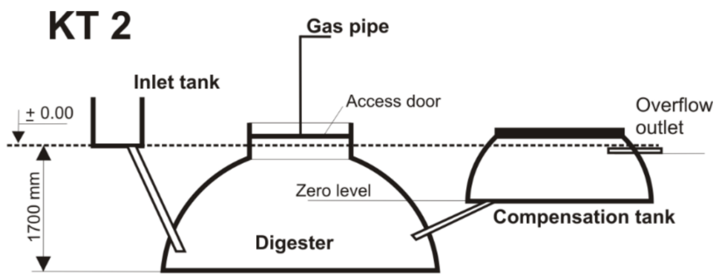
Figure 1 Thua Thien Hue province and the target area.

Description of Biogas Technology in Target Area

The study was done on two types of small-scale biogas plants, specifically KT1 (Figure 2a) and KT2 (Figure 2b). Both types are predominant in the target area. Both types are varieties of the Chinese fixed dome, where KT1 is an appropriate type for a good structure of soil to be easily excavated. KT2 is used in places where soil excavation is difficult or where high levels of groundwater or floods are reported. Both types are unheated and usually built underground, in order to minimize the temperature fluctuations and for space saving reasons. The digester is filled in through the inlet tank and the inlet pipe. The produced biogas is accumulated at the upper part of the digester and the difference between the slurry inside the digester and the digestate in the compensation tank creates a gas pressure. The slurry flows back into the digester from the compensation tank after the gas is released through the gas pipe. Both types and their potential problems are described in detail in the study by Roubík et al. (2016). The Vietnamese small-scale biogas plants operate at the temperature of the surrounding soil as they are built underground. The time of the year significantly influences temperatures in the air, the slurry mixing tank, the soil, and the digesters. The average summer temperatures in Central Vietnam are around 34 °C (mesophilic conditions), creating a suitable environment for the bacterial fermentation; however, during winter time the temperature is in the range of 15–25 °C, which might cause lower biogas production (Cu et al., 2012; Pham et al., 2014).



(a)



(b)

Figure 2 (a) Small-scale biogas plant—fixed dome model (KT1). Reprinted from Roubík et al., 2016. (b) Small-scale biogas plant—fixed dome model (KT2). Reprinted from Roubík et al., 2016.

Data Collection—Questionnaire Survey

The questionnaire survey was carried out with the owners of small-scale biogas plants from June to July 2013. Biogas plants were randomly selected from recipients of government subsidies (n = 107; corresponding to 20% share of total subsidy recipients in the area) listed by the local unit of the Ministry of Agriculture and Rural Development. The recipients were, at the same time, beneficiaries of one of two running projects on building small-scale biogas plants—one supported by the SNV, the other one by the Czech Development Agency (CzDA) (see Figure 2). The questionnaire included nine questions (Table 2). Furthermore, the data results were cross-checked with the local facilitators during field trips in July and August 2016 in order to increase their validity and reliability.

Figure 3 Sign of the project supported by CzDA and implemented by CULS Prague,

Table 2 Overview of variables in the questionnaire.

Variable	Type of the Question	Value	Unit
Capacity of the digester	Close-ended question	No.	m^3
Investor of the construction	Close-ended question	SNV/CzDA	-
Digester type	Close-ended question	KT1/KT2	-
Digester connection to the toilet	Open-ended question	-	-
Animal stable	Open-ended question	-	-
Feedstock materials for the BGP	Open-ended question	-	-
No. of animals	Open-ended question	No.	Heads
No. of other applications powered by biogas	Open-ended question	No.	-
Digestate practices	Open-ended question	-	-

Data Collection—Biogas Composition

There are many analytical methods for biogas quality evaluation based on its final use (Zamorska-Wojdyla et al., 2012). From the technical point of view, the most important parameter is the content of the potentially corrosive components (oxygen, hydrogen, water, carbon dioxide, hydrogen sulphide, and chlorine and fluorine compounds) (Rasi, 2009; Rasi et al., 2011). Biogas composition was measured using a GA5000 multifunctional portable gas analyser (Geotech, Leamington Spa, UK), which is adapted to measurements of CH_4, CO_2, O_2, H_2, and H_2S with the following measurement accuracy of: CH_4 (0–70 vol % ± 0.5%), CH_4 (70–100 vol % ± 1.5%), CO_2 (0–60 vol % ± 0.5%), CO_2 (60–100 vol % ± 1.5%), O_2 (0–25 vol % ± 1.0%), H_2S (0–5000 ppm ± 2.0%), and H_2S (0–10,000 ppm ± 5.0%). For measurements of media (CH_4/CO_2) a dual-wavelength infrared sensor was used, for O_2/H_2S an internal electrochemical sensor was used. The measurements were taken upstream of the H_2S filter to eliminate measurement inaccuracies. Obtained values are the mean of three measurements in the interval of one hour at each biogas plant. Calorific values were set as the quantity of heat produced by complete combustion of a unit of a combustible compound. In total, the measurements were taken in 81 KT1 small-scale biogas plants and 26 KT2 small-scale biogas plants at districts Huong Tra (n = 49) and Phong Dien (n = 58), Thua Thien Hue Province.

Data Analysis

The collected data were categorized, coded, and analysed with descriptive and inferential statistics using the SPSS version 18. Effects of variables such as type of biogas plant, age of the biogas plant, and size of the biogas plant on biogas composition were analysed by the analysis of covariance model. Dummy variables included the type of biogas plant (KT1 and KT2), the age of the biogas plant (>5 years old and <5 years old), and a continuous variable of the size of the biogas plants (m3).

$$\mathrm{Y_i} = \alpha + \beta \mathrm{x_1} + \gamma_1 \mathrm{D_{i1}} + \gamma_2 \mathrm{D_{i2}} + \varepsilon_\mathrm{i} \qquad (1)$$

Yi = Biogas composition;

α = Intercept;

x1 = Biogas plant size (m3);

Di1= Biogas plant types (Di1 = 1 = KT2; Di1 = 0 = KT1);

Di2 = Biogas plant age (Di2 = 1 < 5 years; Di1 = 0 ≥ 5 years);

β = Regression coefficient of biogas plant size on biogas composition;

$\gamma 1$ = The difference of biogas composition between KT2 and KT1;

$\gamma 2$ = The difference of biogas composition between < 5 year and >= 5 year old biogas plants; and

εi = Error term.

Results and Discussion

Feedstock Used for Biogas Production

The majority of respondents (90%) are farmers producing mainly rice. However, many of them are also involved in additional off-farm activities, such as trade, rice noodle production, and rice wine production. All questioned households use pig slurry as their main feedstock for biogas plants and, in all cases, pigs were housed in concrete pigpens (with a concrete floor). Feedstock manure from other animals (65%) is also used as an additive within the surveyed households. This included chicken manure (29%) and human excreta (36%) (Figure 4). These additives are added if they are available in sufficient quantities. In every household, the pigpen is connected directly to the biogas plant, and in 37% of cases toilet outflows are connected to the biogas plant as well. Only in one case was a chicken shed was connected to the biogas plant; in the rest of cases the chicken manure is put in the digester inlet manually. Generally, the feedstock input was unified as biogas owners were recipients of one of two running projects on building small-scale biogas plants and there were criteria on the necessary number of pigs. In addition, further details regarding manure management practices of small-scale farmers in Vietnam can be seen in our previous study (Roubík et al., 2018).

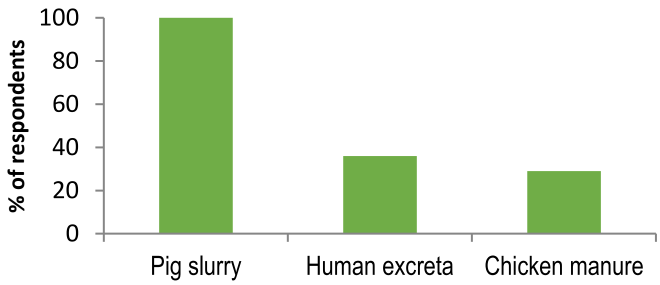


Figure 4 Feedstock used for biogas production (Multiple choices were possible) (n = 107).

Use of Products of Small-Scale Biogas Technology within the Rural Households in Central Vietnam

Small-scale biogas plants have been applied as an optimal livestock waste treatment in Vietnam since the 1960s and, although the history of this technology is rather old, the number of the constructed biogas plants is still limited. With the current number of units around 500,000 (Kinyua et al., 2016; Khan and Martin, 2016) it is still far below the real demand on livestock waste treatment (Nguyen, 2011; Rodolfo et al., 2016) that has increased significantly in the last decade (Huong et al., 2014). The primary use of biogas is for cooking (Roubík et al., 2016). However, it could also be used for lighting in remote areas where electrification is limited (Ghmire, 2013). Furthermore, biogas plants produce residue from the process in the form of digestate, which can be applied as organic fertilizer to enhance agriculture production (Rodolfo et al., 2016; Truc et al., 2017). On a daily basis, a minimum of 20 kg of organic waste is required to operate the smallest biogas plants (4 m3) in the area. Therefore, there is a required number (five growing pigs) of pigs (manure, respectively) to meet the feedstock needs of these plants. This quota is usually met, as the average number of animals in the area is 13–14 piglets and 2–3 sows (Roubík et al., 2016; Roubík et al., 2018).

Biogas for Cooking and Water Boiling

In developing countries, biogas produced from the household biogas plants is used mainly for cooking (Ghmire, 2013). This is also applied to the present study, where 100% of households use biogas primarily for cooking, with an average time of 2.8 h/day. Biogas is usually used primarily for household cooking and boiling water and, afterwards, for cooking of feed for pigs. An average daily production of biogas is 0.499 m^3 (±0.086). Such an amount used for cooking purposes may represent about 8–10 m^3 and 96–120 m^3 of biogas per month and year, respectively. However, according to the study by Vu et al. (2012), the biogas volume needed for a typical farming household of six people is 0.8 to 1 m^3 per day. This difference between average daily biogas productions could be explained by Sasse et al. (1991), as he states that the fixed dome biogas digesters can annually leak around 55% of CH_4 and the production of biogas is also dependent on the temperature of the feedstock. Therefore, the majority of respondents (60%) are still using additional energy sources in form of LPG and/or electricity (for cooking rice in rice cookers) and fuelwood (usually only for cooking of feed for animals).

Biogas for Lightning and Power Generation

The other major possible application of biogas may be for lighting and power generation. Biogas lamps are more efficient than kerosene-powered lamps, but their efficiency is quite low compared to electric-powered lamps (Rajendran et al., 2012). In addition, electricity is now widely available in Vietnam; therefore, use of biogas lamps is very occasional. In the case of our respondents, less than 10% were using biogas lamps. Farmers usually prefer biogas for cooking instead of lighting; also, from the reason that 1 m^3 of biogas is equal to lighting of 60–100 watt bulbs for around 6 h, or cooking 2–3 meals a day for 5–6 persons. As observed during interviews with the farmers, power generation is favoured when farmers have an abundance of biogas. In that case, they purchase a combustion engine, which converts biogas into the mechanical energy in a heat engine and, consequently, the mechanical energy activates a generator to produce electrical power.

Digestate

The residue remaining after treatment (anaerobic digestion) in the biogas plant is called digestate. The use of digestate as a fertilizer is considered beneficial since it provides nutrients (N, P, K) which are easily accessible to plants. Digestate can be applied directly through the overflow outlet or manually. Another option is through pre-treatment (e.g., drying) before application. However, this possibility is used only sporadically. The most common practice is the usage of the digestate directly to the surrounding household home gardens and use of mainly solid parts of digestate as a crop fertilizer for rice. Another way of usage (especially of liquid manure and slurry) is partly limited by a long distance between the biogas plant location and the rice field. In 25% of cases, farmers use digestate as a fertilizer for vegetable and home-garden, which is a very popular way because of its simplicity and convenience for the farmers. Study also showed that usage of digestate for fish feeding is still not adopted in this area, as none of the respondents used digestate for such purpose even though its benefits were proven in the study by Nhu et al. (2015) focused on pig-biogas-fish systems.

Biogas Composition in Various Types of Small-Scale Biogas Plant (KT1 and KT2)

The performance of two models of biogas plants (KT1 and KT2) was observed in order to show the differences between these two types. It was revealed that the KT2 digester has demonstrated a slightly higher production of CH_4 (66.23%) and, at the same time, lower production of carbon dioxide (28.27%) (Table 3). Furthermore, slight differences might be seen among other variables, such as content of O_2, NH_3, or H_2S (Figure 5). Nitrogen, hydrogen, and water vapour were collectively marked as NHW, where slight differences were also recognized. However, factors, such as organic input, or maintenance might be the cause of these discrepancies. Furthermore, Table 4 shows a comprehensive review of biogas composition from small-scale biogas plants reported by other studies from developing countries. As is shown, CH_4 varies from 50% to 75%, and CO_2 from 25% to 50%. Other elements (N_2, CO, O_2, and H_2S) are below 2% in general and, respectively, 1% in case of H2.

Table 3 Biogas composition according to the type of biogas plant, KT1 (n = 83) and KT2 (n = 24).

Variable	Type of Biogas Plant	Mean	95% Confidence Interval	
			Lower Bound	Upper Bound
CH_4 (vol %)	KT1	63.79	62.94	64.63
	KT2	66.23	64.70	67.76
CO_2 (vol %)	KT1	30.97	30.04	31.89
	KT2	28.27	26.59	29.94
NH_3 (vol %)	KT1	0.05	0.04	0.05
	KT2	0.04	0.03	0.05
H_2S (vol %)	KT1	0.10	0.07	0.14
	KT2	0.16	0.09	0.22
CH:CO_2 index	KT1	2.14	2.02	2.25
	KT2	2.24	2.03	2.44
Calorific value (MJ/m^3)	KT1	21.60	21.31	21.89
	KT2	22.36	21.84	22.88

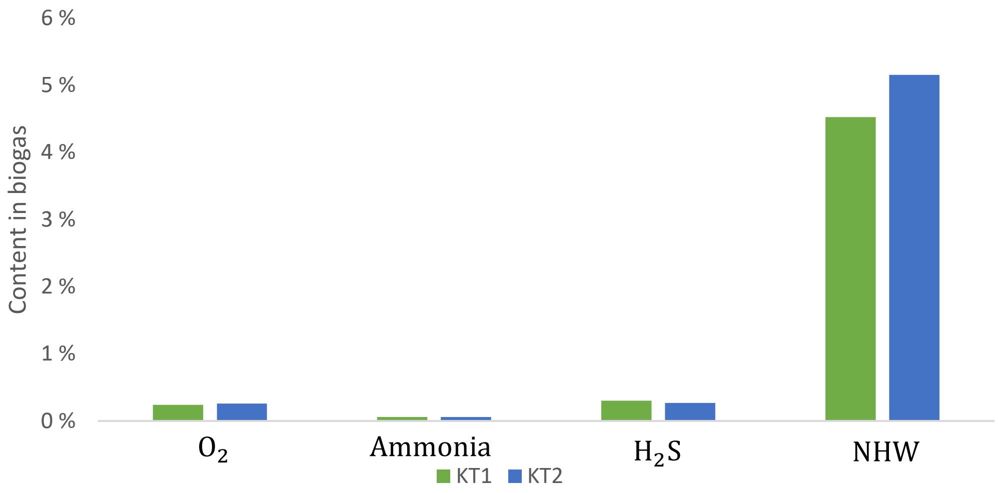


Figure 5 Performance of two models of biogas plants.

There is also the need to take into consideration the substances that can cause operation difficulties (dust, oils, and siloxanes) (Zamorska-Wojdyla et al., 2012). For the purposes of this study, another biogas quality indicator represented by methane and carbon dioxide index (CH_4:CO_2) was set up. This parameter characterises the relation between the content of CH_4 and CO_2 as two major substances influencing the final quality of biogas. From this point of view, a higher index means a higher quality of biogas.

Table 4 Biogas composition from small-scale biogas plants recognized in previous studies.

Feedstock	CH_4 (vol %)	CO_2 (vol %)	N_2 (vol %)	CO (vol %)	O_2 (vol %)	H_2 (vol %)	H_2S (vol %)	Type of BGP	Country	Reference
Animal wastewater	61–72	-	-	-	-	-	0.0043–0.0084	Tubular PVC	Costa Rica	Lansing et al., 2008
Livestock manure	64	34	1.05	0.3	-	0.6	0.05	Floating dome	Pakistan	Mushtaq et al., 2016
Livestock manure	56.2	39.51	-	1.91	-	-	1.84	Laboratory conditions	Nigeria	Adegun and Yaru, 2013
Livestock manure	50–75	25–45	<2	-	<2	<1	<1	Not specified	Developing countries	Bond and Templeton, 2011
Livestock manure	60	35–40	-	-	-	-	-	Not specified	Malaysia	Abdeshahian et al., 2016
Organic waste	50–75	25–50	-	-	-	-	-	Not specified	Developing countries	Surendra et al., 2014
Organic waste	60	-	-	-	-	-	-	Fixed dome	Sub-Saharan Africa	Tumwesige et al., 2014
Generalized values	**50–75**	**25–50**	**< 2**	**< 2**	**< 2**	**< 1**	**< 2**	**-**	**-**	**-**

All surveyed small-scale biogas plants (n = 107) (Figure 6) showed in the average content of methane (CH_4) in biogas of 64.57% (±2.85) and the carbon dioxide (CO_2) of 30.20% (±3.10). The average presence of NH_3 was 0.05% (±0.02) and the presence of H_2S of 0.25% (±0.12). The average value of CH_4:CO_2 index was 2.20 (±0.35). The average calorific value of biogas produced by plants was 21.83 MJ·m^{-3} (±0.96), which corresponds with the typical value of 21–24 MJ·m^{-3} (Bond and Templeton, 2011).

Figure 6 Visit at the small-scale biogas plant.

Biogas Composition According to Various Ages of Small-Scale Biogas Plants

The results presented in Table 5 is uncovering differences between small-scale biogas plants younger than five years and older than five years and its effect on various aspects of biogas quality. However, as shown in Table 5, there are no, or only minor, differences among tested values. This fact leads us to the conclusion that small-scale biogas plants using pig slurry as a main feedstock are sustaining a stable level of biogas quality during their life-span. Especially for the main indicators, which are volume of CH_4 in biogas, CH_4:CO_2 index and calorific value of biogas.

Table 5 Biogas composition from small-scale biogas plants younger than five years (n = 82) and older than five years (n = 25).

Variable	Small-Scale Biogas Plants Younger than Five Years			Small-Scale Biogas Plants Older than Five Years		
	Mean	95% Confidence Interval		Mean	95% Confidence Interval	
		Lower Bound	Upper Bound		Lower Bound	Upper Bound
CH_4 (vol %)	65.44	64.58	66.30	64.57	63.05	66.09
CO_2 (vol %)	29.31	28.37	32.25	29.93	28.27	31.58
NH_3 (vol %)	0.04	0.04	0.05	0.04	0.03	0.05
H_2S (vol %)	0.12	0.08	0.16	0.14	0.07	0.20
CH_4:CO_2 index	2.26	2.14	2.38	2.12	1.91	2.32
Calorific value (MJ/m^3)	22.08	21.79	22.39	21.87	21.36	22.39

Biogas Composition as Affected by Type, Age, and Capacity of the Biogas Plant

There was an effort to identify the factors that fundamentally influence the biogas quality (Table 6), therefore, the effects of variables of the type of biogas plant, the age of the biogas plants, and the size of the biogas plants on biogas composition were analysed. Firstly, the age of the biogas plant was tested as a relevant factor potentially influencing various aspects of the biogas quality. As demonstrated in Table 6, all biogas composition factors (including amounts of CH_4, CO_2, NH_3, H_2S, CH_4:CO_2 index, and calorific value) were not significantly affected by the age of biogas plant ($p > 0.05$). Secondly, the type of the biogas plant was tested as a relevant factor, using KT1 and KT2 models for comparison. As shown in Table 6, CH_4, CO_2, and calorific value were recognized as significantly influenced by the type of biogas plant ($p < 0.01$). The results show that KT2 model demonstrated a higher percentage of CH_4 and, consequently, a higher calorific value and a lower percentage of CO_2 of produced biogas. Another factor under the examination was the digester capacity (size). The results show different CH_4 contents, CH_4:CO_2 index values, and calorific values according to the digester capacity (size).

Table 6 Biogas composition as affected by type, age, and capacity of the biogas plant.

Dependent Variable	Parameter	Coefficient	Std. Error	*t*-Value	*p*
CH_4 (vol %)	Intercept	62.02	1.92	32.32	0.00
	Type of digester [a]	−2.44	0.82	−2.99	0.00
	Age [b]	0.87	0.81	1.08	0.28
	Digester capacity (m^3)	0.52	0.22	2.36	0.02
CO_2 (vol %)	Intercept	30.00	2.10	14.32	0.00
	Type of digester [a]	2.70	0.89	3.03	0.00
	Age [b]	−0.62	0.88	−0.70	0.49
	Digester capacity (m^3)	−0.20	0.24	−0.81	0.42
NH_3 (vol %)	Intercept	0.04	0.02	2.64	0.01
	Type of digester [a]	0.01	0.01	0.81	0.42
	Age [b]	0.00	0.01	0.67	0.51
	Digester capacity (m^3)	0.00	0.00	−0.25	0.80
H_2S (vol %)	Intercept	0.23	0.08	2.73	0.01
	Type of digester [a]	−0.05	0.04	−1.54	0.13
	Age [b]	−0.02	0.04	−0.51	0.62
	Digester capacity (m^3)	−0.01	0.01	−0.87	0.39
$CH_4:CO_2$ index	Intercept	1.56	0.26	5.96	0.00
	Type of digester [a]	−0.10	0.11	−0.87	0.39
	Age [b]	0.14	0.11	1.29	0.20
	Digester capacity (m^3)	0.08	0.03	2.78	0.01
Calorific value (MJ/m^3)	Intercept	20.96	0.65	32.14	0.00
	Type of digester [a]	−0.76	0.28	−2.73	0.01
	Age [b]	0.21	0.27	0.77	0.45
	Digester capacity (m^3)	0.18	0.07	2.38	0.02

Conclusions

Small-scale biogas plants can be a very useful tool for manure management and may help reduce global warming impacts if used appropriately. This technology offers a unique set of benefits, as it is a sustainable source of energy, it is benefiting the environment, and it provides a way to treat and reuse manure. However, if used inappropriately, its benefits may be compromised. In this study, the most common feedstock for a small-scale biogas plant was pig slurry, followed by a combination of pig slurry and human excreta. The majority of biogas plants were connected with the pig stable, or by latrine and stable. An average daily production of biogas equals to 0.499 m3, which does not cover the demand of rural household with six members. Hence, 60% of surveyed households are still using other sources of energy as well. Biogas composition was measured with a multifunctional portable gas analyser. The mean content of methane (CH_4) was 65.44%, and for carbon dioxide (CO_2) was 29.31% in the case of biogas plants younger than five years and, respectively, CH_4 was 64.57% and CO_2 29.93% for biogas plants older than five years. The only dependent factor influencing the biogas quality was between biogas plant size and biogas composition, which was proven at CH_4, CH_4:CO_2 index, and the calorific value. Furthermore, type of the biogas plant affected CH_4, CO_2, and the calorific values of the biogas. Focusing on the influence of age of small-scale biogas plants there are no, or only minor, differences among tested qualitative biogas parameters. Concluding, that small-scale biogas plants sustaining a stable level of biogas quality during their life-span.

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CHAPTER III. - Small-scale biogas plants in central Vietnam and biogas appliances with a focus on a flue gas analysis of biogas cook stoves

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Author was responsible for the idea, conceptualization, methodology, data collection, performed all experimental work, analysed the data, wrote the original manuscript, and executed its revision.

Abstract

The major objective of this paper is to fill the research gap regarding small-scale biogas appliances by performing a flue gas analysis of biogas cook stoves in Vietnam. The methods of data collection included a questionnaire survey of rural households (n = 93), discussions with local consultants (n= 6) and observations in central Vietnam. Furthermore, flue gas analyses of biogas cook stoves were performed (n = 93). As the most common appliances, biogas cook stoves were reported as a substitute for conventional cook stoves, eliminating indoor smoke pollution and related health risks. The majority (96%) of biogas cook stoves were two-flame burners that averaged 2.4 (±0.74) years of age and were in use for over 3 hours per day. High concentrations of CO in its diluted (8,705.35±1,790.01 mg·m^{-3}) and undiluted forms (24,758.2±4,860.2 mg·m^{-3}) were detected in biogas flue gas. The concentration of unavoidable produced NO averaged 0.064 (±0.12) mg·m^{-3}, which is an acceptable value for the transformation of biodegradable wastes into biogas that is consequently burned. The study contributes to covering the data gap, as similar studies have not been conducted in Vietnam. The information and data gained are important for further evaluations of biogas technology in Vietnam and other developing countries.

Keywords: biogas technology; cook stoves; Vietnam; flue gas analysis; emission

Introduction

Quickly rising populations (currently estimated at 92.53 million in Vietnam (IMF, 2016)) and economic progress in the last decade have contributed to the dramatic increase of the livestock sector in Vietnam (Ho et al., 2015; Vu et al., 2015). These changes call for appropriate manure management strategies to minimize potential negative impacts on the environment (Roubík et al., 2016). With the growth of these small-scale farms, Vietnam is facing problems associated with animal waste management (such as environmental pollution and greenhouse gas emissions) (Roubík et al., 2017).

As is common in other developing countries in Southeast Asia, most livestock farms are small-scale farms in Vietnam. In the past, manure from small-scale farms was mainly used for composting or fish feeding or was directly discharged into lagoons behind the pigpens or rivers and lakes, which caused the uncontrolled spread of pathogenic microorganisms and was an environmental threat (Vu et al., 2007; Ho et al., 2015; Roubík et al., 2016; Roubík et al., 2018). Furthermore, rural households are highly dependent on fuelwood and forest residues for their energy needs (Subedi et al., 2014), as they inefficiently burn these resources and can consequently become exposed to hazardous pollutants such as respirable suspended particulate matter, carbon monoxide and nitrogen oxides (Semple et al., 2014; Shane and Gheewala, 2017). These pollutants, as noted by Fullerton et al. (2008) and Xiao et al. (2015), may be directly linked to the risk of cancer, cardiovascular diseases and increased risk of respiratory diseases.

As an alternative to traditional methods, the anaerobic digestion (AD) of manure in small-scale biogas digesters has a number of advantages (Dhingra et al., 2011; Naik et al., 2014; Vu et al., 2015), such as the purification of pig slurry (Yen-Phi et al., 2009); the provision of renewable energy in the form of biogas used mainly for home cooking (Lu et al., 2006; Zhang et al., 2013; Naik et al., 2014), water boiling and lightning; and the provision of digestate used as fertilizer, energy source or for fish feeding (Adu-Gyámfí et al., 2012; Wu et al., 2014; Ho et al., 2015; Brunerová et al., 2016). Biogas technology is simple in design and construction, low-cost, effective and locally available (Yen-Phi et al., 2009); therefore, it can contribute to solving environmental (Dhingra et al., 2011), energy, economic and social issues (Cu et al., 2012). For these reasons, the technology has become popular (Ho et al., 2015).

Although biogas technology was introduced nearly 30 years ago, the number of constructed small-scale biogas plants is still limited and far below the real demand for livestock waste treatment, which has increased significantly (Nguyen, 2011; Roubík et al., 2017). Biogas production technology has extensive environmental benefits in comparison with conventional technologies, as well as in comparison with other forms of renewable energy (Lu et al., 2006; Zhang et al., 2013; Pehme and Veroman, 2015). However, if technology is inappropriately managed, its benefits may be compromised (Bruun et al., 2014; Roubík et al., 2016). Furthermore, there are still some unscrutinised factors associated with biogas technology that must be examined. Notably, flue gas analyses of biogas cook stoves must be formed to determine the quality of combustion (Obada et al., 2014a; Malaťák et al., 2016), which has a direct effect on the service life of the equipment (Roubík and Mazancová, 2016).

Understanding the concentrations and determinants of exposure to combustion-derived pollution in households that use biomass fuels is necessary for the adequate design, implementation and evaluation of prevention policies (Fullerton et al., 2009). The World Health Organization recommends that $PM_{2.5}$ (particulate matter less than 2.5 microns in diameter) exposure averaged over 24 hours should not exceed 25 $\mu g \cdot m^{-3}$, and 24-hour exposure to CO should be kept below 7 $\mu g \cdot m^{-3}$ (WHO, 2010). The study by Fullerton et al. (2009) implied that it is common to see household PM2.5 exposure reach peak values that exceed 500 $\mu g \cdot m^{-3}$ and see 24-hour average values range from 100-300 $\mu g \cdot m^{-3}$. These values (over 120 $\mu g \cdot m^{-3}$) are often found in houses that burn charcoal and fuelwood (Fullerton et al., 2009). It is essential to realize that switching from the combustion of wood and charcoal to biogas as the primary household energy source (mainly in terms of meal preparation) has the potential to lead to substantial reductions in $PM_{2.5}$ and CO exposure (Semple et al., 2014). The expected emission reductions achieved by shifting from fuelwood and/or charcoal to biogas are likely to be large, although there are some uncertainties (sustainable use of biogas plants, incidence of complications, level of adoption of the technology and the emissions from the biogas cook stoves). Household biogas cook stoves (various models), although individually small in size, are numerous and thus have the potential to significantly contribute to inventories of GHGs (Obada et al., 2014b) and to influence the emissions exposure of household users in a significant way. Emitting a substantial amount of fuel carbon as a product of incomplete combustion (such as carbon monoxide, methane and total non-methane organic compounds, as well as carbon dioxide) can be expected (Ramana, 1991; Roubík and Mazancová, 2016; Malaťák et al., 2016).

Global warming, which is caused by increasing emissions of CO_2 and other greenhouse gases (GHGs) as a result of human activities, is one of the major threats currently confronting the environment (Fan et al., 2007). CO_2 accounts for the largest share of GHGs globally (Fan et al., 2007), and CO_2 from agricultural activities accounts for approximately 13.5% of total GHG emissions (Phan et al., 2012). If emissions are allowed to increase without limits, the greenhouse effect can possibly destroy the environment for humans and other living creatures and even threaten the existence of humankind (Fan et al., 2007).

Therefore, the major objectives of this paper are to extend the research of Roubík and Mazancová (2016) in Sri Lanka, to continue to fill the gaps associated with small-scale biogas appliances, and to perform a flue gas analysis of biogas cook stoves in developing countries. This survey provides an in-depth understanding of these issues by considering the possible risks. This topic remains a continuing concern with the need for biogas technology in rural areas of developing countries.

Materials and Methods

Target area, data collection methods and statistical analysis

The research was carried out in 93 rural households in two districts, Huong Tra (n=37) and Phong Dien (n=56), which are located in the province of Thua Thien Hue in central Vietnam (Figure 1). Huong Tra is a rural district in the north part of the central coast of Vietnam with a population of over 115,000 inhabitants covering an area of 521 km2. The district is located on the northern outskirts of Hue and can therefore be considered a peri-urban area. Phong Dien has a population of over 105,000 inhabitants and covers an area of 954 km2. The district has a varied geography with mountains, plains and coastline.

Methods of data collection included a questionnaire survey at the level of biogas plant owners (n = 93), discussions with local consultants (n = 6) and observations. Furthermore, flue gas from biogas cook stoves was analysed in all households surveyed.

The questionnaire survey was used to obtain information about biogas technology owners, time spent on the maintenance of biogas technology, the funding and economic aspects of the technology, types of inputs, hours spent cooking, digestate practices and information about biogas cook stoves. The questionnaire consisted of closed and open-ended questions focused on various categories (Table 1). The questionnaire survey of head of households was given at all visited biogas plants using stratified sampling between August and September 2014. To increase the survey validity, the data and results were cross-checked with local facilitators during field trips in July and August 2016.

Table 1 Main categories of the questionnaire.

Categories	Main issues
Information about the biogas plant and its maintenance	Type, volume, age, cleaning, connection of latrine to the biogas plant
Information about biogas cook stoves	Type, price, age, frequency of use
Information about the cooking routine	Time, frequency, type of meals prepared, etc.

Information about biogas	Quantity, quality
Use of other fuels	Type, frequency, costs, availability
Livestock	Type, quantity, weight, potential for biogas production

Collected data were categorized, coded and analysed in Microsoft Excel 2013. Due to the nature of the data, Spearmen's correlation coefficient (ϱ) was used to detect possible relations between the recalculated concentration of CO_2 from the flue gas analysis and the (i) age of biogas cook stoves, (ii) connection of a biogas plant to a toilet (using human excreta as co-feedstock), (iii) size of a biogas plant, (iv) daily usage of a biogas cook stove. ANOVA was used to determine possible variances in the flue gas analysis of biogas cook stoves among districts (Huong Tra and Phong Dien) and the concentration of CO_2 from flue gas among various communities.

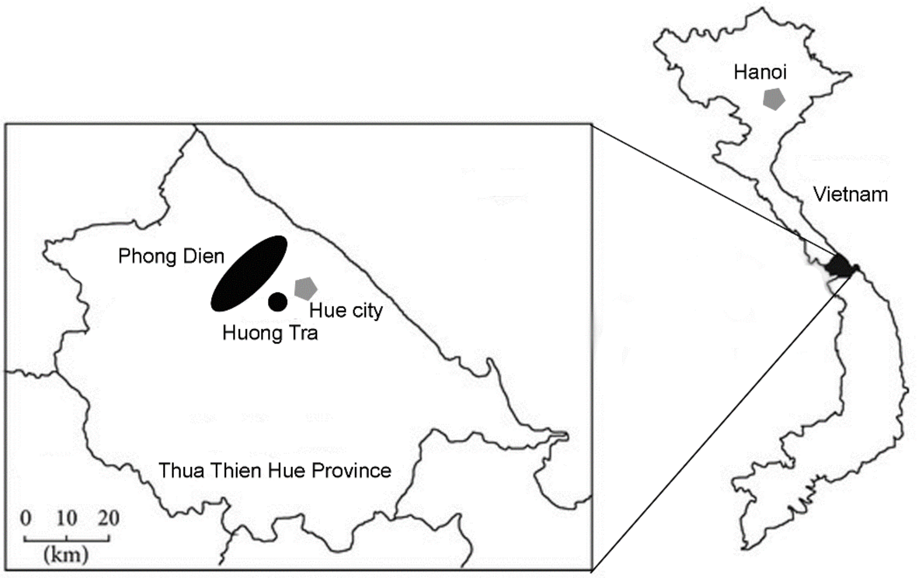

Figure 1 Map of the target area (central Vietnam, Thua Thien Hue Province; adopted from Roubík et al., 2018).

Flue gas analysis

The flue gas analysis of combusted biogas was performed by placing the probe into the flue gas stream for up to 240 seconds, based on when the flue gas reading stabilized, at every visited small-scale biogas plant (n=93). The equipment used included a portable device TESTO 330-2 (Testo AG, Germany), which is capable of capturing the gas concentrations of CO and NO by recalculating the concentrations of CO_2 and NO_2. As specified by the manufacturer (Testo AG, Germany), the recommended minimum measurement time for obtaining accurate values is 3 minutes for a 90% response. After every measurement, the device was flushed according to the recommended flushing times (automatically established by the device according to the ppm concentrations).

The principle of recalculating the mass concentration of CO_2 is as follows:

$$CO_2\ [mg \cdot m^{-3}] = \frac{[CO_{2max} * (O_{2ref} - O_2)]}{O_{2ref}} \qquad [1]$$

where:

$CO_{2}max$ - maximal concentration of CO_2 [mg·m-3]

$O_{2}ref$ - reference oxygen value (21%)

O_2 - measured concentration in %.

The principle of recalculating the mass concentration of CO is as follows:

$$CO\ [mg \cdot m^{-3}] = \left[\frac{O_2 - O_{2refer}}{O_{2ref} - O_2}\right] * CO_{ppm} * 1.25 \qquad [2]$$

where:

$O_{2}refer$ - cross-referential oxygen value (3%, according to the manual-Testo AG, Germany).

The principle of recalculating the mass concentration of NOx is as follows:

$$NO_x[mg \cdot m^{-3}] = \left[\frac{O_2 - O_{2refer}}{O_{2ref} - O_2}\right] * NO_{x\,ppm} * 2.05. \qquad [3]$$

The conversion factors (1.25 and 2.05 for the concentrations of CO and NOx, respectively) are applied in the above formulas [2] and [3] correspond to the standard density of the relevant gas in mg m^3. For NOx, the standard density of NO^2 is used because only NO^2 is a stable compound and NO reacts very quickly with oxygen (Testo, 2011).

Results and Discussion

Practices of small-scale biogas plant users

Small-scale biogas plant users use pig manure as a primary source of feedstock (Figure 2). The average surveyed farm with a biogas plant disposed of manure from 1.80 (± 0.85) swine and 10.17 (± 4.80) piglets. These livestock values corresponded with those noted by Roubík et al. (2016) and Roubík et al. (2018). The average weight of a piglet was almost 22 (± 12.75) kg and that of a sow was almost 80 (± 24.43) kg (more details in Table 2). Pigs in the area are commonly fed with commercial feed that is high in protein and carbohydrates, in addition to local feed or a mixture of both. Local feed typically consists of agricultural residues, such as rice and rice bran mixed with kitchen waste residue (used by all households), sweet potatoes, banana tree parts, water hyacinth, and soybean or cassava leaves, among others.

Figure 2 A woman from a Vietnamese rural household flushing pig manure into the biogas plant (left); Pigs in a concrete pigpen (right).

Cu et al. (2012, 2015) reported similar findings, as confirmed in a previous study by Roubík et al. (2016). The ratios of feed type were different and highly variable in time and primarily depended on the current conditions and the availability of feed resources. Hence, the volume and composition of manure were also highly variable. Biogas or firewood was used to prepare the pig feed depending on the amount of biogas produced. Additionally, an average of 1.3 hours per day of additional fuelwood collection was reported in 49.6% of cases. It is important to realize that biogas mainly competes with (free) solid biomass in central Vietnam; however, as calculated by Roubík et al. (2016), the average payback period for biogas plant with a subsidy was 2.25 (±2.04) years; alternatively, it was 4.46 (±3.22) years without a subsidy, which is acceptable for most farmers.

Table 2 Characteristics of raised swine and pigs in small-scale households (n=93).

No. of swine	**No. of Households %**	**No. of piglets**	**No. of Households %**
0	56.99	0	31.18
1-2	30.11	1-5	10.75
3-5	8.60	5-10	27.96
6-10	3.23	11-20	26.88
11-20	1.08	21+	3.23
Average weight of a swine	**No. of Households %**	**Average weight of a piglet**	**No. of Households %**
Less than 50 kg	18.18	Less than 10 kg	27.78
51-100 kg	69.70	11-20 kg	25.00
Over 100 kg	12.12	Over 20 kg	47.22

Household biogas appliances

Biogas appliances are essential parts of biogas technology. In terms of small-scale biogas plants applied in rural households, biogas cook stoves and biogas lamps are the most common appliances (in our study, 100% of owners of biogas plant had a biogas cook stove); however, other appliances do exist (such as radiant heaters, incubators, refrigerators, engines). Radiant (infrared) heaters are used in agriculture to achieve temperatures for raising young stock (mainly piglets and chicken), and their infrared thermal radiation is developed through a ceramic body that is heated to 600-800 °C by a biogas flame (Kossmann and Pönitz, 1999). The incubators are supposed to imitate and maintain optimal hatching temperatures for eggs (as they are used to increase the brooding efficiency). In these indirectly warm water-heated planar-type incubators, biogas burners heat water in a heating element for circulation through the incubating chamber.

As the most common appliances, biogas cook stoves are substituted for conventional cook stoves and energy sources, and they eliminate indoor smoke pollution and, hence, the related health risks (i.e., respiratory diseases, burning accidents or eye ailments). As noted by Anderman et al. (2015), the use of biogas cook stoves may even lead to high diet diversity due to the ability to simply adjust cooking temperatures. Biogas lamps can be used to generate light by the combustion of biogas and provide adequate levels of safe illumination instead of using fuel base lightning, which can also have direct negative effects on human health.

Biogas lamps and their use in central Vietnam

Only 9% of respondents had biogas lamps, and 14% planned to purchase one in the close future (1 year); 77% did not plan on purchasing biogas lamps at all. Such a low adoption rate was associated with (according to the respondents) i) preferably using biogas for cooking, ii) a high rate of problems with biogas lamps, and iii) easily accessible electricity for lightning. In developing countries, ordinary kerosene lamps are the most common type of fuel-based lighting (Tumwesinge et al., 2014); their light output varies from 10 to 100 lm (depending on the type of lamp and the wick used), with the recommended level of illumination required for reading varying from 100 to 200 $lm.m^{-2}$ (Rajvanshi, 2003). In global measures, fuel-based lightning is estimated to produce greenhouse gas emissions of over 190 million tonnes of carbon dioxide per year (Evans, 2005). Furthermore, a lack of access to clean and efficient fuels in households can negatively affect health in many ways. The most important effects are those that directly result from air pollution caused by burning solid fuels, often indoors and in simple stoves (Bruce et al., 2000; WHO, 2006; Rylance et al., 2013; Tumwesinge et al., 2014; Anderman et al., 2015). There is consistent evidence that indoor air pollution increases the risk of chronic obstructive pulmonary disease and acute respiratory infections in children, and these illnesses are the most important causes of death among children under 5 years of age in developing countries (Bruce et al., 2000; Rylance et al., 2013).

In comparison, biogas lamps can be used to generate light by the combustion of biogas. These biogas lamps usually consist of a gas inlet hole, an air inlet hole, an air inlet adjustment valve, a mixing tube, a fire-resistant clay head and a gauze mantle. This mantle holder usually consists of a gas nozzle for the flow of combustible biogas and air holes for the proper mixing of air/gas. The burning biogas heats a mantle until it glows brightly. The bright light is given off by a biogas lamp as a result of incandescence, i.e., an incandescence effect. The intense heat-induced luminosity of special metals (thorium, cerium, lanthanum, etc.) occurs at high temperatures of 1000 – 2000°C. At 400-500 lm, the maximum light flux can be achieved by a biogas lamp because it is directly comparable with a 25-75 W light bulb. The luminous efficiency ranges from 1.2 to 2 $lm \cdot W^{-1}$. By comparison, the overall efficiency of a light bulb is 3-5 $lm \cdot W^{-1}$, and that of fluorescent lamp ranges from 10 to 15 $lm \cdot W^{-1}$.

The flame from the lamp must be regulated in such a way that the hottest part of the flame matches the form of the mantle. A proper air mixture and an appropriate mantle size play the biggest roles. The methane content of biogas sometimes changes (Sasse et al., 1991; Tumwesinge et al., 2014). Therefore, the brightness of the light will also change. The direct performance of a biogas lamp depends on the optimal turning of the incandescent body (the gas mantle) and the shape of the flame at the nozzle. The incandescent body must be surrounded by the inner (meaning hottest) core of the flame at the minimum gas consumption rate (Sasse et al., 1991). However, if the incandescent body is too large, it will have dark sports, and if the flame is too large, gas consumption will be too high for the light-flux yield (Tumwesinge et al., 2014). Therefore, the lampshade reflects the light downward, and the glass prevents the overly rapid loss of heat.

Biogas cook stoves and their daily use

A biogas cook stove must be designed to suit basic local requirements, such as ease of cleaning and repair, good burning ability, simplicity and safeness of use requirements (Tumwesinge et al., 2014). However, these requirements vary from location to location and need to be linked to the cooking habits of the local people (Grima-Olmedo et al., 2014). However, in general, biogas cook stoves are similar to conventional appliances that run on commercial gas fuels. The gas demand is higher in cultures with more complicated cuisines (Tumwesinge et al., 2014), as in the case of Vietnam, especially in terms of using excessive amounts of flame to cook faster. It is essential to realize that biogas cook stoves often do not achieve a high and stable combustion efficiency (Obada et al., 2014b; SNV, 2001). Therefore, emitting a substantial amount of fuel carbon as a product of incomplete combustion (such as carbon monoxide, methane and total non-methane organic compounds, as well as carbon dioxide) can be expected (Ramana, 1991). For a biogas cook stove, user comfort should always be considered (position of the tap, gas flow regulation capacity of the tap and primary intake regulation). Furthermore, the stability of the frame and size and location of the burner frame must be considered. For the convenience of biogas cook stove users, the stability of the flame port burners is also important, and from the point of view of the manufactures, simplicity and the use of locally available materials are emphasized.

The majority (96%) of biogas cook stoves among our respondents in central Vietnam were two-flame burners (Figure 3), which were initially set and fixed to sustain the efficiency at a high practical level. The remaining 4% of cases were various tentative biogas cook stoves. The surveyed biogas cook stoves averaged 2.4 (±0.74) years old, and they were in use for over 3 hours per day (3.17 ±1.22 hours per day), with a minimum of 0.5 hours per day and a maximum of 8 hours per day. The price of biogas cook stoves in the region started at less than 30 USD and reached up to 400 USD, mainly depending on country of origin (the cheapest usually coming from China, and the most expensive coming from Japan).

Figure 3 Two-flame biogas cook stoves (left and right) in a Vietnamese rural household.

Flue gas analysis of biogas cook stoves

Table 3 shows the average values calculated in the flue gas analysis for all 93 biogas plants. Notable results are related to the high concentration of CO ($mg \cdot m^{-3}$) detected. This high concentration might be caused by one and/or various combinations of the following factors: insufficient burning, the use of inappropriate biogas cook stoves and inappropriate maintenance, as similar results were also reported by Roubík and Mazancová (2016) for biogas cook stoves in Sri Lanka. Based on biogas users and our observations, the biogas cook stoves of Chinese origin have suffered from deformation and burner cracks likely caused by low-quality material not suitable for achieving operational temperatures and burner loads based on the weight of the cooking mass and cooking hours. Table 3 shows the measured difference between the concentration of CO in its diluted (8,705.35 ±1,790.01 mg·m^{-3}) and undiluted forms (24,758.20 ±4,860.20 mg·m^{-3}). These values are higher than in the case of the majority of medium-scale biogas plants in Sri Lanka (Roubík and Mazancová, 2016), which might be caused by different feedstocks (as the feedstock in Sri Lanka was mainly composed of kitchen waste, followed by toilet and animal waste).

The concentration of unavoidable produced NO equals c(NO)=0.064 (±0.12) mg·m^{-3} on average, which is still an acceptable value for the transformation of biodegradable wastes into biogas and its consequent burning (Roubík and Mazancová, 2016). According to the Occupational Safety and Health Administration (OSHA), the permissible exposure limit for nitric oxide (NO) exposure is 30 mg·m^{-3} over an 8-hour workday (NIOSH, 2015). However, significant differences are observed between the districts, as Phong Dien exhibits a much higher concentration of unavoidable produced NO, and NO was not detected in Huong Tra district.

The typical flue gas exit temperature ranges from 440°C to 500°C (Anonymous, 2013). The average temperature of flue gas (TS) of almost 440°C seems to be appropriate for the average use of biogas cook stoves. However, similar to the case in Sri Lanka (Roubík and Mazancová, 2016), respondents reported the occasional use of high and excessive flames to accelerate the cooking process (i.e., cooking and boiling water) in 86% of cases. However, it is essential to note that such practices can lead to the malfunction of a biogas cook stove (Roubík et al., 2016) and high emitted emissions (Roubík and Mazancová, 2016).

The optimal air/gas ratio is expected to be over 55% (Lam and Heegde, 2012). The measured air/gas efficiency was 53.98% on average, which is an adequate value for well-operating biogas stoves. However, the further potential of a cook stove could be maximized by improving air/gas regulation systems (KEBS, 2013). However, as shown in Table 3, much smaller values of efficiency were found in Phong Dien district. This can be explained by the use of more extensive flame and flue gas temperatures in this district, mainly due to the different cooking practices (using biogas cook stoves also for off-farm activities, such as rice wine preparation). If the biogas flame has too much fuel (biogas) without regulation, then it will burn incompletely (and inefficiently) and release unwanted CO and carbon particles (Fulford, 1996). Biogas cook stoves should run with a small excess air percentage to avoid the danger of the flame having too much fuel (Fulford, 1996). Additionally, when the excess air percentage is too high, it cools the flame and decreases the efficiency. The calculated average excess air percentage (3.97%) was similar to that reported by Obada et al. (2014b) (1%). The slight difference might be due to the higher amount of inlet air jets; however, a similar value was observed in Sri Lanka as of 3.99% (Roubík and Mazancová, 2016). The obvious variations are clear, as shown in Table 3, as the excess air percentage varies between the two districts, corresponding with the differences between the air/gas efficiency ratio.

The recalculated average concentration after CO_2 settling for all examined biogas plants is 2,104.59 (±788.99) mg·m^{-3} after stabilization, with a minimum of 342.72 mg·m-3 and a maximum. 5,997.6 mg·m^{-3}. The high values can be caused by the combination of several factors, such as extensive flames and temperatures within biogas cook stoves, various biogas qualities (associated with the input materials of biogas plants and the anaerobic digestion process) and maintenance differences for biogas cook stoves, as concluded by Roubík and Mazancová (2016). Figure 4 demonstrates the average values of CO_2 (mg·m-3), which vary in time; however, their stabilization is observed after the first minute of flame establishment.

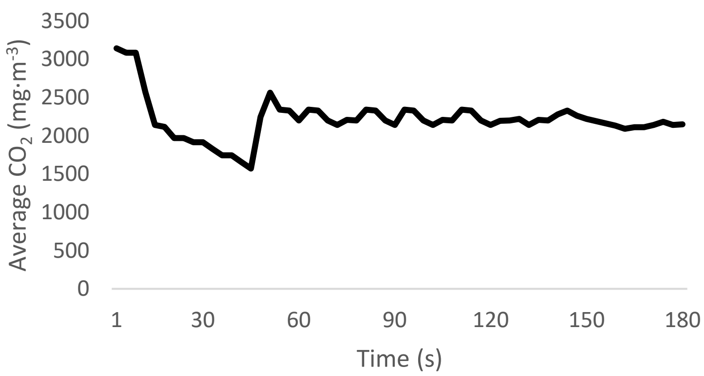

Figure 4 Average value of CO_2 (mg·m^{-3}) over time (n=93).

Table 3 Values from flue gas analysis (n=93).

	O_2 (%)	CO_2* (%)	CO (mg·m^{-3})	CO undiluted (mg·m^{-3})	NO (mg·m^{-3})	TS (°C)**	Efficiency of flow (%)	Excess air (%)	Flow (l·min^{-1})
Huong Tra district (*n=37*)									
Mean	13.32	4.99	13,301.68	36,687.51	0	446.88	56.51	3.82	0.66
SD	2.59	1.65	1,426.78	3,356.69	0	95.48	9.46	1.96	0.01
Phong Dien district (*n=56*)									
Mean	14.68	4.20	4,299.91	13,391.3	0.16	429.55	48.97	4.29	0.65
SD	2.33	1.46	0,814.68	4,626.95	0.26	86.92	14.09	1.97	0.01
TOTAL (*n=93*)									
Mean	13.82	4.66	8,705.35	24,758.2	0.064	436.08	53.98	3.97	0.65
SD	2.61	1.68	1,790.01	4,860.2	0.12	92.95	11.58	1.92	0.01

* CO_{2max} equals 13.6% **Average temperature of flue gas measured at the biogas cook stove outlet

Furthermore, ANOVA was used to show potential differences in the concentration of CO_2 ($mg \cdot m^{-3}$) among various communities (Phong Son and Phong An, n = 42; Huong Van, n = 10; Huong Toan, n = 10; Huong An; n = 18) of the two districts (Phong Dien and Huong Tra). The null hypothesis was rejected (p-value 0.2927; 0.8537; 0.1463, respectively, at α=0.05). Spearman's rank correlations between the concentration of CO_2 and various variables are presented in Table 4. We can see that variables such as the size of the biogas plant and the connection of the toilet to the biogas plant were not significant. Similar results were reported in Nigeria (Obada et al., 2014b), Sri Lanka (Roubík and Mazancová, 2016) and China (Edwards et al., 2004). However, if the feedstock differs, the results of the CO_2 concentration may significantly differ (as we expected for the connection of a toilet). The age of biogas cook stoves was evaluated as an influencing variable, as the CO_2 concentration generally increases with age. Age may increase the accumulation of dirt on biogas cook stoves, as well as decrease the optimal condition of the device. The daily usage of biogas cook stove (in hours) was also examined and was considered an influencing factor. With more stable use, the long-term concentration of CO_2 decreases.

Table 4 Correlation between the concentration of CO_2 and various factors in all visited households (n=93).

	Age of biogas cook stove (years)	**Size of biogas plant (m^3)**	**Connection of toilet to the biogas plant**	**Experience with bad biogas odour**	**Daily usage of biogas cook stove ($hours.day^{-1}$)**
	(n=78)	**(n=78)**	**(n=66)**	**(n=79)**	**(n=79)**
$c(CO_2)$	0.268*	0.134	-0.328	0.404**	-0.222*

* α=0.05; ** α=0.01

As shown in Table 4, an interesting correlation was observed between the concentration of CO_2 and the experience of a bad biogas odour. Such an experience with bad odour was identified in almost one-fifth of biogas plants (17.3%); however, a bad smell on a regular basis was reported in only 9% of cases. A bad smell may signal the presence of H_2S, which can easily be removed by the use of an H_2S absorbent via cleaning every two months (Roubík et al., 2016). Such recognition of a bad smell from incompletely burned biogas can therefore be considered as a signalling factor of high concentrations of CO_2 in flue gas and/or the presence of H_2S.

Recommendations

Switching from the combustion of wood and charcoal to biogas as the primary household energy source (mainly in terms of meal preparation) has the potential to lead to substantial reductions in exposure to harmful elements (especially CO). However, further understanding of the concentrations and determinants of exposure to combustion-derived pollution in households that use biomass fuels is necessary because there is currently a lack of real-world direct evidence regarding the effects of such a switch and a lack of high-quality indoor air pollution data in rural households where biogas installations exist. In the ideal case, longitudinal data from households before and after switching to biogas would be extremely valuable. Further emphasis should be place on investigating the determinants of exposure based on different waste materials (feedstocks) for the biogas plants.

Conclusions

Biogas technology contributes to sustainable waste management (pig manure and toilet waste) in the target area. However, there are some challenges that must be addressed, such as understanding the concentrations and determinants of exposure to combustion-derived indoor pollution in households. The most common biogas appliances are biogas cook stoves and biogas lamps. The majority (96%) of surveyed biogas cook stoves were two-flame burners, which averaged 2.4 years old and were used for over 3 hours per day. High concentrations of CO were detected in biogas flue gas, including in diluted (8,705.35±1,790.01 $mg \cdot m^{-3}$) and undiluted forms (24,758.20±4,860.20 $mg \cdot m^{-3}$). These high concentrations may be caused by a combination of several factors, such as insufficient burning, inappropriate/low-quality biogas cook stoves, inappropriate maintenance and the composition of feedstock. A more detailed analysis of these factors is needed. The concentration of unavoidable produced NO equals c(NO)=0.064 (±0.12) $mg \cdot m^{-3}$ on average, which is an acceptable value for the transformation of biodegradable waste into biogas that is consequently burned. The observed average temperature of flue gas (TS) (almost 440°C) is appropriate for the average use of a biogas cook stove. However, the respondents reported the occasional use of high temperatures to accelerate the process (i.e., cooking and boiling water) in 86% of cases. These high temperatures can potentially lead to biogas cook stove malfunctions. Low air/gas efficiency was found in households in which cooking was also used for commercial purposes (e.g., wine making). The recalculated average concentration after CO_2 settling equalled 2,104.59 $mg \cdot m^{-3}$. The results show that CO_2 emissions increase with the age of biogas stoves and are higher for shorter cooking times.

The study fills an existing data gap, as similar studies have not been conducted before in Vietnam. The information and data gained are important for further evaluations of biogas technology and associated research and development in areas of Vietnam and developing countries in Southeast Asia.

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CHAPTER IV. - Current approach to manure management for small-scale Southeast Asian farmers - Using Vietnamese biogas and non-biogas farms as an example

Adopted from: **Roubík H.,** Mazancová J., Phung L.D., Banout J., 2018. Current approach to manure management for small-scale Southeast Asian farmers - Using Vietnamese biogas and non-biogas farms as an example. Renewable Energy 115(C), 362-370. https://doi.org/10.1016/j.renene.2017.08.068

Author was responsible for the idea, conceptualization, methodology, data collection, performed all experimental work, analysed the data, wrote the original manuscript, and executed its revision.

Abstract

Pig manure is produced in large volumes in Vietnam. If managed properly it reduces waste volume and produces plant nutrient-rich residues. If not managed properly, it leads to negative effects on environment. The objective of this paper is to investigate and analyse all aspects of current manure management practices in Vietnam. A survey was conducted among biogas plants owners (n=141), small-scale farmers with no biogas plants (n=50) and local authorities and facilitators (n=9) via focus group discussions, semi-structured interviews and a questionnaire survey in 2012 and 2013. All households surveyed housed their pigs in concrete pigpens with natural ventilation. Manure was treated in all surveyed households with biogas plants compared to only 24% of households without biogas plants. The knowledge and the management of digestate were recognized as unsatisfactory. Respondents appreciated improvement in environment and economic benefit due to the use of biogas plants. The potential of biogas daily production per household is more than two times higher (2.32 m^3 than the actual production (1.09 m^3). This paper provides an in-depth understanding of various problems with the management of digestate and considers possible risks. The findings have practical implications for manure management practices in Vietnam and other Southeast Asian countries.

Keywords: manure management, developing countries, Vietnam, small-scale farmers, biogas technology, digestate

Introduction

In Southeast Asian countries, the traditional demand for pork is increasing, leading to a rapid increase in pig production leading to large volumes of animal manure to be managed (Thornton, 2010; Huong et al., 2014b). Appropriate manure management strategies are required that have minimal effects on the environment, facilitate the efficient recycling of plant nutrients and preferably generate energy with little or no global warming potential (Vu et al., 2015; Semiyaga et al., 2015). In Vietnam, farm households commonly raise pigs, and small-holders continue to account for 80% of total pig production (Huong et al., 2014b). If animal manure is appropriately managed, waste volume is reduced and residues are enriched with plant nutrients (Mata-Alvarez et al., 2000). However, if not managed properly, animal manure has significant negative effects on the environment (Vu et al., 2007; Vu et al., 2015); air and water pollution are possible risks (Kinyua et al., 2016). Additionally, contamination of food crops is possible also with various pathogens (Huong et al., 2014a).

The use of small-scale biogas plants is among the possible treatments of manure (Roubík et al., 2016; Kinyua et al., 2016; Wang et al., 2016a). The production of biogas through the process of anaerobic digestion (AD) provides a clean, efficient, and low-cost renewable source of energy (Molino et al., 2012; Yu et al., 2008) and the digested matter is a high quality fertilizer for crops (Abinh and Vinneas, 2007; Lantz et al., 2007; Sommer et al., 2004; Molino et al., 2012; Adu-Gyamfí et al., 2012). Recently, researchers have begun to focus on the following issues with the use of digestate: influence on yields (Shi et al., 2001; Kouřimská et al., 2012; Li et al., 2006), influence on crop resistance against abiotic stresses (Mahmoud et al., 2009), effects on characteristics of photosynthesis, including photosynthetic rate, transpiration rate of crops and relevant ecological factors (Zhang et al., 2010), advantages compared with those of manure (Massé et al, 2007; Lansing et al., 2010; Thy et al., 2003), effects on improving the physical and chemical features of soil (Mahmoud et al., 2009; Li et al., 2006; García-Sánchez et al., 2015) and effects of application on changes in soil microbial communities (García-Sánchez et al., 2015). In previous studies, the replacement of chemical fertilizers by digestate was a verified success (Liu et al., 2008), which also contributed to a reduction in the use of non-renewable energy sources to produce chemical fertilizers (Li et al., 2012).

Biogas derived from AD of animal, human and other organic waste has a long history of use as a source of household energy in developing countries (Dutta et al., 1997; Jewitt 2011; Wang et al., 2016a). In Vietnam, AD of animal manure has been practiced since the 1960s (Huong et al., 2014b), and has since grown in popularity primarily because of massive promotion by the government in combination with international organizations, e.g., SNV Netherland Development Organization. From 2003 till 2013, SNV helped build 110,000 small-scale biogas plants, with plans to construct another 200,000 biogas plants in 2013-2018 (Anonymous, 2011). With the support of SNV and other organizations, biogas technology is now affordable and is well suited for small-scale farmers (Cu et al., 2012) as both a management practice for manure and an alternative energy source. However, the current development of biogas plants remains far below the actual demand for management of livestock (pigs predominantly) waste, which has increased significantly (Ngan, 2011) and is expected to continue to increase for 30 years (Thornton, 2010). Currently, most biogas plants are simple, unheated small-scale biogas plants (Cu et al., 2015), with a significant number of those unstable and without controls because of a lack of knowledge about the management of these plants (Roubík and Mazancová, 2014; Cu et al., 2015).

The primary objective of this paper was to investigate and analyse all aspects (Environmental, Economic, Technological, and Social) of the current manure management practices in central Vietnam to contribute to the current discussion on the use of organic wastes. As inappropriate practices lead to environmental and health risks, identifying the manure management practices and the consequences within the context of long-term sustainability and natural resources management is essential. In this paper, an in-depth understanding of the practices of manure management is provided, including possible risks and key recommendations for further actions.

Methods

Target area and Data collection

The survey was conducted in districts Huong Tra and Phong Dien (Table 1) in Thua Thien Hue Province in central Vietnam (Figure 1). The sampling area covered rural areas in which most pig production was concentrated that were a maximum two hours by motorbike from the city of Hue (Gerber et al., 2005). Methods of data collection included focus group discussions, semi-structured personal interviews, the questionnaire survey and observations. The questionnaire survey was conducted among randomly selected small-scale biogas owners (n=141), small-scale farmers without a biogas plant (BGP) (n=50) and local authorities and facilitators (n=9) from June to September 2012 and from July to September 2013. The questionnaire survey collected information with particular attention to currently used manure management practices (Table 2). The questionnaire was pilot tested and then subsequently adjusted and approved by experts from the Agricultural Forestry Fishery Extension Centre in Hue City (AFFEC) before final distribution. Farmers (with and without BGP), facilitators and local authorities were interviewed using a semi-structured interview for 1 h. To increase the scope of the study, four focus groups were formed with biogas owners selected by convenience (n=41). The results of these participatory methods were compared with those of observations of farmers (owners and non-owners of BGP).

Table 1 Classification of the study area.

District	Commune	Village	Number of respondents	Characteristics of district
Huong Tra				
	Huong Toan	Huong Toan	12	Approximately 20,000 inhabitants, with 19 villages. Primary activity in the district is agriculture connected with rice. A noodle factory is in the district. Farmers are often focused on production of noodles or rice wine.
		Duong San	20	
		Duong Son	28	
		An Van	28	
		Huong Chu	19	
	Huong An	Huong An	12	

		Dong Tram	11	
		Binh Thanh (Tam Hiep)	12	
		Xuan Dai	16	
Phong Dien				
	Phong Son	Ca Bi 3	17	Approximately 17,000 inhabitants, with 13 villages. Primary activities are agriculture, livestock, and forestry.
		Ca Bi 10	14	
		Hien Si	11	
	∑	**12**	**200**	

Table 2 Main categories of the questionnaire (*n=150**).

Category		**Focus of the questions**
(I)	Socio-economic characteristics of respondents related part	District, villages, sex, role in household, size of family, amount of members living in farm, education, occupation, income, farm size, crops, equipment in household
(II)	Manure management practices related part*	Animal production and related questions (number of animals, their weight, feeding, housing), manure management practices, human excrements management practices, manure treatment, use of treated manure, cleaning of pigpen housing, digestate management, fertilizing practices, technically oriented questions and sources of information about the biogas technology, technology adoption related part (reasons for technology purchasing and currently recognized benefits), perception of biogas technology from the view of the non-users

*BGP owners *n=100*, Non-BGP owners *n=50*

Data analyses

The collected data were categorized, coded and analysed with descriptive and inferential statistics using the statistical software package Statistica 10 and Microsoft Office Excel. Differences between the manure management practices of small-scale biogas owners and those of small-scale farmers were analysed using Chi-square tests in cross tabulations. For an adequate comparison of farm performance, F-test was used to determine independent variances between farm size and rice yield to determine differences between small-scale biogas owners and small-scale farmers. Current biogas generation and biogas potential from different types of excrements per household were calculated according to typical biogas yields per kg in mesophilic conditions (20-45°C) (IAEA, 2008).

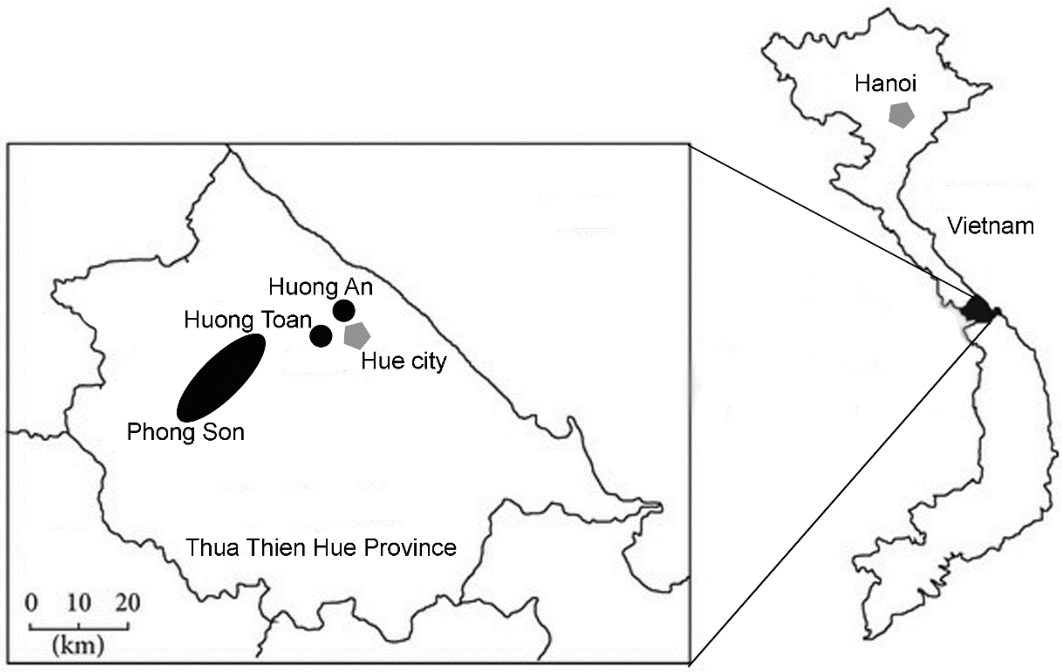

Figure 1 Target area in Vietnam.

Conceptual framework of cluster analysis

Cluster analysis was used to identify and describe the reasons for adopting biogas technology and the currently recognized benefits. The reasons for adopting biogas technology on BGP farms were divided into the following clusters: Environmental, Economic, Technological and Social. These clusters were formed based on a micro-level perspective, i.e., the household level. Disparity (D) between the motivating factors for adoption of biogas technology and the current benefits recognized by BGP owners was calculated as follows:

$$D = A_{MF} - A_{CB} \qquad [1]$$

where AMF is an average among motivating factors for technology adoption and ACB is an average among current benefits recognized by BGP owners.

Results and Discussion

Background of small-scale farms in study area of central Vietnam

The size of rural farms with a biogas plant averaged 2,821 m^2, with approximately 2,000 m^2 for rice production. For farms without a biogas plant, the average size was 3,332 m2 with almost 3,000 m^2 for rice production. In contrast to farmers with a biogas plant, who were required to focus on livestock and providing sufficient organic matter for the biogas plant, the focus of farmers without a biogas plant was more on crop production, which likely explained the difference between sizes of farms with and without a biogas plant ($F=0.298$; $p<0.05$). Additionally, according to this data, both farms were larger than the state average caused by lower population density.

For 90% of the respondents, farmer was the occupation. Both farmers with a biogas plant and without a biogas plant produced rice as the primary crop. For 72% of these households, the primary source of income was farming. Twenty-eight percent of households also generated income from off-farm activities, which included trade (7%), rice noodle production (5%) and rice wine production (4%). Total income was less than 2,000,000 VND per household a month for 49% of the respondents, less than 1,000,000 VND per household a month for 24%, and less than 4,000,000 VND per household a month for 16%. Additionally, from a socioeconomic perspective, when off-farm activities increasingly affected growth of the family income at the household level, the timing of manure management activities required scheduling for when farmers returned to the farms and were not employed by other activities.

Households with a biogas plant used varieties of Chinese fixed-dome biogas plant - type KT1 and KT2 (detailed description in the study by Roubík et al., 2016). Most biogas plants in the survey (49%) were of a volume of 6 m^3 and were three years old (over 54%); however, the ages ranged between 1 and 12 years.

Manure production in the target area of central Vietnam

The average farm surveyed with a biogas plant disposed the manure from 13-14 piglets and 2-3 sows and sometimes other animals. Animal feeding significantly influences nutrient flows because diet affects the composition of excreta (Petersen et al., 2007). Pigs were fed mostly with a commercial feed high in protein and carbohydrates, in addition to local feed or a mixture of both. Local feed typically consisted of agricultural residues, such as rice and rice bran mixed with kitchen waste residue (used by all households), sweet potatoes, banana tree parts, water hyacinth, and soybean or cassava leaves, among others. Cu et al. (2012, 2015) reported similar findings. The ratios of feed type were different and highly variable in time and depended primarily on current conditions and availability of feed resources, and consequently, the volume and composition of manure were highly variable. For the energy required for preparation of pig feed, biogas or firewood was used, depending on the amount of biogas produced.

Pigpen housing system in the target area of central Vietnam

All households surveyed housed their pigs in concrete pigpens with natural ventilation, a concrete floor and for most, a corrugated iron roof (Figure 2). If a biogas plant is present, solid floors were typically connected to the biogas plant inlet to ease watering the manure into a tank. Some of the surveyed households (26%) reconstructed and renovated their pigpens because of biogas plant installation. Pigpens were typically cleaned (with water) once a day in winter and twice a day in summer.

Figure 2 Congrete pigpen in Vietnam.

Current manure management practices in the target area of central Vietnam

Emissions to air and water are to a certain extent an unavoidable consequence of the recycling of livestock manures within agriculture (Petersen et al., 2007); however, these emissions must be minimized. Therefore, the management of livestock manure to control losses to the environment and prevent spread of contaminants is fundamental to develop sustainable production systems. The surveyed farms reported three forms of manure, i.e., liquid manure, solid manure and slurry. Manure management was affected by whether a farm had a biogas plant or not. In central Vietnam, the current practices for manure management (Table 3) include feed for biogas plants, composting, storage without treatment, storage with subsequent treatment and direct disposal with no treatment. Pig manure separately manure was used on only 54% of farms with a biogas plant but on 86% of non-biogas plant farms. Pig slurry combined with human excreta was used on 41% of biogas plant farms, and on 14% of non-biogas plant farms, pig manure was combined with human excreta and other organic wastes. However, in households without biogas plants the common practice for human excreta was to remain in reservoirs under houses or in toilets from which it soaked into the ground with possible environmental consequences described in studies by Jensen et al. (2008) and Vu et al. (2015) from Vietnam and by Chai et al. (2009) from Southeast Asia. The variance in use of human excreta is due to whether toilets are connected to biogas plants that transform this type of waste into clean energy (Bond and Templeton, 2011). Therefore, human excreta are a resource that could generate economic and environmental benefits with the production of biogas (Jensen et al., 2008; Jewitt, 2011). Of the surveyed farms with biogas plants, 16% used pig manure, human excreta and excrements from other animals, such as chickens, ducks, or cattle, to produce biogas. Of the biogas plant owners, 45% raised hens or chickens but only 16% added this manure into biogas plants; this practice primarily reflected persistent concerns about avian influenza; which is also noted in the study by Vu et al. (2007). In all surveyed biogas plant households, the pigpen was connected to a digester and in 35% of households, with a toilet outflow; however, no connections occurred between chicken sheds and digesters. Hence, this type of manure must be transferred to the inlet tank manually, which increased the inconvenience of manure management to the biogas plant users.

Table 3 Manure and digestate management (*n=150*).

	Biogas plant Owners[1] (%)	Non-biogas plant Owners[1] (%)	P-value[3]
Manure and excreta use			
Pig	54	86	**
Pig and Human excreta	41	0	NS
Pig, Human and others	5	14	*
Manure treatment			
Feed for biogas plant	100	0	NS
Composting	0	10	NS
Storage and treatment	0	14	NS
Storage without treatment	0	8	NS
Direct disposal (no treatment)	0	68	NS
Digestate management/Treated manure			
Pre-treatment	5	0	NS
Crop fertilizer	33	12	**
Vegetable and home-garden fertilizer	25	20	**
Feed for fish	1	0	NS
Discharge to environment	10	68	*
No treatment	26	0	NS

[1] Biogas plant owners *n=100* and non-biogas plant owners *n=50*.

[2]In the case of non-biogas plant farms, composted or treated manure was considered.

[3]In calculations: *p-value is less than 0.05; **p-value is less than 0.01; NS is not significant.

Manure is a valuable energy and nutrition resource, when used appropriately. All respondents with a biogas plant used manure as a feed for the plant and none used any other form of manure treatment. Cu et al. (2012) found similar results. Therefore, we assumed that all farmers with biogas plants adopted the technology and discontinued ineffective practices. By contrast, farmers without biogas plants used different practices to manage manure, including composting (10%), storage and treatment (14%), storage without treatment (8%) and direct disposal (in a lagoon next to the household) as the most common practice (68%). Both direct disposal and storage without treatment lead to environmental threats that include air and water pollution and risks to human and animal health with the spread of pathogens (Burton and Turner, 2003; Ribaudo et al., 2003; Vu et al., 2007;). Another challenge in manure management is the uncovered storage of manure, which is a source of unpleasant odours and ammonia emissions (Martinez et al., 2003; Vu et al., 2007).

Current digestate management in the target area of central Vietnam

Digestate management is also one of the current concerns in developing countries (Cu et al., 2012; Vu et al., 2015). According to our results, the only pre-treatment was in the form of sun-drying in front of the house on concrete floor, or next to the biogas plant (on the ground) to ensure easier transportation of digestate to rice fields and was performed in only 5 % of cases. Furthermore, our survey showed that 33 % of farmers used primarily the solid parts of digestate as a fertilizer for rice. Use of liquid part was limited by long distances between biogas plant locations and rice fields (average distance 1,031 m). From the perspective of farmers, labour input for transport and a lack of transport vehicles/devices were the primary barriers, confirmed in other studies from Vietnam (Cu et al., 2012) and Tanzania (Jackson and Mtengeti, 2005). For 25% of those surveyed, farmers used digestate as a fertilizer for vegetable and home-gardens. This application is very popular because of its simplicity and convenience. However, as the application is not regulated – the flow of digestate is constant - this practice often had similar effects to those that discharged digestate directly into the environment. Similar findings are reported by Vu et al. (2015) in Vietnam and Bos and Kombe (2009) in Uganda. Cultivated home-garden crops were primarily banana, pomelo, cassava, peanut, and sweet potatoes, and these crops were fertilized with digestate on 25% of farms with a biogas plant and on 20% of non-biogas plant farms that used composting or other treatments of manure. Only 1% of surveyed farmers used digestate as feed for fish. Cu et al. (2012) noted a higher frequency of digestate used as fish feed in areas with better conditions for establishment of fishponds, particularly those areas near Hanoi. From our survey, approximately 20% of respondents had access to a pond to raise fish in central Vietnam; however, only 1% of respondents actually raised fish and used digestate as feed for fish. People did not believe that treated manure was safe for use as fish feed. Nevertheless, in Vietnam (Vu et al., 2007), Cameroon (Efole et al., 2012), China (Wu et al., 2014) and Cambodia (Sophin and Preston, 2001), the results are satisfactory when digestate is used to feed fish. In China, the integrated biogas-utilization system is gaining popularity, and the integrated "pig-biogas-fish" system is becoming more widely applied (Wu et al., 2014). In Vietnam, another constraint was the over-application of digestate into ponds with potential harm to fish (Cu et al., 2012). Therefore, more attention must be focused on the transmission of information from implementers to facilitators, and consequently to biogas plant owners. In 10% of households, digestate was discharged directly into the environment into canals, lakes, rivers, and ditches or into soil. For more than one-quarter of cases (26%), no treatment was reported. Thus, the problems with the management of digestate are a fundamental issue that require an immediate solution. In the study by Zhou et al. (2011) and Chen et al. (2010, the conclusion is similar that lack of knowledge is the primary cause of the problems. Therefore, the large volume of digestate produced by biogas plants may compromise the potential of the entire technology (Dahlin et al., 2015).

Our results showed that water used to wash pigpens on both biogas plant and non-biogas plant farms was excessive, which causes problems for biogas plants (Roubík et al., 2016) (see Figure 3), including the lack of organic matter in digestate (Cu et al., 2012). Farmers commonly used as much water as necessary to completely spray and clean the manure from pigpens; however, this practice typically led to high water/manure ratios in biogas plants. Respondents were unaware of any limitations connected with the use of appropriate amounts of water; this information should be transmitted by competent local facilitators and receive more discussion during workshops. On biogas plant farms, the average ratio of washing water/manure was 12/1 and 15/1 in winter and summer, respectively; with smaller ratios reported on non-biogas plant farms of 10/1 and 12/1 in winter and summer, respectively. Higher ratios on biogas plant farms were most likely caused by the efforts of pigpen owners to maintain clean, renovated pigpens; however, excessive water use caused the final digestate to have low contents of solids and further management was considerably more difficult. According to SNV recommendations (Bos and Kombe, 2009) and those of a previous study of Roubík et al. (2016), for optimal biogas plant operation, the ratio should be approximately 3-6:1, independent of external temperature. This ratio could be reached by either a decrease in water use or an increase in manure use; in some cases, connection with toilets was used to increase the portion of manure (35% of biogas plants had potential for easy connection to a toilet). In general, for a family of four to five members per farm with a biogas plant and 100-400 g (250 g average) of faeces per member per day, an additional 1.125 kg of human faeces would be available daily, which could generate an additional 0.225 m^3 of biogas per day. In Cambodia, when biogas owners have specific training focused on the quantity of water to be added, better quality digestate was produced from the digester, which increased use of this valuable by-product and improved appreciation of the properties (Schmidt and Jordan, 2008).

Currently, for the treatment and management of digestate, numerous possibilities include composting, conventional digestate management, drying (with a belt or a drum dryer), thermal concentration, physical-chemical treatment and solar drying (Rehl and Muller, 2011). Nevertheless, for small-scale farmers, not all of these approaches were applicable. Therefore, appropriate digestate treatment and management methods must be established that are consistent with local conditions and abilities. To ensure the recycling of nutrients contained in the digestate from small-scale biogas plants, better methods and technologies must be developed to avoid compromising the advantages of biogas technology.

Figure 3 Digestate floating out of the outlet.

Biogas potential on biogas farms in the target area of central Vietnam

Pig manure was a primary source of feedstock for small-scale biogas plants in Vietnam. According to Cu et al. (2012) from a study in Vietnam, farmers also add too much manure to digesters, in part because farmers are unaware of the biomass biogas potential (Cu et al., 2015). The animal excrements created per average surveyed household are shown in table 4, with the average minimal biogas yield from this excrement equal to 2.32 m^3 per day per household (considering full transformation of animal manure). However, compared with the current usage of manure in biogas plants, biogas generation per household was estimated as 1.09 m^3 per day; therefore, the actual generation was 46.98% of the biogas potential. Farmers did not use the excrements of some animals, primarily those from cattle, ducks and hens. However, Cu et al. (2015) analysed diverse manures from animals in production for suitability in small-scale biogas plants in Vietnam. Farmers mostly preferred mixed feeding as it was cheaper but maintained growth rates, although differences in the composition of feed lead to different qualities and quantities of gas produced in biogas plants. Therefore, further research and assessment of biogas potential from households with different livestock systems are required (Tuan et al., 2006; Cu et al., 2015). Some farmers interviewed (18%) also used antimicrobials or antibiotics as feed additives in the previous year, with potential subsequent effects on the immediate environment (Vu et al., 2007). Additionally, notably, livestock manure contains many microorganisms, protozoa and viruses, including food-borne diseases, which may pose a risk to human and animal health (Vu et al., 2007). Potentially hazardous components, such as growth hormones, antibiotics and heavy metals, were also reported in pig feed (Ribaudo et al., 2003; Cu et al., 2012), and when over-applied, these substances may cause degradation of water quality. Therefore, pig feed with high concentrations of N and P, heavy metals and pharmaceuticals requires further observation, and more focus is required on feeding practices (Gollehon et al., 2001; Cu et al., 2015) in the effort to achieve environmentally friendly manure management practices.

Table 4 Animal production on farms with a biogas plant (*n=141**).

	No. of head	Average weight per head (kg)	Animal Excrement per HH (kg)	Usage for biogas plant (%)	Current biogas generation per HH (m^3)	Minimum biogas yield from manure (m^3)
Pigs	13.5	35.1	36.74	96.0	0.7600	0.80
Hens	6.7	1.8	1.21	16.0	0.1900	1.21
Sows	2.3	99.8	9.81	97.0	0.1300	0.14
Ducks	1.6	-	0.20	2.0	0.0010	0.04
Cattle	0.5	60.0	4.00	1.0	0.0014	0.14
			Σ		**1.09**	**2.32**

*Biogas plant owners from the questionnaire survey *n=100* and FGDs *n=41*.

Biogas technology adoption in the target are of central Vietnam

The attitudes of farmers towards biogas technology were also an important factor. In recent years, many biogas plants were installed in Vietnam (Roubík et al., 2016), with the primary increase supported by the introduction of financial compensation. Non-biogas plant farmers recognized that some of primary problems on their farms were the odours and hygienic problems connected with manure; and as noted in the study by Cu et al. (2012), reducing odour is important motivation for using biogas.

Environmental, Economic, Technological and Social clusters were used to identify the reasons for adopting biogas technology on biogas plant farms (Figure 3). The most important factors for adopting biogas technology based on perceptions of the respondents were as follow: clean environment (70%), saving money (57%) and gas for cooking (48%). When we compared the factors for adopting biogas technology with the current benefits of using biogas technology for farmers, the most appreciated benefits were saving money (79%), a clean environment (70%), and the higher heating value of biogas than that of wood (39%). These results showed a consistent appreciation of the relationship with the environment and a large tendency to consider economic benefits. The distribution of these factors into clusters provided a more complex view on the disparity between motivating factors and the current benefits (Table 5). A positive disparity for environmental and economic factors and a negative disparity for technological factors were identified, with the negative disparity possibly caused by complications with technology and equipment. Additionally, recognition that technological advantages were greater in current benefits than as motivating factors was expected, and the disparity indicated an appreciation of the technology from new perspectives. These disparities can be compared with those from Cambodia (Phanthavongs and Saikia, 2013) and Nepal (Singh and Maharjan, 2003) for which the primary recognized benefits are "time-saving" (on cooking) and a healthier environment (only in Cambodia).

Table 5 Motivating factors and current benefits as perceived by farmers with a biogas plant (*n=141**).

Clusters	Motivating factors for adopting biogas technology (% of respondents)	Average frequency (%)	Current benefits recognized in using biogas technology (%)	Average frequency (%)	Disparity
Environmental	Clean environment (70); waste problems (14); manure management (2)	28.7	Clean environment (70); health improvement (26); soil fertility (6)	34.0	5.3
Economic	Saving money (57); saving time (15); support from organization (1)	24.3	Saving money (79); saving time (35)	57.0	32.7
Technological	Biogas for cooking (48); cooking for pigs (7); biogas for lighting (12)	22.3	Higher heating value than firewood (39); energy source (10); regulation of flame (7); use for lighting (7); generation of electricity (1)	10.7	11.6
Social	Local facilitators (77); neighbours (13); public media (10)	33.3	0	0	33.3

* Biogas plant owners from the questionnaire survey *n=100* and FGDs *n=41*

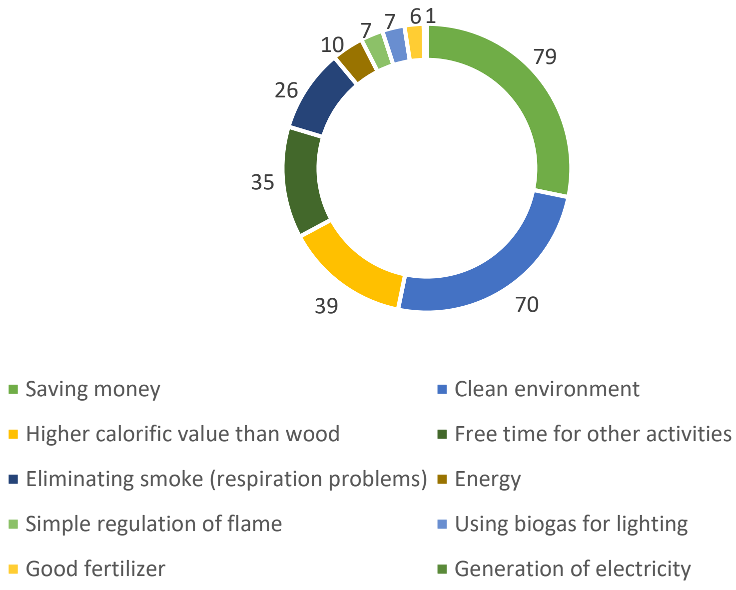

Figure 3 Current benefits recognized by BGP owners (n=141*).

* BGP owners from questionnaire survey *n=100* and FGDs *n=41.*

For farmers with a biogas plant, the primary source of information related to biogas technology was commune staff and local facilitators (77%), followed by neighbours (13%) and public media (10%). The public media had an important role in promotion, particularly at the national level. In central Vietnam, the facilitators were a major influence within the community, which was also confirmed in the study by Cu et al. (2012). A broadcast media programme is required to advertise nationwide the benefits of biogas technology in parallel with information on the negative effects of uncontrolled waste and inappropriate manure management (Ngan, 2011). Moreover, as demonstrated in a study on household decision-making by Qu et al. (2013) in China, information supplied by the government (instead of other resources such as family, friends or media) on biogas technology increases the likelihood a farm constructs a biogas plant. Therefore, such programmes and the distribution of information should be continuous to develop better awareness and attitudes among farmers towards biogas technology.

Non-users perception of biogas technology in the target are of central Vietnam

Potential biogas users (n=50) (see Figure 4) were defined as those farmers that had the possibility to build a biogas plant (territorial proportion). Of these respondents, 88% demonstrated knowledge of biogas technology, with 80% that acknowledged the multi-dimensional advantages of the technology; however, only 64% were willing to adopt the technology, and of these, only 37.5% had sufficient possible financial support. Despite the conclusions of our results, as also demonstrated in a paper from China (Li, 2009), only approximately 12% of households suitable to produce and use household biogas had adopted the technology. The primary barriers in adopting biogas technology as defined by non-users were lack of finance (76%), lack of animals (44%), not being selected for a subsidy (36%) and lack of space for biogas plant installation (20%). However, further socioeconomic factors also influenced the adoption of biogas technology. As described in a study from China (Qu et al, 2013), governmental promotion has a significant effect on decisions by households; however, some significant variables predicted whether a household would actually construct a biogas plant, i.e., age of the head of the household, number of household members and total household income. Despite the tremendous potential of this technology, barriers remain because of high investments costs and lack of finance in the rural areas of developing countries. Many factors explain the acceptance and success of biogas programmes, with subsidies from the government, increased crop yields, improvement in quality of life and saved time as the primary factors (Katuwal and Bahara, 2009). However, subsidies cannot sustain biogas indefinitely, which raises the question of whether biogas plants are a sustainable solution.

Figure 4 Small-scale farmer in central Vietnam.

Future challenges for manure management in central Vietnam

The rapid industrialization and economic progress in Vietnam in the last decade has led to an increase in population growth demanding more livestock products (Thornton, 2010; Bruun et al., 2014) causing more challenges associated with the management of manure (Cu et al., 2012). The generation of more manure will have potential consequences with broad and long-term implications for human health, the economy and the environment (Chadwick et al., 2015). With the generation of nutrients (e.g., N, P_2O_5 and K_2O) and emissions of methane (CH_4) (Chadwick et al., 2015) from manure or emissions of ammonia (NH_3) and greenhouse gases (CH_4, N_2O, and NO) from the storage of digested pig manure (Wang et al., 2016b), the agronomic and environmental implications are negative. From a perspective of policy and planning, the responsibility should first be with the biogas owners and facilitators, followed by the biogas programmes and national planning authorities. Additionally, a GIS-based tool is required that planning authorities could use to explore strategically the best location for construction of new, centralised medium-scale biogas plants or composting plants to have a fluent supply of raw materials, in addition to recipients for the final products. Furthermore, from the perspective of policy and planning, it is also important to determine the extent to which such programmes reach rural poor farmers. Most of the programmes that implement biogas technology have not targeted the "poorest of the poor" because these households do not have the minimum, required number of livestock. Because of the current economic status of rural households, family sized biogas plants remain costly and unaffordable for poor households (Katuwal and Bohara, 2009), which therefore, are excluded from the benefits of biogas technology, in addition to government subsidies. Biogas technology in Vietnam remains primarily focused on family sized biogas technology, but the technology has potential for more applications in community sized biogas plants and municipal waste recycling. Use of other alternative biodegradable feedstock should also be encouraged and promoted (Katuwal and Bohara, 2009), which in Vietnam include kitchen, garden biodegradable, municipal and slaughterhouse wastes that should be used more widely.

Key recommendations to improve manure management in central Vietnam

This list of recommendations includes various aspects of manure management that should be considered in further policy actions:

- Creation and implementation of an integrated system "soil-plant-animal" among farmers to raise awareness and alleviate negative effects of manure management.
- Incorporation of policy changes to prevent discharges of animal manure (including liquids) to surface waters that are properly distributed among farmers and facilitators and adaptation of technologies for effective manure management in Vietnam.
- Further research on the effects of application of manure and digestate within crop production systems and vegetable and cut and carry grass, as well as on soil quality and crop yields in Vietnam.
- Continuous development of demonstration farms with biogas plants as an effective way to promote positive messages on manure and digestate management with organization of training courses on improved manure and digestate management practices. Remuneration for practicing sustainable manure management may also be a particularly useful strategy to motivate farmers to adopt recommended manure management practices.
- Further incorporation of integrated systems using organic manure and inorganic fertilizers that offer potential for the sustainable management of manure and that minimize environmental pollution and improve soil quality while providing economic benefit.
- Incorporation of decision-support software to assist in the design of manure management systems and nutrients flows.
- Incorporation of GIS-based tools to explore strategic locations for centralised, medium-scale biogas plants for use as manure management processors.
- Involvement of Context Specific Knowledge as a tool for extension facilitators to improve their skills.

Conclusion

This paper extends the current state of knowledge of the manure management practices among small-scale farmers in central Vietnam. When managed properly, manure represents a valuable resource. Based on our results, with the use of biogas plants, manure management practices by owners improved. However, many limitations remain with the management of digestate that require immediate solutions in many developing countries. Broader information on manure management practices during trainings should be incorporated.

We calculated the total biogas potential from all manure and excrements available in the household and its biogas production potential. The results showed that the biogas potential is two times higher than current biogas generation. We assume that not all manure fed the biogas plant. Part of it currently goes directly to the environment (in a lagoon next to the household), or is not simply collected. Therefore, bigger involvement from facilitators is needed in terms of increasing range of used manure and wider incorporation of connection between biogas plants and toilets. Reasons for adopting biogas technology were divided into Environmental, Economic, Technical and Social clusters providing so a complex view of the motivating factors and also the currently valued benefits recognized by biogas plant owners. Appreciation of the relationship with the environment was consistent and many were inclined to recognize the economic benefits. In general, the understanding of biogas technology was relatively high among farmers (the exception was the lack of knowledge about digestate management); however, the primary barrier to a wider dissemination of this technology was the absence of financing. In conclusion, problems with digestate management are a fundamental issue that requires an immediate solution. This paper contributes to information mapping on the current manure management practices among small-scale Vietnamese farmers and provides support for solutions to current problems.

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CHAPTER V. - Uncovering the dynamic complexity of the development of small-scale biogas technology through causal loops

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Abstract

Development of biogas systems has a relatively long history, but its main expansion has occurred in the last few decades. The benefits of small-scale biogas plants, which provide opportunities to solve manure management problems and produce energy, have convinced almost 800,000 rural households to install biogas plants in Vietnam. The objective of our study is to identify the system of implementation of small-scale biogas technology from the farmer's perspective, presenting all of the major stakeholders, factors and processes involved and to establish the principle relationships and feedbacks among them. This paper uses an innovative approach to the problems using the methodology of system dynamics and employing causal loop diagrams elaborated using data collected from the target groups (biogas plant owners, facilitators, key informants) in Vietnam from 2016 - 2017. The results show the complete causal loop diagram, where the motivation of farmers is a key variable that influences the final decision regarding purchasing (or not) a biogas plant and keeping it (or not) functional. The important variables and relationships are clustered into technical, financial, and satisfaction aspects. The causal loop diagrams will serve as a decision support and policy-making tool for influence assessments of various measures and decisions.

Keywords: small-scale biogas; biogas development; biogas technology; causal loops; system dynamics; biogas policy

Introduction

In the developing world, population growth and industrial development is causing a continuous increase in energy demand, and the difference in consumption and availability of energy sources is getting greater (Demirbas and Demirbas, 2007; Yasar et al., 2017). Access to energy influences living standards and overall development (Demirbas and Demirbas, 2007). Currently, the rising energy demand is still mainly covered by fossil fuels (Olah, 2005). The developing world is still facing a scarcity of a clean and reliable energy supply. Therefore, the use of biogas technology at the small-scale level belongs among possible solutions, providing the transformation of organic waste into energy in the form of biogas (Roubík et al., 2018). The production of biogas through the process of anaerobic digestion (AD) provides a clean, efficient, and low-cost renewable source of energy (Yu et al., 2008), and in addition, digested residue (digestate) for use as a high-quality fertilizer (Thy et al., 2003; Kouřimská et al., 2012).

Development of biogas technology in Vietnam has a relatively long history, but its main expansion has been recognised in last several decades (Ngyuen, 2011). The benefits of small-scale biogas plants provide an opportunity to solve manure management problems and simultaneously generate energy for cooking and/or lightning and/or electricity generation and have convinced almost 800,000 families raising pigs to install biogas plants (BGPs) (SNV, 2017b). The majority of small-scale farmers were financially subsidised by several supporting projects, while others decided to construct their BGPs with their own resources (Ngyuen, 2011; Roubík and Mazancová, 2016). Nevertheless, the number of small-scale BGPs already built in rural areas of Vietnam is still lower in comparison to the actual situation regarding the need for proper livestock waste management (Ngyuen, 2011; Roubík et al., 2017; Roubík et al., 2018).

Household biogas programmes have experienced rapid development in recent years, with notable results achieved. However, further progress may be affected, as some of the promotional activities such as subsidies and cost buy-downs encourage further construction of small-scale BGPs, but often do not ensure long-term operation and proper maintenance, which are the keys for success of this technology (Roubík and Mazancová, 2016; Tucho et al., 2016).

Biogas systems in developing countries history and future prospects with particular attention on Vietnam

There are assumptions that biogas was used already in Assyria in the 10th century B.C. and that AD of solid waste was applied in ancient China (He, 2010). In any event, well-documented attempts at AD of biomass by humans are dated into the middle of the 19th century in New Zealand, India (Meynell, 1976) and the UK (McCabe and Eckenfelder, 1958). Then, the development of microbiology as a science has escalated into the identification of anaerobic bacteria during the AD process (Buswell and Hatfield, 1936). In Germany, AD was first used in 1920 with the gas supply into the public network, and the first large-scale BGP started to operate in 1950 (Ni and Nyns, 1996). In China, AD was first commercially used at the household level by Guorui Luo in 1921 (He, 2010). The break point of biogas technology came in the 1970s with high oil prices, which motivated research for further alternative energy sources (Bond and Templeton, 2011). It brought exponential growth in the number of medium- and large-scale BGPs, interest in the technology in the USA (Hashimoto and Varried, 1979; Chen et al., 1978) and Europe (Smith et al., 1979) and the fast development of small-scale biogas systems in Asian, Latin American and African countries.

In the early 1980s, more than 7 million BGPs were installed worldwide, mainly in Asia (Steiner and Kandler, 1984). Nowadays, millions of BGPs can be found in the developing world. In Vietnam, it is thought that over half a million BGPs have been installed (Khan and Martin, 2016), with no signs of a slowing trend in the current expansion, which points on importance of this topic for further research. There is still enormous potential for more BGP implementation in the world (Ravindranath and Hall, 1995; Hossain, 2003; Dimpl, 2010; Singh and Maharjan, 2003; Chen et al., 2010; Rajendran et al., 2012) based on existing designs and government support only, with specific adjustments. However, the growth potential is limited by several factors. From the technical point of view, the growing number of BGPs is also bringing a growing number of complications and problems (Aburas et al., 1995). Recognized system failures of small-scale BGPs divided into seven main subsystems in Vietnam can be found in detail in the study by Roubík et al. (2016).

From an economic point of view, the cost of the technology itself or spare parts is a limitation for some farmers (An et al., 2006). The rapid development of BGP implementation has been mainly occurred under the substantial support from governments, development projects and aid agencies (Kristoferson and Bokhalders, 1991; Mwakaje, 2008). After support termination, the development of newly constructed BGPs has slowed down significantly (Desai, 1992; Zhou et al., 2011). Therefore, political measures are needed to encourage the adoption of the technology, as well as capacity building, technical training, financing mechanisms and dissemination strategies (Karekezi, 2002; Greben and Oelofse, 2009; Zhou et al., 2011). However, technology transfer in developing countries is often problematic (Klinenberg et al., 2014). Common challenges are insufficient resources for operation and unsatisfactory maintenance after project implementation (Klinenberg et al., 2014; Schillenbeeckx et al., 2012).

Agricultural sector in Vietnam

The agricultural sector has been changing in Vietnam recently. There can be recognised a phenomenon of how livestock and poultry raising is turning from small into small-scale household farms, where at least some forms of technological approaches are applied. For example, in October 2015, animal populations in Vietnam were as follows (in millions of heads): buffaloes 2.5, cattle 5.4, pigs 27.7, and poultry 341.9, meaning that in comparison with 2014, the aforementioned animal populations increased by 0.1%, 2.5%, 3.7% and 4.3%, respectively. The live weight of buffaloes, cattle and slaughtered poultry rose in comparison with those in the previous year by 0.1%, 2.2%, 4.2% and 3.8%, respectively. The growing trend of the livestock sector has been noticed in other developing countries as well (Thornton, 2010) in supplying the global food market.

In the last decades, Vietnam has turned from a country facing food shortages into an exporter of agri-products. This move (characterized by doubling the gross product in the period from 1991 to 2000) was facilitated by the so-called *doi moi* (a top-down initiated) reforms in the 1980s (Castella and Quang, 2002; Nin et al., 2003), which emphasized the role of rural households as the important unit in agricultural production and allocated them with relevant means of production.

National Biogas Programme in Vietnam

The National Biogas Programme (NBP, in full *Biogas Programme for the Animal Husbandry Sector of Vietnam*) has been implemented by SNV (Netherlands Development Organisation) in cooperation with the Ministry of Agricultural and Rural Development of Vietnam since 2003. Till March 2017, the NBP has covered 55 provinces and cities all over Vietnam, resulting in 158,500 biogas digesters installed (with a reduction of approximately 800,000 tonnes of CO_2). In addition, more than 790,000 rural individuals have benefitted from the technology. The NBP also involves training and technical support - nearly 1,700 biogas masons and 355 biogas construction team leaders have been trained. Thousands of people were familiarized with and encouraged to use biogas technology. The NBP has also introduced the innovative Results-Based Financing mechanism to deploy the full potential of biogas enterprises (SNV, 2017b). After three years of operation of this mechanism, 146 active enterprises have been established in 18 provinces, and they have constructed over 35,000 biogas plants (SNV, 2017a). Ghimire (2013) in his study summarized the main lessons learned from the biogas programmes in various Asian and African countries, pointing to identification of key players and their capacities, different ways of financing, including transparent and easily administered incentives stimulating the market, and building a platform at the national as well as regional levels to facilitate information exchange and cooperation. The current period of the NBP ends in 2020. Based on the accessible sources, the follow-up exit strategy has not been published yet. SNV (2017a) assumes that with the current pace of distribution of an accumulated 20,000 biogas plants per year, it will take approximately 20 more years to saturate the active demand.

Objective

This paper is based on the implementation of the National Biogas Programme highly promoting the introduction of biogas technology among rural households in Vietnam. So far, the complexity of the system at the household level has not been described. The objective of our study is to identify the system of biogas technology implementation, from the motivation of farmers to well-functioning biogas plants in Vietnam (using Central Vietnam as an example), presenting all major stakeholders and factors involved and setting up the principle relationships and feedbacks among them. The paper aims to contribute to the creation of policy and action plans. The paper uses an innovative approach to the problematics by using the methodology of system dynamics. The paper is aimed only at the identification of all possible factors, not at proving their importance. This will be an objective of our future work focusing on the elaboration of a simulation model.

Theory and Methods

Our paper is inspired by the study by Cavicchi (2016), who focused on a contextual explanation of the causal processes of biogas development and sustainable outcomes in Italy using causal loop diagrams as an appropriate tool.

Theory

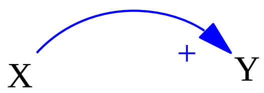
System Dynamics is a discipline that uses modelling and computer simulation to understand, analyse and improve complex dynamic systems (Forrester, 1961; Pruyt, 2013). The underlying idea is that the behaviour of the system is largely determined by its own structure, individual elements and especially by the interconnections between them. System dynamics' argumentation is actually based on the principles of cognitive limitations (Miller, 1956), mental modelling (Doyle, Ford, 1998; Kim, Senge, 1994) and bounded rationality (Simon, 1956, 1979), which describe the limitations of human ability to manage huge amounts of data and information, make rational choices, and address a number of variables and their interconnections in real problems, etc.

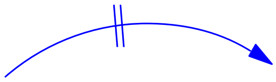
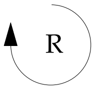
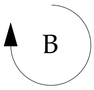
System dynamics is currently applied in a wide range of complex systems in the fields of economics, management, sociology, ecology, and many other areas (Forrester, 1961; Sterman, 2000; Meadows, 2008). The essence of system dynamics consists of defining the problem from a dynamic perspective, where individual elements of the systems are causally interconnected. The dynamic complexity of the systems grows from the feedback structure of the systems, delays between cause and effect and its non-linear relationships, adaptability and resilience, and such systems have counterintuitive behaviour and are characterised by policy resistance (Sterman, 2000). System dynamics is employed to improve the understanding of complex systems. It usually leads to the creation of computer simulation models and management flight simulators; it helps generate understanding of the complexity of the dynamics, and in particular, helps create an understanding of the implications of applied policies and serves to design effective policies (Sterman, 2000). Policy, according to Forrester (1987: 159) is the rule "*by which information sources are converted into a continuous flow of decisions*".

The computer simulations in system dynamics theory are supposed as a necessary aid to understanding the dynamics of complex systems (Forrester, 1961; Coyle, 1996; Sterman, 2000). The system dynamics simulation model expresses the examined object as a system of first-order differential equations. System dynamics simulation models allow the use of soft variables, "*what if analysis*", sensitivity analysis and identification of leverage points (Sterman, 2000; Meadows, 2008). System dynamics models allow a comparison of different scenarios. System dynamics does not focus only on individual discrete events in the development, but underlines the behavioural patterns (Forrester, 1987). To improve the understanding of system behaviour, system dynamics methodology requires the model to be causally closed (Forrester, 1994); the model must contain all relevant variables in an endogenous form and be closed in feedback loops. The model also must not omit key soft variables and variables that are hard to quantify, despite the fact that it complicates the modelling process. "*To omit such variables is equivalent to saying that they have zero effect– probably the only value that is known to be wrong!*" (Forrester, 1961: 57).

When assessing the system using system dynamics, we define the system initially using a Causal Loop Diagram – CLD, and subsequently, a Stock-Flow Diagram – SFD is created. CLD is a substantial tool used for the definition and representation of the structure of feedback systems. CLD, according to Sterman (2000: 137), allows you to 1) quickly record hypotheses about the causes of dynamics, 2) obtain a mental model for individuals or groups, and 3) discuss important feedbacks that seem to be causing a problem. CLD consists of variables that are connected with oriented links, which represent the influences of the variables. The basic building blocks used in system dynamics in the CLD model with icons are shown in Table 1.

Table 1 Symbols of the Causal Loop Diagram (based on Sterman, 2000: 138-139).

Symbol	Interpretation	Mathematics
	"All else equal, if X increases (decreases), then Y increases (decreases) above (below) what it would have been." "In the case of accumulations, X adds to Y."	$\frac{\delta Y}{\delta X} > 0$ In the case of accumulations, $Y = \int_{T_0}^{T} (X + \cdots) dt + Y_{T_0}$
	"All else equal, if X increases (decreases), then Y decreases (increases) below (above) what it would have been."	$\frac{\delta Y}{\delta X} < 0$

	"In the case of accumulations, X is subtracted from Y."	In the case of accumulations, $$Y = \int_{T_0}^{T} (-X + \cdots)\mathrm{d}t + Y_{T_0}$$
	Delay mark	
 R	Causal loop Reinforcing	
 B	Causal loop Balancing	

Polarity-oriented linkages show how the independent variable affects the dependent variable. Feedback loops are important for system behaviour. Feedbacks can be either positive (self-intensifying, labelled as the "+" sign or the letter R as Reinforcing) or negative (balancing, labelled as the "-" sign or the letter B as Balancing). The polarity of the loop describes the effect of the change on one of the variables throughout the whole loop. In case the change of the value of variable consequences in the reinforcing of the original change the loop is positive, when the feedback effect is negative to the initial change, the loop is negative.

In our example (Figure 1), we focus on the dynamics of population growth. As the population grows, so also does the number of births, with a certain time delay. This leads to a bigger population in general (reinforcing loop – R loop). On the other hand, as the population grows, so too does the number of deaths, which lessens the population (balancing loop – B loop). In an isolated environment with limited access to resources, population growth would consume the resources and would decrease the life expectancy and increase the number of deaths of individuals of that population (B loop). Decreased life expectancy increases the desire to have more children, and this leads to an increased birth rate per woman (R loop).

CLD does not enable mathematical modelling of the system. The starting point for mathematical modelling is SFD. More about CLD and SFD can be found e.g., in Sterman (1989, 2000) and Meadows (2008).

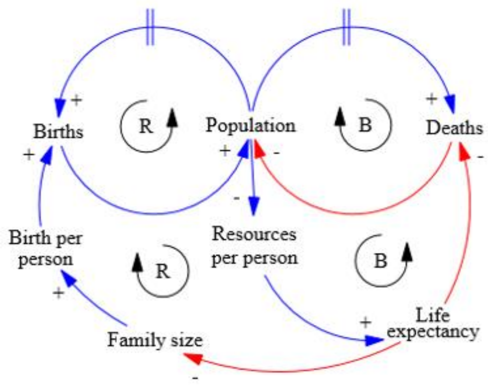


Figure 1 Example of Causal Loop Diagram.

Methods and data sources

The study is based on the qualitative system analysis to identify factors and processes within biogas development from the farmers' perspective in Central Vietnam. The causal loop diagram is based on information and data collected from target groups in two districts - Huong Tra and Phong Dien of the province Thua Thien Hue, Central Vietnam (Figure 2) in 2016 and 2017. The province consists of 1,149,800 inhabitants, 51% of which are considered as rural (General Statistics of Vietnam, 2016). The province lies in a tropical humid climate. The average temperature oscillates approximately 25°C, which is generally convenient for the implementation of small-scale biogas technology. The average precipitation reaches 1600–4000 mm per year, with a monsoon period from September to December

The target groups in the districts of Huong Tra and Phong Dien covered 124 farmers, the owners of a biogas plant, who participated in a questionnaire survey. Furthermore, 9 local authorities (district and commune facilitators) and 3 key informants (one from the Agricultural Forestry Fishery Extension Centre in Hue City (AFFEC) and two from Hue University of Agriculture and Forestry) were interviewed in a semi-structured interview lasting approximately 1 hour. The data were cross-checked by observations.

The data were ordered and processed into a CLD through repetitive cycles of checks to achieve a consistent and complex view of the system of biogas development. We can divide the cycles into three main categories according to origins of used data: 1) data from the questionnaire survey and focus groups with BGP owners and interviews with facilitators served as the basic core, 2) cross-checking data via in-depth interviews with key informants, and 3) verification and supplementation of information in the literature. The final CLD is drawn with the VENSIM software.

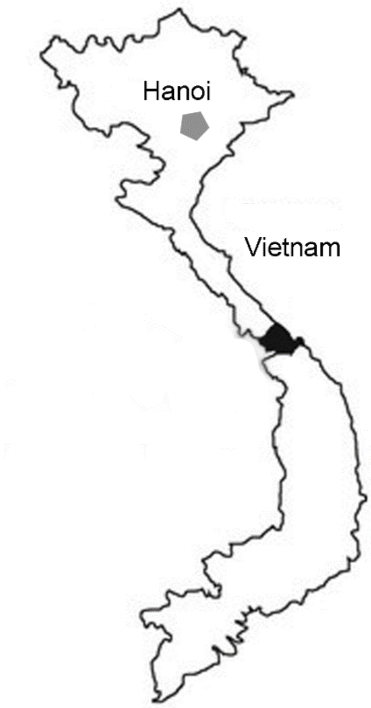


Figure 2 Target area of Central Vietnam.

Results and Discussion

Main stakeholders in biogas technology implementation in Central Vietnam

The view on the issue is taken at the level of small-scale farmers – owners of BGPs. The main stakeholders that play a role in the process are as follows (ordered from the bottom): farmers, extension services, and government.

Farmers – owners of the biogas plant

The population of the target province Thua Thien Hué is considered rural, with 51% (General Statistics of Vietnam, 2016) being directly involved in farming and related activities, such rice cultivation and pig breeding. All surveyed farmers owned at least 5 pigs to sufficiently feed the BGP. Some farmers are also involved in off-farming activities, such are wine and noodle making, small shops, etc. The survey results show that the size of rural households varies from four to five members, of which 2.2 persons are involved in active work. Qu et al. (2013), in their study from China, reported that a larger family show a higher probability to use biogas technology because they have more labour to take care of a biogas plant, and at the same time, they are motivated to save on their higher energy costs for cooking. The surveyed respondents showed various levels of education: tertiary (34%), secondary (55%), primary (10%) and without education (1%). Some authors (Putra et al., 2017) proved that years of formal schooling was an important determinant influencing biogas technology adoption, while others did not find it to be significant (Qu et al., 2013; Li, 2009). The surveyed households built the Chinese digester type – fixed dome digesters in accordance with the NBP. Based on the soil type, the KT1 or KT2 type of digester is implemented. The majority of surveyed households own BGPs with a volume 6 m^3 and 2 years old (54%) (more details in Roubík et al., 2016). In accordance with the activities of the NBP, all surveyed farmers were supposed to attend trainings related to the biogas technology; however, only 79% confirmed participation, and out of them, only 48% showed their satisfaction with the quality of the training. More details about the relationship between gained knowledge and satisfaction with biogas technology can be found in Roubík et al. (2016).

AFFEC – Agriculture, Forestry and Fishery Extension Centre

The public extension system in Vietnam was founded under the jurisdiction of the Ministry of Agriculture and Rural Development (MARD) in 1993. Extension services in the field of agriculture and forestry were provided by the Department of Agriculture and Forestry Extension (DAFE), while those in the field of fishery by the Department of Aquaculture Management of the Ministry of Fishery. In 2003, the first structural transformation happened to optimize the governance and provision of public services of these bodies - DAFE was divided into the two following sections: the Department of Agriculture and the National Agriculture Extension Centre (NAEC); and under the Ministry of Fishery a new body was established – the National Fishery Extension Centre (NFEC). The second transformation occurred in 2008, when the Ministry of Fishery was incorporated into MARD and the Agriculture and Fishery Extension Centres merged into a unique NAEC.

The Extension Centres can be found in all 63 Vietnamese provinces and cities. In 648 districts, there are 585 Extension Stations subordinated to the provincial Extension Centres or the District People Committees (Van Bo, 2012). The Extension Centres involve local facilitators working at the commune, district and provincial levels. Commune facilitators are direct employees of communes, while district and provincial facilitators are paid by the government. Based on our survey, district and commune facilitators have 5.3 (±2.4) years of experience in the field of biogas technology. The commune facilitators supervise 10.0 (±1.9) villages with 122.2 (±65.5) biogas plants (BGPs) on average. In the extension service hierarchy, the commune facilitators are subordinate to district facilitators. In our case, the commune facilitators are subordinate to the facilitator from the Huong Tra district Agriculture Forestry Fishery Extension Service (AFFES), with 10 years of experience, 60 villages and 4 commune facilitators under his administration; and to the facilitator from the Phong Dien AFFES, with 7 years of experience, 70 villages and 4 commune facilitators under his administration. Technical management connected with the issue of biogas technology of the whole province - 150 villages and 40 facilitators - is up to the provincial facilitator from the Agriculture, Forestry and Fishery Extension Centre (AFFEC). Facilitators play an essential part in BGP implementation. They approve the eligibility of the selected farmers (the selection is performed by the Peoples' Committee of the commune) and coordinate the masons, which are contacted by the Extension Centre, in building the BGPs.

The Government

In general, many authors (e.g., Jan and Akram, 2017; Chen and Liu, 2017; Qu et al., 2013) agree that the government plays an important role in biogas technology development. In Vietnam, the government is, represented by the Ministry of Agriculture and Rural Development, which implements the National Biogas Programme (NBP) (chapter 1.3). The NBP currently provides the structure of the programme, qualified human resources, including trainers, trainings for facilitators, farmers and masons, and dissemination of information among farmers (through AFFEC – chapter 3.1.2.), and a subsidy of 45 – 90 USD for BGP construction, with an expected exit strategy decreasing the subsidy; however, the exact value is not currently clear. Qu et al. (2013) emphasizes the possible failure of further biogas technology diffusion once the governmental programmes end.

Aspects and process of biogas development from farmers' perspective

To uncover the system dynamics of biogas technology implementation, we present the complete CLD (Figure 3), where motivation of farmers is our key variable that influences the final decision regarding the purchase (or not) of a biogas plant and keeping it (or not) functional. This complete CLD involves all stakeholders, variables and their relationships. The important variables and relationships are clustered into technical, financial, and satisfaction aspects, which are elaborated in separated CLDs, with only relevant causal loops marked and named, and formal aspects, including adequate information dissemination.

To increase the clarity of the diagrams, the parameters that are not causally closed are written in red. The grey variables in pointy brackets represent the shadow of the variable, which is used to minimise the crossing of the links.

The motivation of a farmer is first influenced by the technical aspects (Figure 4) of implementation of biogas technology, such as the availability of a construction site; for the digester of 6 m^3, we calculate ca 19 m^2 is required in the garden, with the requirement of the distances of 2 m from trees and at least 10 m from the well. Furthermore, another influence is the availability and accessibility of necessary construction material, which is in practice composed of 1,100 pieces of bricks, 1,500 kg of cement, 6 kg of steel rod reinforcement and plastic tubes. It is also important to consider the distance from town - we assume that the costs of construction materials as well as the cost of transportation will be higher and may hinder the motivation of the farmer. We also involve agro-climatic conditions that define the optimal time for BGP construction (not in a monsoon season from September to December). The household then has to be capable of providing enough feedstock for the BGP, which means owning 5 pigs as a minimum. Greater motivation of farmers leads to a higher number of newly built BGPs in the districts/regions (B1). However, having the BGP in the garden is not the same as having a functional BGP in the garden. During our observation of BGPs, we have recognised cases when BGPs were not in use anymore for different reasons, such as the lack of pigs, the low efficiency of produced biogas, the malfunction of a biogas cooker and others (more can be found in Roubík et al., 2016). Regular maintenance can prevent failure of the functionality of the BGP. Furthermore, relevant rehabilitation and repair activities can put the abandoned BGPs back into operation (R1).

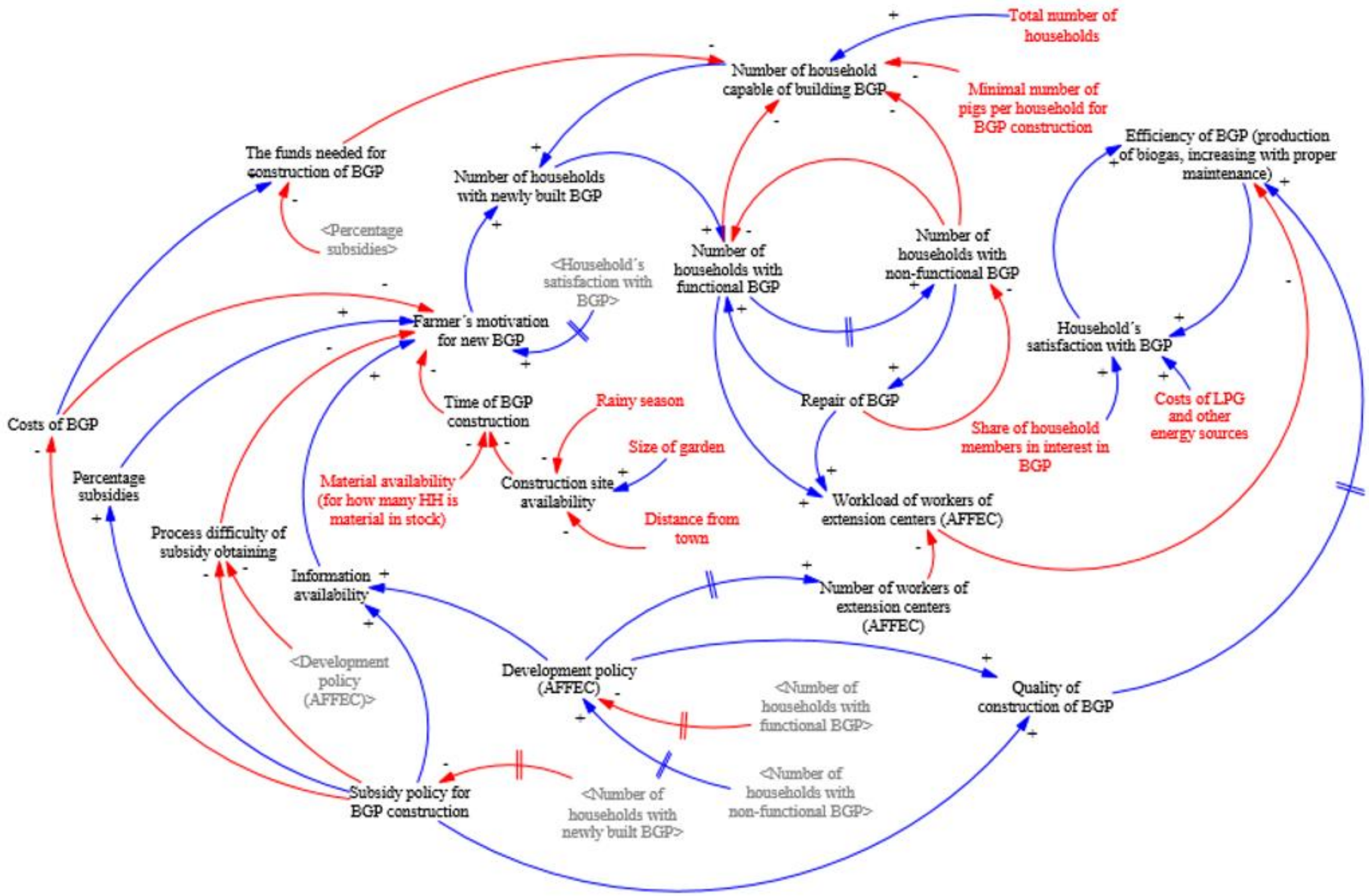


Figure 3 Complete Causal Loop Diagram of biogas development from the farmer´s perspective.

The number of households capable of building a BGP determines the number of households with a newly built BGP (functional or not in future), and consequently, the real space where the new BGP can be built. This means that the number of "capable" households will decrease as the biogas development is saturating (B2).

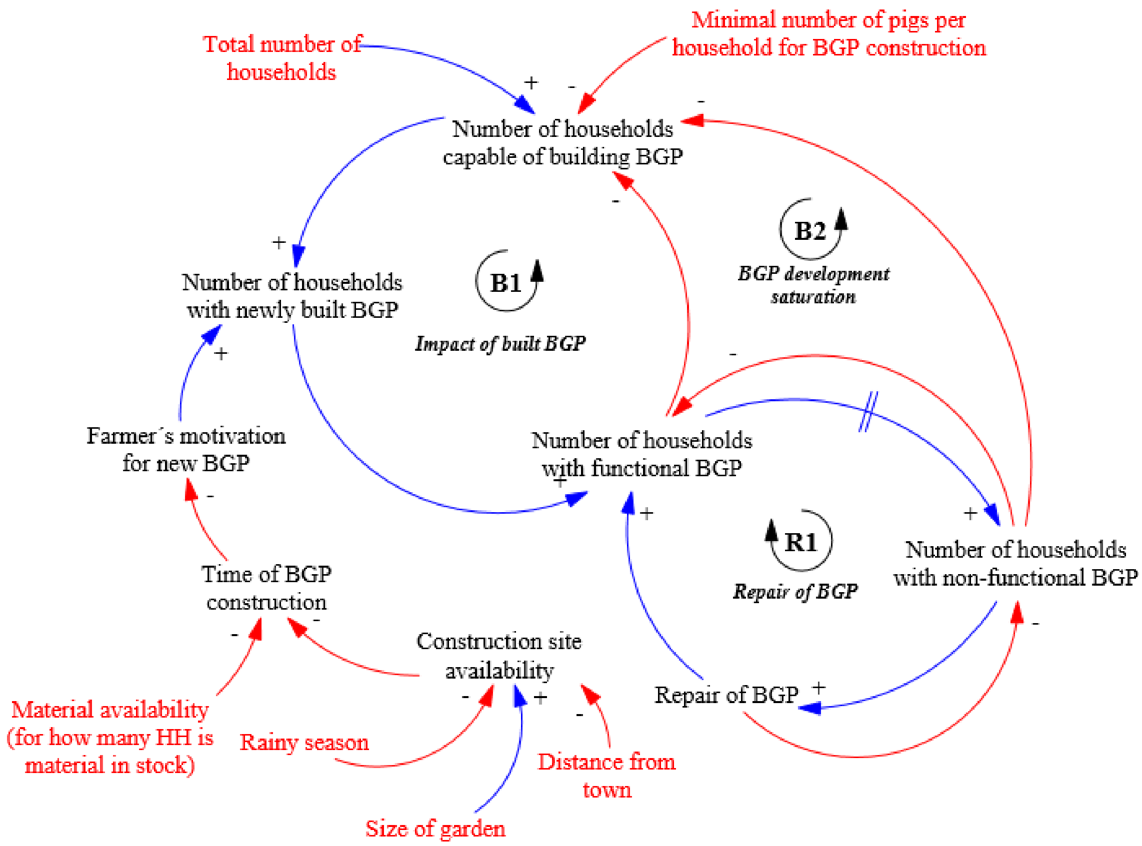


Figure 4 Technical aspects.

The financial aspects (Figure 5) are another cluster of variables that play a key role in a farmer's motivation in various ways. The impact of subsidy policy on a farmer's motivation (B3) is represented by three causal loops that vary in stimulating (*Information availability* and *Percentage subsidies*) or suppressing (*Process difficulty of subsidy obtaining*) the motivation of the farmer to build the BGP, and consequently, to contribute to the increase in the number of households with newly built BGPs. The current subsidy policy for BGP development provides farmers with a subsidy of 10 – 20% of the total costs of the BGP (which varies from 45 to 90 USD) for the BGP with a volume of 6 m^3. If the farmer decides to have a bigger volume for the BGP, he pays more - the subsidy is not increased. In the future, if the subsidy decreases, the real costs for farmers will increase, which will demand higher funding from their side. Then, not all farmers have access to financial sources (the most common ways to obtain financial resources in the area are available savings, the possibility of borrowing from family or getting a loan) and are not capable of building the BGP (B4). Although the subsidy is available, farmers often do not know about it or the application process is too problematic and incommodious for them, resulting in lower motivation. Furthermore, farmers have to fulfil the requirement on the minimum number of pigs (5 heads) to become technologically (assurance of enough production of pig slurry to feed the BGP) and economically (application for subsidy) eligible. Previously published articles (summarized in Qu et al., 2013) pointed to the fact that farmers with low incomes have difficulties investing in a BGP. Hence, most biogas users belong to upper and medium-income groups, which are capable of investing the rest if the governmental subsidy covers one-third of the total price of the BGP.

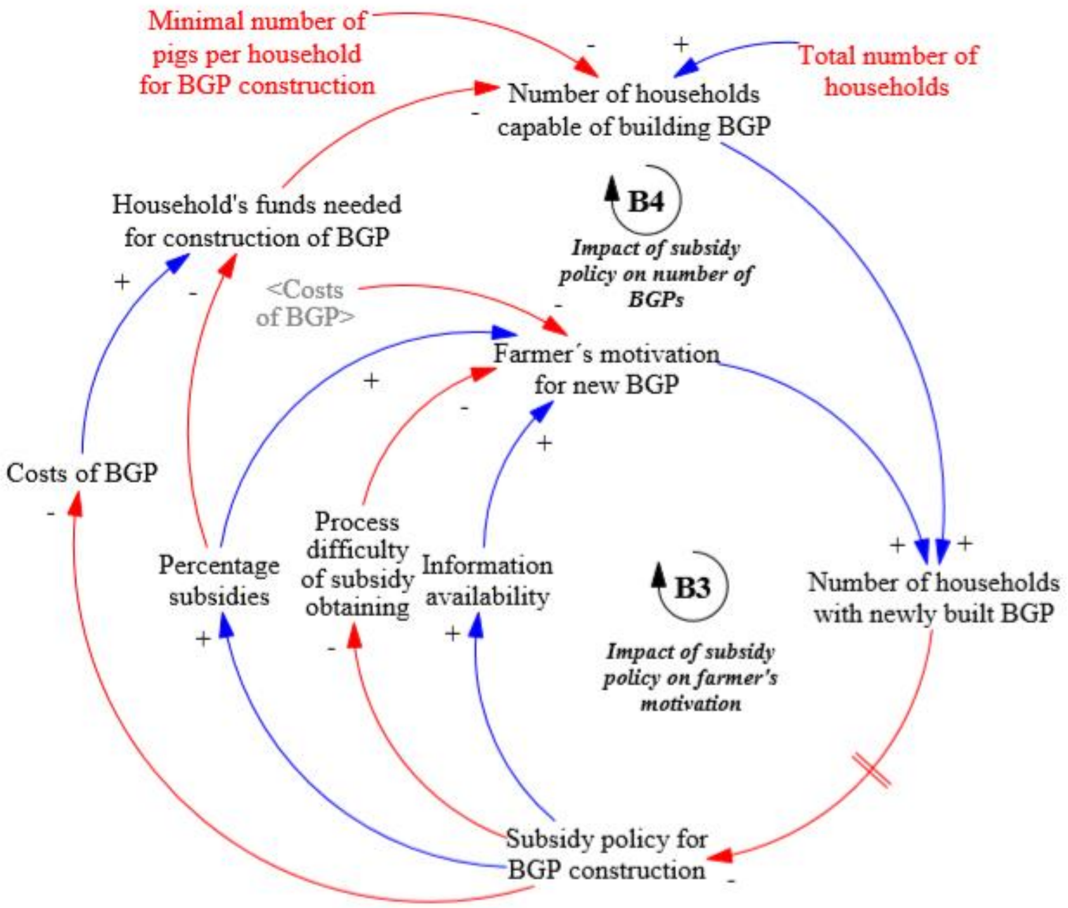


Figure 5 Financial aspects.

Furthermore, there are also formal aspects in the process of gaining a BGP, such as enough finances and discussions with village/commune leaders and with the People's committee. The commune can get subsidized only limited number of BGPs as stated in the NBP. Farmers usually register for the BGP, and if there are more farmers interested than the subsidies available, then selection by commune leaders is applied. The list of chosen farmers is sent to the People's committee. Facilitators visit the farmers and check their eligibility, then send the list to the Extension Centre of the AFFEC. Before the construction of BGPs, the chosen farmers attend trainings and are provided with relevant printed materials about biogas technology and the BGP. Farmers choose the volume of the BGP and receive the relevant subsidy. It takes up to two months from the decision of farmers to finish the BGP. In the meantime, farmers sometimes reject construction because they want to stop breeding pigs, or when the BGP has started to be built, the conditions are more difficult than expected, e.g., the soil contained too much water or there were too many stones.

One of the key players is the AFFEC and its capacity to disseminate adequate information about BGPs and provide technical support to new and already operating BGPs. The study by Qu et al. (2013) from rural China demonstrated that if farmers receive information about biogas technology from the government rather than other sources, they are much more likely to build BGPs. Abbas et al. (2017) emphasize, in their study from rural Pakistan, the role of extension services in the increase in the adoption rate of biogas technology, as well as in the improvement of the perception of farmers regarding the economic benefits of the technology. A well-established development policy of the AFFEC influences the quality of construction of BGPs, and consequently, its efficiency, resulting in high satisfaction with BGPs and enhanced motivation of farmers. Improvements in biogas development policy together with enhancements of the performance of the AFFEC (incl. providing competent facilitators) lead to the facilitation of the process of getting a subsidy for BGP construction and also to a higher quality of constructed BGP (trained and skilled masons and facilitators). This directly positively influences farmer's motivation and consequently the increased number of households that have implemented their interest in biogas technology.

Farmers are also motivated by their satisfaction with biogas technology (Figure 6) that provides multiple benefits and that is either owned by them or by their neighbours. In the first case, we suppose that farmers already own the BGP and that they are satisfied with its operation, efficiency (production of biogas increasing with regular and well-done maintenance (R2)) and benefits and that they are motivated to keep the BGP functional. The functionality is not fully in the hands of the family members but also of the workers/facilitators of AFFEC, who are able to help with the technical problems; however, their number is limited, and their workload is high, as mentioned above. The second case is related to the satisfaction of the owners with the efficiency of the BGP positively influencing their neighbours to build BGPs. The lifespan of the fixed-dome digester is estimated at 20 to 25 years. Nevertheless, as we observed, some farmers abandoned the technology much earlier (after 5 to 10 years). A study from Uganda (Lwiza et al., 2017) reported abandonment of biogas technology 4 years after installation. The principle stated factors for abandonment included problems with the functionality of biogas plants and low or no availability of spare parts, reduced labour supply (children started school attendance), inability to sustain livestock production (sales, epidemic diseases, thefts), and dissatisfaction with real biogas performance (not a perfect substitute fuel for staple food cooking and lighting) in comparison with users' expectations.

The *Impact of Development policy on household's satisfaction* (B5) with biogas technology is represented by three causal loops, highlighting the assumptions of well-designed *Development policy* at the AFFEC level (*Quality of construction of BGP*, *Number of workers of extension centres (AFFEC)* and their *Workload*), leading to higher *efficiency of BGP* and satisfied farmer households.

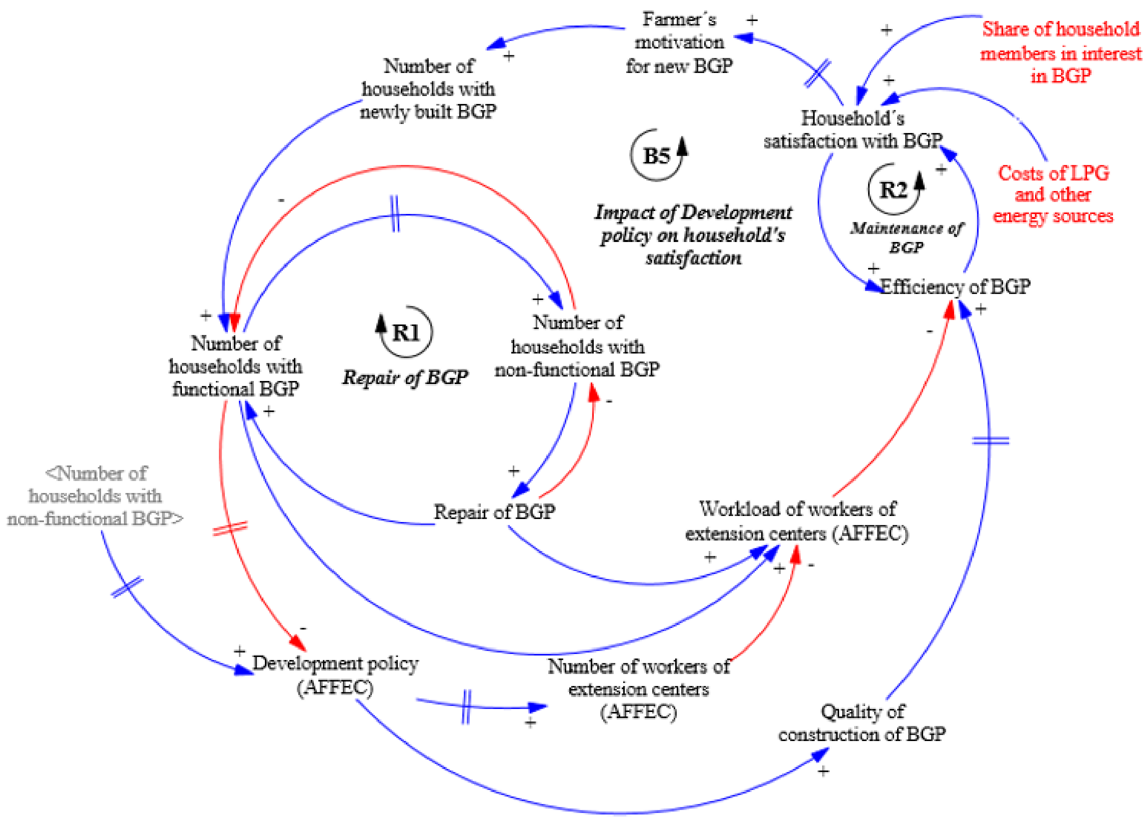


Figure 6 Satisfaction aspects.

The NBP aims at the progressive growth of BGPs in the region. However, there is a need to consider a factor of functionality of the BGPs. Increasing the number of BGPs does not always mean an increasing number of functional BGPs in the long term. Each BGP requires regular maintenance, such as cleaning every 5 - 10 years, when breaking of floating scum in the digester takes place (Spuhler, 2014). If the BGP is not working properly, it compromises most of the benefits of this technology (Roubík et al., 2016).

Conclusion, Outlook and Recommendations

The view on the development of biogas system in Central Vietnam is taken at the level of small-scale farmers who own biogas plants. The main stakeholders that play a role in the process are as follows (ordered from the bottom): farmers, extension services, and the government. As the complexity of the biogas technology among rural households in Vietnam has not been described before, this paper provides insight into the system of biogas technology implementation from the motivation of farmers to well-functioning biogas plants, presenting all major stakeholders and factors involved and setting up the principle relationships among them. The paper aims to contribute to policy-making and the creation of action plans. The proposed approach provides a feedback concept with relationships and their mutual influence amongst each other.

The system description via causal loop diagrams developed in our study is the first attempt to investigate the development of biogas technology from farmers' perspective. The causal loop diagrams will serve as a decision support and policy-making tool for influence assessments of various measures and decisions. The current system is applied to the case of Vietnam and its National Biogas Programme; however, it could be applied to fellow developing countries that have biogas programmes with a similar structure. In addition, the system may be developed further by adding new elements and/or analysing additional decisions and measures.

In further research, we expect to develop a more detailed dynamic model and simulate scenarios that will provide the desired insight into the issue. In addition, several models of subsystems will be developed, e.g., presenting a system of biogas technology itself.

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5. CONCLUDING REMARKS

This dissertation is prepared in the form of a series of scientific papers. As obvious in the following figure (Figure 1), this dissertation is covering complete assessment of small-scale biogas technology in Southeast Asian countries. The perspective is shown on the case country of Vietnam for clarity and contextuality, however, further examined countries can be found in the appendix (papers **VI.** to **XI.**).

The technical perspective is covered especially in the papers **I., II.,** and **III.**

The social perspective is covered especially in the papers **IV.** and **V.**

The economic perspective is covered especially in the paper **V.**

The environmental perspective is covered in the papers **I., II., III. IV.,** and **V.**

The future development of biogas technology is covered in the paper **V.**

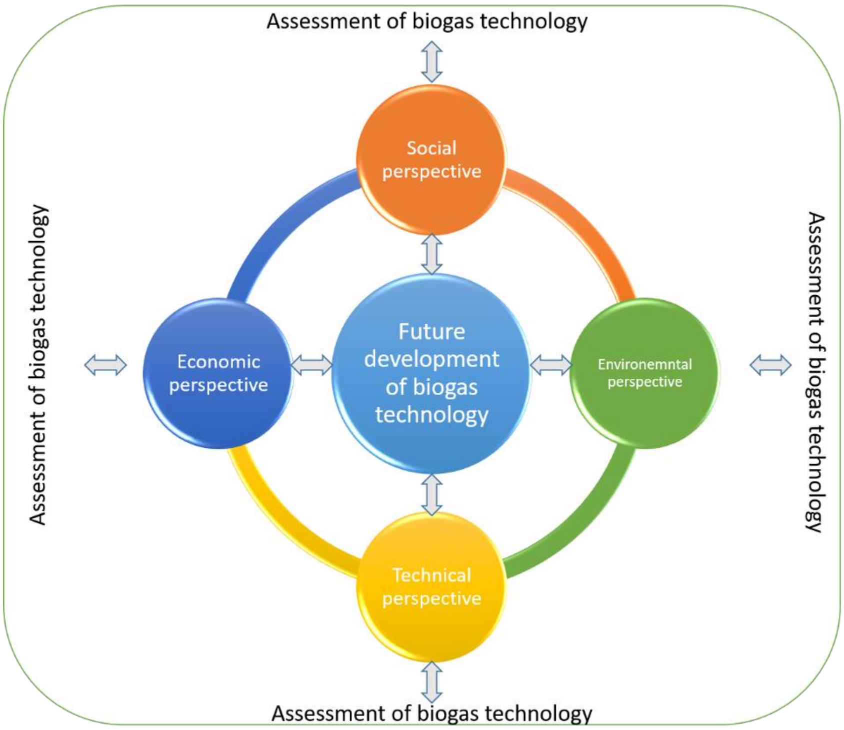

Figure 1 Approach to cover a complete assessment of small-scale biogas technology in Southeast Asian countries.

Small-scale biogas plants can play a vital role in farming systems and add value to agricultural waste and livestock excreta. This technology offers significant advantages, especially in regard to energy, the environmental and economic development. However, it needs to be noted, that one third of examined biogas plants have experienced problems with biogas technology. Therefore, an innovative problem analysis of biogas technology was developed in this research. Furthermore, the average payback period for biogas plant was calculated for 4.46 years without any subsidy in Vietnam. This is an important motivation indicator for the owners of biogas plants, as for the good adoption of technology is necessary to have relevant return on investment. In addition, this study indicates importance of working information flow between actors.

Households use biogas mainly for cooking and not for lightening or electricity generation. Cooking includes not only food for family, but also preparation of food for livestock, when there is some superfluous biogas. The average daily biogas production equals to 0.499 m^3, however, such an amount is not covering demand of a typical rural household. Therefore, the majority of respondents are still using additional energy sources in form of LPG and/or electricity (for cooking rice in rice cookers) and fuelwood (usually for cooking of feed for animals). The content of CH_4 and CO_2 in biogas from small-scale biogas plants was 64.34% and 30.36%, respectively. Nevertheless, it needs to be stated, that biogas quality is stable during life-span of small-scale biogas plants.

Our research revealed high CO emissions in flue gas which were associated with low-quality biogas cook stoves and feedstock type and low-quality biogas cook stoves are remaining an issue. Low air/gas efficiency was found for commercial cooking using household stoves. CO_2 emissions increase with the age of biogas stoves and are highest for short cooking times. In addition, our study on flue gas fills an existing data gap, as similar studies have not been conducted before in Southeast Asia. The information and data gained are important for further evaluations of biogas technology and associated research and development in areas of developing countries in Southeast Asia.

The management of digestate is a fundamental issue and requires an immediate solution. Currently, it is not satisfactory and insufficient use of digestate is undermining benefits of biogas technology. Excessive water use for washing pigpens was reported for both types of farms – those with biogas technology as well as for farmers without biogas technology. The biogas potential was actually calculated as being two times higher than actual biogas generation, if majority of livestock organic waste would be used for biogas technology and use of water would be optimized. Furthermore, the information on and the management of digestate were recognized as unsatisfactory.

Reasons for adopting biogas technology were divided into Environmental, Economic, Technical and Social clusters providing so a complex view of the motivating factors and the currently valued benefits recognized by biogas plant owners. Appreciation of the relationship with the environment was consistent and many were inclined to recognize the economic benefits. In general, the understanding of biogas technology was relatively high among farmers (the exception was the lack of knowledge about digestate management); however, the primary barrier to a wider dissemination of this technology was the absence of financing.

Last, but not least, this research presents an innovative approach that uses system dynamics. A system dynamics complex model is proposed based on the motivation of farmers to well-functioning biogas plants. The system description via causal loop diagrams developed in our study is the first attempt to investigate the development of biogas technology from the farmers' perspective. The causal loop diagrams will serve as a decision support and policy-making tool for influence assessments of various measures and decisions.

The findings of this study have a number of practical and important implications for future practices in Vietnam and other Southeast Asian countries regarding small-scale biogas technology. In addition, our study is concluding that small-scale biogas plants sustaining a stable level of biogas quality during their life-span. The information and data gained are important for further evaluations of biogas technology and associated research and development in developing countries in Southeast Asia. The final results of this study are useful not only for further researchers, but also for local authorities in Southeast Asia, especially for facilitators at the local level, as well as for programme designers and policy makers.

Systematic empirical studies of this topic are a high priority for further research activities. In further research, we expect to develop a more detailed dynamic model and simulate scenarios that will provide the desired insight into the issue. In addition, several models of subsystems will be developed, e.g., presenting a system of biogas technology itself. Furthermore, in the following research, we also expect to present a full systematic greenhouse gas emission analysis of typical household biogas plant, which will be quantifying avoided emissions by use of a biogas plant.

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10. APPENDIX CONTAINING FURTHER ABSTRACTS OF PAPERS

Small-and medium-scale biogas plants in Sri Lanka: Case study on flue gas analysis of biogas cookers

Adopted from: **Roubík, H.,** Mazancová, J., 2016. Small-and medium-scale biogas plants in Sri Lanka: Case study on flue gas analysis of biogas cookers. Agronomy Research 14(3), 907-916.

Author was responsible for the idea, conceptualization, methodology, data collection, performed all experimental work, analysed the data, wrote the original manuscript, and executed its revision.

Abstract

Biogas technology has received attention in Sri Lanka already from the initial days of the energy crisis in 1973. Biogas production by anaerobic fermentation is a promising method of producing energy while achieving multiple environmental benefits. The study was carried out in the different areas of Sri Lanka at the level of biogas plants owners (n=51) and local consultants (n=4) in August 2014. Methods of data collection included semi-structured personal interviews and questionnaire survey. Further, at 51 biogas plants flue gas analysis was done through the portable device TESTO 330-2, which is capable of capturing the gas concentration of CO and NO; consequently by recalculating the concentration of CO_2 and NO_2. Surprisingly, the quite high concentration of CO was detected c(CO)=1008.92 mg·m^{-3}, which might be caused by one and/or various combinations of the following factors such as insufficient burning, inappropriate biogas cookers and inappropriate maintenance. The concentration of NO is under the value of 0.046 mg·m^{-3}, which is under the permissible exposure limit of nitric oxide. Average temperature of flue gas is within the typical flue gas exit temperature for burning in biogas cookers (TS = 449.16°C) and flue gas excess air (4.0 %), however the air/gas efficiency (54.0 %) was recognized at lower value than the optimal one for small- and medium-scale biogas plants. Easy energy access is a trigger for development, especially in terms of human, social and economic development and biogas plants represents a boon for farmers and rural people to meet their energy needs. However, further

factors must be also examined and evaluated, such as exploration of gas composition and its microbiological content, emission analysis exploring particle size distribution, emission rates and potential harmful exposures.

Keywords: biogas technology, biogas cookers, Sri Lanka, flue gas analysis

Suitability of small-scale biogas system for the rural areas in northern Sumatra

Adopted from: **Roubík, H.,** Mazancová, J., 2018. Suitability of small-scale biogas system for the rural areas in northern Sumatra. Submitted to Renewable Energy (20/06/2018).

Author was responsible for the idea, conceptualization, methodology, data collection, performed all experimental work, analysed the data, and wrote the original manuscript.

Abstract

Almost a half of rural population of Indonesia suffers from lacking access to safe sanitation, protecting users and environment, and lacking access to energy. Several international programmes have been implemented to improve the situation in both aspects at once. One such option is application of small-scale biogas systems that produce biogas via anaerobic digestion of organic waste materials. A baseline field survey using semi-structured personal interviews based on questionnaires was carried out among randomly selected rural households (n=196) in northern Sumatra in July-August 2014. The follow-up field visits to verify the results from the first stage were organised in August-September 2016. The collected data were categorized, coded and analysed using Microsoft Office Excel software. We applied predictive modelling based on statistical data from previous years. This paper investigates the potential development of small-scale biogas system and its suitability in rural areas of northern Sumatra. The increasing demand for farm animal products and the growth of the livestock population leads to the production of a large amount of organic waste. Such waste needs to be handled, and one way to manage this waste is small-scale biogas technology, which offers significant advantages, especially regarding energy, environment and economic development.

Keywords: Biogas; Waste management; Livestock; Indonesia; Sumatra

Identification of Context Specific Knowledge as tool for facilitators and their quality involvement – using Vietnamese practice as an example

Adopted from: **Roubík, H.,** Mazancová, J., 2018. Identification of Context Specific Knowledge as tool for facilitators and their quality involvement – using Vietnamese practice as an example. Submitted to NJAS - Wageningen Journal of Life Sciences (29/08/2016).

Author was responsible for the idea, conceptualization, methodology, data collection, performed all experimental work, analysed the data, and wrote the original manuscript.

Abstract

In Central Vietnam two key actors in the extension performance of biogas technology are involved: owners of biogas plant and facilitators. Facilitators as the immediate providers of advice and services are in a direct contact with local farmers and belong to the Vietnamese national extension network. This paper aims at identifying the current state of extension services and creating proper recommendations for further process of trainings in the target area through identification of Context Specific Knowledge (CSK). CSK can serve as a tool for facilitators and their quality involvement for improvement of current training practices in the area. It also provides performance indicators (PIs) for facilitators' quality assessment. PIs should be a consistent part of the educational process for evaluation of knowledge transmission success. More research in terms of facilitator's impacts on the knowledge transition process towards the BGP owners should be done to prove sustainability of the extension services.

Keywords: Biogas technology, Quality assessment, Extension Services

Small-scale biogas sector in central Vietnam: ways of financing of the technology

Adopted from: **Roubík, H.,** Mazancová, J., 2016. Small-scale biogas sector in central Vietnam: ways of financing of the technology. Agrarian Perspectives XXV., 312-318.

Author was responsible for the idea, conceptualization, methodology, data collection, performed all experimental work, analysed the data, wrote the original manuscript, and executed its revision.

Abstract

Biogas technology is considered as one of the important drivers to struggle challenges as access to energy resources, economic development and environmental pollution. As it solves waste management problems and simultaneously produces biogas and digestate as a by-product. Although household biogas programs have experienced rapid development and achieved remarkable benefits, the current widespread reduction in the use of digesters may hinder further progress. Hence, it is important to comprehend the economic aspect of the technology from the view of its financing as the main beneficiaries are rather poor farmers. The survey was conducted in the province of Thua Thien Hue in central Vietnam from July to September 2012, furthermore followed by field visits in June and July 2016. The target group covered randomly selected owners of small-scale biogas plants (n=141). The collected data were categorized, coded and analyzed using MS Excel. The results revealed that only 6 % of households fully financed the construction of biogas technology with their own savings. This emphasizes the need of various methods of co-financing (mainly subsidies or loans). The subsidy from the National Biogas Program was used by 88 % of the households. Only one third of farmers would consider building biogas plant without subsidy which shows high importance of involvement of other actors. Our findings divulged a high degree of participation of family members in decision on investment in a biogas technology; however, the role of a male household head was dominant in the final decision. Vietnamese domestic biogas sector plays a vital role in farming systems and adds value to agricultural waste. It offers advantages in regard to energy, environmental and economic development. However, in terms of financing of this technology our study reveals that it is not adequately available to the poorer and poorest farmers. Further policy implications should be executed.

Keywords: Biogas, Biogas sector, Technology financing, anaerobic digestion, socio-economic aspects

Livestock manure management practices in rural households in Tapanuli Utara regency of North Sumatra

Adopted from: **Roubík, H.,** Mazancová, J., Situmeang, R.C., Brunerová, A., Simatupang, T.M., 2017. Livestock manure management practices in rural households in Tapanuli Utara regency of North Sumatra. Agronomy Research 15(4), 1782-1794. http://dx.doi.org/10.15159/ar.17.055

Author was responsible for the idea, conceptualization, methodology, data collection, performed all experimental work, analysed the data, wrote the original manuscript, and executed its revision.

Abstract

Livestock manure management is a big challenge for low income economies including the region of North Sumatra, Indonesia. Currently, low percentages of manure managed cause illegal disposals, and negative impacts on public health and environment. Therefore, the objective of this study was to assess the current trends among livestock manure management practices in rural households and to recognize potential problems with it. The questionnaire survey using randomly selected households (n = 196) was administered in the province of North Sumatra, Tapanuli Utara regency, from July to August 2014; then followed by several field visits from August to September 2016. Data obtained in the survey were analysed with descriptive statistics and cross tabulation. Majority (81%) of rural households handle manure in the process of either composting (75%) or sun-drying (6%). Remaining 6% of the respondents does not handle manure at all. Manure could represent valuable energy and plant nutrition resource, if used appropriately. However, if not handled at all or handled inappropriately, it can lead to the environmental problems. Our results revealed that current ways of stabling of livestock are inappropriate from the environmental perspective. The stabling has got only dusty earthen floor, which makes difficult for farmers wash out the excrements and pollution. Hence, there is a need to improve manure management practice to eliminate potential threats as current practices do not protect either humans, animals or environment against the risk of contamination with potential zoonotic pathogens.

Keywords: manure management, waste management, Indonesia, livestock sector, rural household, Sumatra

Quantification of biogas potential from livestock waste in Vietnam

Adopted from: **Roubík, H.,** Mazancová, J., Phung, L.D., Dung, D.V., 2017. Quantification of biogas potential from livestock waste in Vietnam. Agronomy Research 15(2), 540-552.

Author was responsible for the idea, conceptualization, methodology, data collection, performed all experimental work, analysed the data, wrote the original manuscript, and executed its revision.

Abstract

Quantification of biogas potential in Vietnam is highly needed to provide sufficient information for authorities properly support their future policy decisions. To achieve the aim of this investigation, two methods were applied: (i) the method for calculation of the amount of manure and its biogas potential from chosen livestock obtained from statistical data and (ii) the method for future forecast using middle scenario applications based on previous development of specific category, presuming homogenous continuation of growth. The total biogas energy potential in Vietnam was quantified to approximate 120,000 T·Jy-1 in 2015 and has the potential of increasing to 127,000 TJ·y-1 by 2020. However, when considering current manure management practices (including accessibility factor and collection efficiency) biogas potential was quantified to the values of almost 67,000 T·Jy-1 in 2015 and over 71,000 T·Jy-1 by 2020 if the current manure management practices remain unchanged. Biogas has the potential of generating renewable energy, while meeting requirements related to waste treatment and minimizing environmental impacts. This study shows that animal waste is a promising sustainable energy source in Vietnam which can be efficiently utilized for the generation of biogas energy as well as electricity. Furthermore, anaerobic digestion of livestock waste has the potential to play a vital role in farming systems by adding value to agricultural waste and livestock excreta, and reducing their presence in the environment therefore enhancing public health. There is a high development potential for the decentralized energy generation due to the exploitation of small-scale biogas plants in Vietnam. However, it is essential to realize that competition to other energy generating technologies is present.

Keywords: biogas potential, quantification, biogas, Vietnam, livestock waste, anaerobic digestion, manure management