ISSN 2226-6062

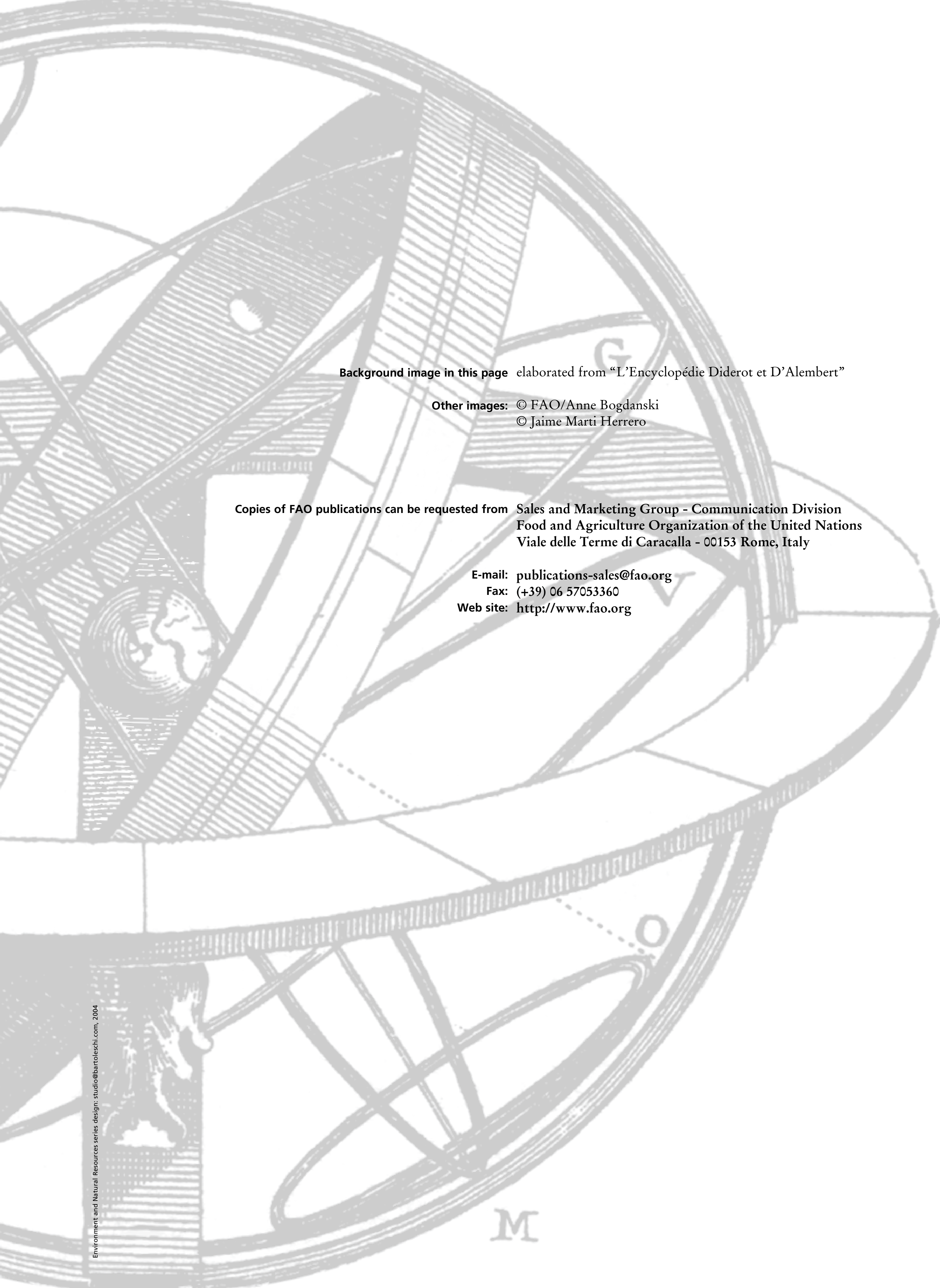
55

BIOSLURRY = BROWN GOLD?

A review of scientific literature on the co-product of biogas production

ENVIRONMENT AND NATURAL RESOURCES MANAGEMENT WORKING PAPER

ENVIRONMENT CLIMATE CHANGE [ENERGY] MONITORING AND ASSESSMENT



Background image in this page elaborated from "L'Encyclopédie Diderot et D'Alembert"

Other images: © FAO/Anne Bogdanski
© Jaime Marti Herrero

Copies of FAO publications can be requested from **Sales and Marketing Group - Communication Division**
Food and Agriculture Organization of the United Nations
Viale delle Terme di Caracalla - 00153 Rome, Italy

E-mail: **publications-sales@fao.org**
Fax: **(+39) 06 57053360**
Web site: **http://www.fao.org**

Environment and Natural Resources series design: studio@bartoleschi.com, 2004

ISSN 2226-6062

55

ENVIRONMENT AND NATURAL RESOURCES MANAGEMENT WORKING PAPER

ENVIRONMENT CLIMATE CHANGE [ENERGY] MONITORING AND ASSESSMENT

Bioslurry = Brown Gold?

A review of scientific literature on the co-product of biogas production

Lennart de Groot and Anne Bogdanski

Food and Agriculture Organization of the United Nations
Rome 2013

E-ISBN 978-92-5-107929-4 (PDF)

ACKNOWLEDGEMENTS

We would like to thank all colleagues who provided technical insights and useful feedback for this report: Mathias Varming contributed to an earlier draft, Olivier Dubois, Theodor Friedrich, Klaas Dietze, Andreas Thulstrup, Yuji Niin, Alessandro Flammini, Christina Seeberg and Jaime Marti Herrero gave detailed feedback. Support to the editing of this document was provided by Sharon Darcy and the layout was carried out by Maria Guardia. Jaime Marti Herrero provided us with the majority of the pictures used in this report.

SUMMARY

In recent years, there has been an increasing interest in anaerobic digestion of farm and household residues in many parts of the world. Smallholder biogas digesters and community biogas plants can be found all throughout Asia, but also progressively in Latin America and Africa.

Anaerobic digestion produces two main outputs: biogas and bioslurry, the digestate or digester effluent. While biogas is used to produce energy, the large potential of bioslurry has often been overlooked. A large part of both the scientific and grey literature focuses on the production of energy alone, but does not venture into the multiple uses and intricacies of bioslurry use. Technical organizations such as NGOs, extension services and local universities and, last but not least, smallholders themselves, are often not fully aware of the multiple benefits of bioslurry use, nor do they know of the risks associated with handling and applying it on their farm.

This review therefore attempts to synthesize the findings of the growing peer-reviewed literature on bioslurry to provide a sound and scientific basis for bioslurry use. At the same time, it sets out to identify the various research gaps.

The majority of research has been conducted on the effect of bioslurry use on different soil structure and fertility parameters as well as on biomass and crop yield compared to the use of other organic fertilizers, or to the application of synthetic inputs. While, in general, it can be stated that bioslurry has proven to have positive effects on yields of grains, vegetables and fruit compared to not using any soil amendments and fertilizers at all, the comparison with other organic fertilizers such as undigested farm yard manure or compost, and with synthetic fertilizers like urea, remains very ambiguous.

The results vary widely between different experimental designs. In some cases bioslurry outperforms synthetic or other organic fertilizers, in others it is the other way round. These results are not surprising, however, if one considers the varying nature of bioslurry in terms of organic matter and nutrient content, the characteristics of different types of soil and the nutritional requirements of different crop species.

Only two studies examined the impacts of bioslurry on crop quality in terms of the amount and the variety of proteins and macro and micronutrients, which proved to outperform conventional fertilizers. However, the limited number of studies does not permit general conclusions to be drawn.

No studies have analysed the implications of bioslurry use on long-term soil fertility. This might be particularly interesting when compared with synthetic fertilizer use.

Some researchers analysed the effects of bioslurry on fish production. All studies showed positive results, as slurry considerably increased the population of phyto- and zooplankton, thereby increasing the amount of fish feed in the ponds. Most authors therefore stress the potential of substituting conventional fish feed with bioslurry.

Only few research papers looked at the potential of feeding other animals such as

cattle and swine with bioslurry. The only two scientific studies found on this subject recommended to use slurry as animal feed only in times of food scarcity, or to use it as an additive to the normal diet. The studies do not report any incidence of disease.

A couple of papers report on the potential of using bioslurry as pesticide. Studies found that bioslurry is a good alternative to synthetic pesticides in order to combat nematode manifestations. Others report on the effects of bioslurry as an alternative to conventional fungicides. The researchers found that the biogas effluent does have fungicidal properties, yet in the studies it did not perform as well as its synthetic counterpart. Further research is needed to determine the full potential of bioslurry as pesticide and fungicide for different pest and fungi species. Further efforts are also needed to determine the ideal quantity and interval between bioslurry applications.

Despite limited research in this field, two studies clearly showed that the organic matter fraction of bioslurry has the large potential to reduce or inhibit toxic substances in soils. This has been shown for the herbicide *atrazine* and the insecticide *chlorpyrifos.*

The associated risks of spreading the slurry directly on crops or incorporating it into agricultural soils are frequently overlooked. It is often falsely believed that the anaerobic digestion process inevitably kills all pathogens present in animal manure. The scientific literature clearly shows that both temperature and retention time are crucial parameters to determine whether the resulting effluent can be used without causing health risks. Bioslurry does in many cases still contain a considerate amount of pathogens such as bacteria, nematodes or viruses, although often in smaller quantities than in undigested manure. This has been shown for the bacteria *Clostridium perfringens, Listeria monocytogenes, Salmonella spp.,* yet further research is still necessary in this field. The same applies for the effectiveness of anaerobic digestion on nematodes and viruses.

Some seeds, including those from undesired weeds, survive the anaerobic digestion process. Studies in this respect are scarce, but available literature indicates that the operating temperature of the digester and the time of digestion play a significant role in reducing the germination potential of seeds.

There seems to be no indication that bioslurry contains more heavy metals than undigested manure. However, there might be the risk of heavy metal accumulation in biogas sludge that is also used for crop fertilization.

When the available bioslurry cannot be used at once, it needs to be stored; composting can be a solution at this point. After bioslurry is mixed with other biodegradable materials, the composted fertilizer can be stored for several weeks although the characteristics and nutrients value diminish because of biological decomposition. The composted fertilizer has similar qualities to manure and can be used as basal fertilizer or as an additive to bioslurry. Since composted bioslurry can be more easily stored and transported than liquid slurry, it can be used when actually needed.

Surplus bioslurry can be sold, and thereby generate additional income. Composted bioslurry has the advantage of being considerably cheaper than synthetic fertilizer. A case in Vietnam showed that the cost of bioslurry self-production was 20 times less than the cost of purchased urea.

Despite this large cost benefit, the profitability of bioslurry use compared to purchased fertilizers and the sale of surplus bioslurry has hardly been covered in literature. Few technical reports indicate that by the full or partial replacement of synthetic fertilizer with bioslurry on farm or the sale of surplus, composted bioslurry can be very profitable. Data on this issue would make a very strong case for anaerobic digestion in general, and bioslurry use in particular.

Other outstanding issues for further research concern the risk of over-fertilization leading to soil acidification and water runoff when bioslurry is applied in large quantities.

CONTENTS

iii Acknowledgements
iv Summary
vii Acronyms

1 **1. INTRODUCTION**
2 1.1 Objective of the paper
2 1.2 Scope, target group and structure
3 1.3 Background

5 **2. RESULTS**
5 2.1 Bioslurry as fertilizer
6 2.1.1 Bioslurry as fertilizer for crops and vegetables
9 2.1.2 Bioslurry as fertilizer for fish ponds
10 2.2 Bioslurry as feed for livestock
11 2.3 Bioslurry as pesticide and fungicide
12 2.4 Bioslurry for soil remediation
12 2.5 Anaerobic digestion and its effects on pathogen and seed viability
14 2.6 Accumulation of heavy metals in bioslurry
15 2.7. Over-fertilization through slurry application
15 2.8 Bioslurry methods of storage
16 2.8.1 Bioslurry as material for compost

19 **3. CONCLUSIONS**
22 3.1 Recommendations

25 **4. REFERENCES**

ACRONYMS

BP	Biogas Programme
B	Bioslurry
C	Carbon
CB	Concentrated bioslurry
C/N ratio	Carbon-to-nitrogen ratio
EC	Electrical conductivity
FAO	Food and Agriculture Organization
FYM	Farm Yard Manure
IFES	Integrated Food-Energy Systems
IPCC	Intergovernmental Panel on Climate Change
K	Potassium
KCL	Potassium Chloride
$MgSO_4$	Magnesium Sulphate
N	Nitrogen
NH_3	Ammonia
NH_4^+-N	Ammonium Nitrogen
NO_3^--N	Nitrate Nitrogen
OM	Organic matter
P	Phosphorus
PMC	Pressmud cake
SNV	Netherlands Development Organization
SF	Synthetic Fertilizer

CHAPTER 1 INTRODUCTION

Anaerobic digestion of animal waste and crop residues is a widely used technology for waste management and the production of renewable energy. The process leads to the synthesis of biogas that can replace fossil fuels and contribute to the mitigation of climate change. Often overlooked, but not less valuable, is the by-product of this process, the digester effluent or digestate[1]. This so-called bioslurry has the potential to improve soil fertility and soil structure, to act as pesticide and to stimulate algal growth in ponds for feeding fish and ducks.

Small-scale farmers throughout the world use biogas digesters to treat on-farm biowaste such as manure, human excreta or plant residues. When mixed with water, the organic farm residues undergo an anaerobic digestion process. During the process, bacteria transform the biodegradable organic compounds into biogas, nutrients, organic matter and other substances such as amino acids and fats.

In the first stage of digestion, complex organic compounds such as proteins, fats and carbohydrates are broken down and dissolved by microbial enzymes. In the second stage, the resulting components are further converted to acetic acids, hydrogen (H_2), carbon dioxide (CO_2) and other volatile fatty acids. In the third stage, methane (CH_4), i.e. the biogas and other end products are produced. These mainly non-gaseous end products can be further divided into:

- the **scum**, which is the solid matter that floats on the surface of the liquid slurry;
- the **liquid effluent, i.e. bioslurry,** which retains a high content of organic matter (OM), Nitrogen (N), Phosphorous (P) and Potassium (K), as well as a range of other macro- and micronutrients like Calcium (Ca), Magnesium (Mg), Iron (Fe), Manganese (Mn), Zinc (Zn); and different amino acids, as explained in more detail below; and
- solid residues, which is the matter on the bottom of the digester and often called **sludge**; it contains a high fraction of nutrients, and can therefore be used as an effective fertilizer once diluted or composted. As sludge production is low, it can remain in the tank for years before used.


A household biogas digester and bioslurry outlet
© Jaime Marti Herrero

1 In the literature, bioslurry is also referred to as biogas slurry, biogas-manure, digested slurry, digester-effluent, post biogas wastewater, sludge or biol.


Bioslurry
© Jaime Marti Herrero

This review will focus on the properties and different uses of the liquid effluent, the bioslurry (B).

1.1 OBJECTIVE OF THE PAPER

Bioslurry is applied in several ways, for example, as crop or fruit fertilizer, fish pond feed or as basic material for compost making, as seen in the daily life of many smallholders who own a household biogas digester. However, experience also shows that the full potential of B use is often not fully utilized. Many farmers who use anaerobic digestion are not fully aware of the different benefits and risks of B use, and those who do are often not trained in how to apply B in each particular case.

Much current knowledge on the benefits of B use is documented in technical reports or workshop proceedings published by local NGOs or development agencies and is distributed over the Internet. These documents contain valuable data and trends retrieved from local experiments, and highlight major constraints of B use and existing knowledge gaps.

Some of these constraints and gaps have been addressed by academic research conducted throughout the world, but not all of the results have been widely disseminated or communicated to their potential end users, smallholders or technical agencies. Academic research results are usually published in peer-reviewed journals, which are out of reach for most smallholders and local organizations in developing countries, meaning that a valuable source of information remains largely untapped.

To address this problem, this report sets out to display the current state of knowledge on B research, focusing on *peer-reviewed literature.* It will thereby complement the various sources of grey literature that are publicly available.

1.2 SCOPE, TARGET GROUP AND STRUCTURE

The document aims to identify consolidated facts regarding B, on the one hand, and the scope for future work on the other. The latter will be particularly interesting for the identification of further research that will be necessary in order to deliver technically sound and practical guidelines of B use at the household level.

The paper is tailored to inform experts from technical organizations such as local NGOs, as well as technical cooperation organizations and local governments that are dealing with household biogas and slurry production, of the different potentials and constraints of B use. It also addresses research institutions and universities, presenting knowledge gaps and research needs.

The core section of this paper can be found in the following "Review" section. This section focuses on the various reported characteristics of B in peer-reviewed literature and sums up the suitability of B for each purpose. A collation and a summary of the main issues of the literature reviewed can be found in appendix A. The conclusion section sums up the main points of the discussion, with particular emphasis on both solid findings and on knowledge gaps that need to be filled before thorough guidelines can be prepared for smallholder B use.

1.3 BACKGROUND

The review was commissioned based on an assessment of different biogas systems in China and Vietnam[2] (Box 1) within a FAO project on Integrated Food-Energy Systems where it became clear that B is still widely underutilized due to several knowledge gaps on its adequate use and other constraints. For example, in a survey performed among Vietnamese biogas users in 2007, only 60 percent of respondents utilized any of the B from their biogas plant (BP, 2007). In some cases, B was not used at all due to various reasons such as a lack of knowledge of the benefits of B and the correct application procedures.

On the other hand, a screening of available literature indicated that over the past 30 years, a variety of scientific experiments on the various aspects of B use had been conducted around the world and published in peer-reviewed journals. However, it became obvious that no study had attempted to gather these different sources in order to present a comprehensive picture of the current state of scientific knowledge on B use.

This review draws from a wide array of peer-reviewed articles (ranging from overview papers to specific experiments) related to B retrieved from databases like "Web of Science", "Scopus" and "Science Direct". While the review as such is restricted to peer-reviewed journals only, we used some comprehensive technical reports to identify future research needs and gaps. The reports include technical work done on B use in Vietnam (BP, 2007) and in Nepal (Gurung, 1997), which, to our knowledge, represent two of the most comprehensive compilations of information on B use in these countries.

2 Bogdanski, A., Dubois, O., Chuluunbaatar , D. 2010b. Integrated Food-Energy Systems. Project assessment in China and Vietnam, 11. – 29. October 2010. Final Report. FAO; http://www.fao.org/bioenergy/download/26794-0140d2e14b981e9923be4670c73e05c95.pdf

BOX 1

BIOGAS IMPLEMENTATION SCHEME AND BIOSLURRY USE IN VIETNAM

Smallholder biogas schemes have been receiving much attention from the Vietnamese government, international organizations, local NGOs and universities, since the country embarked on an integrated land management scheme after land rights had been given to individual farmers during the *Doi Moi* economic reforms initiated in 1986. One example is the "National Biogas Programme" that has been supported by the government and the Netherlands Development Organization SNV; another example is the "VAC integrated system" approach by the Vietnamese Gardeners' Association (VACVINA) and The Center for Rural Communities Research and Development (CCRD). Both programmes focus on integrated smallholder systems that involve gardening, aquaculture and animal husbandry, to make optimal use of the land.

The Biogas Programme for the Animal Husbandry Sector of Vietnam (BP), is a joint venture implemented by the Vietnamese Ministry of Agriculture and Rural Development (MARD) and the Netherlands Development Organisation, SNV (BP, 2007). BP has so far set up over 100 000 digesters across the country, and aims to set up another 64 000 by the end of 2011 (SNV, 2011). BP provides training for masons who build the digesters, quality assurance, and a US$67 subsidy per digester once the unit has been certified as working correctly. The digesters have a fixed dome roof, are underground (to save space), and are made of brick. Overall prices vary, as the masons decide their fees individually and prices of raw materials vary, but a typical system costs around US$550 (Ashden Awards, 2010).

CCRD and VACVINA have been using a market-based approach to upscale the use of small-scale biogas digesters since 1997. Since 2000 they have set up around 6 000 digesters across 61 provinces in Vietnam (personal communication Thanh, 2011).

Benefits

The digester's main output is biogas, which can substitute other fuel use in the household. It is estimated that each digester saves an average family US$5 to 10 per month in fuel[3] purchase, and time usually spent on collecting wood fuel (Bogdanski, 2011 & Teune, 2007). Additional to these financial benefits of the biogas production, the digester produces B, which can substitute or compliment synthetic fertilizer use among other uses.

Actual bioslurry application

The BP and the Vietnamese Institute of Energy have been monitoring the use of B by the farmers who have been supported through the BP. In phase 1 of the BP (2003-2005), only 41 percent of the farmers used any of the B. In 2006 and 2007, that number increased to around 60 percent (BP, 2007). The lack of knowledge and poor awareness of the benefits among farmers were seen as the major reasons that limit the wider use of B. A small qualitative study conducted by BP also suggests that a significant amount of farmers who do not utilize B simply do not have any interest or enough land for crop cultivation (BP, 2007).

Those who use B mainly do so to fertilize vegetables (BP, 2007). Other reported uses include fertilizing fish ponds, rice and various cash crops and using B as a pig feed supplement.

3 Both kerosene and fuelwood

CHAPTER 2

RESULTS

This chapter focuses on the various reported characteristics of bioslurry (B) in peer-reviewed literature and sums up its suitability as fertilizer and soil amendment (2.1), as feed for livestock (2.2), as pesticide and fungicide (2.3), and for soil remediation (2.4). The review further elaborates on the effect of anaerobic digestion on pathogen and seed viability (2.5) and on the potential accumulation of heavy metals in bioslurry (2.6). It talks about the risks of over-fertilization through bioslurry application (2.7), and summarizes findings on methods for bioslurry storage and composting (2.8).

2.1 BIOSLURRY AS FERTILIZER

In peer-reviewed literature, the most tested use of B is the fertilization of cereal crops, and to a lesser extent of non-cereal crops such as fruits and vegetables. In this chapter, the general lessons learned from B being used as a substitution for both synthetic fertilizers and other organic fertilizers are addressed. To help the broad understanding of the following discussion and conclusion sections, some general issues regarding fertilization will be explained below in Box 2.

Bolivian farmer spraying his vegetable field with bioslurry.
© Jaime Marti Herrero

B is generally incorporated into the soil before planting or, after dilution with water, sprayed directly onto vegetables and fruit crops during the growth period. The various studies that focus on the effects of B as fertilizer, pesticide or fungicide briefly report on the *rate* and/or *quantity* of B application, yet the exact methodology is often not clear or specified in detail. No study has specifically tested the effects of different application schemes on the various parameters.

One positive exception is an educational video published by SNV, Vietnam (SNV, 2008), which gives a detailed explanation of how B should be applied to different crops (rice, maize, wheat, spring peanuts), vegetables (cabbage, kohlrabi, green cabbage, tomato), fruits (*Malpighia glabra,* durian), tea, coffee and ornamental flowers.

BOX 2

SYNTHETIC AND ORGANIC FERTILIZERS

The term "**synthetic fertilizer**" covers all chemically produced fertilizers that perform the vital role of providing plant nutrients to the soil. These fertilizers deliver one or more of the three main macronutrients, Nitrogen (N), Phosphorous (P) and Potassium (K). These are, as the name suggests, produced synthetically, which requires significant amounts of energy. Urea, also known as carbamide, is the main N-containing substance in the urine of mammals. Because of its high amount of nitrogen, it is used as an organic fertilizer. Urea fertilizer is generally produced synthetically and is the most widely used fertilizer globally (Faostat, 2011). However, it requires 29-42 Giga joule of energy per tonne to produce this type of fertilizer (IPCC, 2006). This has a great impact on the climate and the environment, and it means high fossil fuel dependency for farmers, with associated variable and increasing prices. Furthermore, phosphate rock, which is the input for phosphorous fertilizer, is a limited resource, and has become increasingly scarce (FAO, 2006), and therefore expensive.

The term **"Organic fertilizer"** comprises material from animal or plant origin. It covers all soil amendments that add to the pool of soil organic matter, namely organic compounds and carbon (C). Soil organic matter improves the physical properties of the soil by improving its structure and water holding capacity and by preventing nutrient leaching. This group of fertilizers includes Farm Yard Manure (FYM), fly ash[4] and crop residues. Since high temperatures promote the decomposition of organic matter in soils (FAO, 2006), the addition of organic matter to soils is particularly important for maintaining long-term soil fertility. Organic fertilizers usually also provide some measure of N, P and K, as well as varying amounts of micronutrients.

2.1.1 Bioslurry AS fertilizer for crops and vegetables

Bioslurry (B) application compared to no fertilizer use (NF) and to other organic fertilizers (OF)

Identical yields between B and OF treatments for various cropping systems

Möller *et al* (2008) investigated the effects of different organic fertilizers (B, undigested liquid slurry (ULS) and solid FYM) on yields of grains, tubers and fodder in different cropping systems – clover and grass ley, potatoes, maize, rye, peas, spelt and spring and winter wheat. They found that the yields did not significantly differ between the different treatments except for spring wheat, where the B treatment led to higher yields. Möller *et al* (2008) explain this higher yield by the fact that spring wheat is a short cycle crop characterized by a short and intensive period of N uptake. The crop therefore makes immediate use of the readily available NH_4^+-N in B, which explains the difference in yield.

4 Fly ash is a by-product from coal combustion and consists of cinders, dust, and soot (Encyclopaedia Britannica, 2011)

Potato yield higher with B than with OF and without fertilizer

In the potato field trial in the Northern region of the Peruvian Andes (Garfi *et al* 2011, see previous section), soil was treated with B, control (no fertilization), pre-composted manure (7-day treatment) and a mixture of B and precomposted manure. In the forage crop field trial the soil was amended with the control, B diluted by 50 percent with water, and 100 percent B. The amount of nitrogen applied on the field increased with the percentage of B. The potato yield increased by 27.5 percent with B, by 15.1 percent with precompost manure and by 10.3 percent with the mixture, compared to the control. The forage yield increased by 1.4 percent (50 percent concentration) and by 8.8 percent (100 percent concentration) compared to the control. The results suggest that B is an appropriate substitute for precomposted manure in potato fertilization. The results with the two forage types indicate that it can be applied in a range of doses, according to the amount produced by the digester.

Wheat yield higher with B than with OF and than without fertilizer

Garg *et al* (2005) compared wheat yield after B application to no fertilizer use and to fly ash application. The B treated sample performed better than both, without fertilizer and with OF, yet none of the results were significant.

Cassava leaf biomass and protein content higher with B than with OF

Two field studies were conducted by Chau in Vietnam. The author's first experiment Chau (1998a) demonstrated that frequent (every three days) application of B gave higher yield of cassava leaf biomass with higher protein content than supplying the same quantity of nitrogen from raw pig and cattle manure. The average total biomass yields per harvest were 8.68 t/ha for B and 7.18 t/ha for manure.

Duckweed yield lower with B than with OF; protein content higher with B

The second experiment (Chau, 1998b) showed that with the same content of N in raw manure and B, plant nutrients derived from B lead to higher concentrations of crude protein (total protein content) in duckweed, than nutrients from raw manure. However, cultivation with raw manure gave slightly, but significantly, higher duckweed yield compared to B.

Sugar-cane yield with B higher than with no fertilizer, yet lower than with VC

Singh *et al* (2007) compared sugar-cane yields after the treatment with no fertilizer, FYM, vermicompost (VC), synthetic fertilizer (SF) and B. The highest planted cane yield was obtained with VC application (76.7 t/ha). Statistically, there was no difference to the yields obtained from SF application (76.1 t/ha). The treatment with B yielded 71.9 t/ha, which was higher than with FYM (70.9). Both values are lower, yet no indication is given whether this difference to SF is significant. No fertilizer application gave a result of 53 t/ha.

TABLE 1.

Comparison between yields of crops and vegetables with bioslurry (B) and different organic fertilizers (OF) (undigested liquid slurry (ULS), farm yard manure (FYM), vermicompost (VC), fly ash (FA), precomposted manure (PCM)): higher yield (=); lower yield (-); equal yields (=).

	B	OF					References
Yield		**ULS**	**FYM**	**VC**	**FA**	**PCM**	
Winter wheat, rye, spelt	=	=	=				Möller *et al*, 2008
Spring wheat	+	-	-				Möller *et al*, 2008
Potato	+					-	Garfi *et al*, 2011
Wheat	+				-		Garg *et al*, 2005
Cassava leaves	+		-				Chau, 1998a
Duckweed	-		+				Chau, 1998b
Sugar cane	-			+			Singh *et al*, 2007
Sugar cane	+		-				Singh *et al*, 2007

Bioslurry (B) compared to synthetic fertilizer (SF)

Rice yield higher with B than with SF

In Gnanamani and Kasturi Bai (1992), the yield of rice grain showed a 23 percent increase when soil was amended with B, compared to SF (containing N,K,P).

Lettuce yield higher with B than with SF

Wenke *et al* (2009) showed a significant increase in plant growth parameters of lettuce when plugs filled with sterilized river sand were amended with B compared to SF (containing N). The weight of shoot biomass with B (1.01 g/plug) was higher than with SF (0.6 g/plug), and the average number of leaves with B amounted to 11.8, and with SF to 9.8.

Rice yield identical with B and SF

In Bharde *et al* (2003), rice yield and nutrient uptake under B and prilled urea application were similar to 100 percent substitution.

Kohlrabi yields identical with B and SF

Lošák *et al* (2011) conducted a one-year vegetation pot trial. Four treatments were used to grow seedlings of Kohlrabi: untreated control, B, urea and another synthetic fertilizer (containing N, P, KCL and $MgSO_4$). B was obtained from a digester fed with pig manure and maize silage. During application, the synthetic fertilizer and B contained a similar rate of nutrients (N, P, K, Mg). After harvesting of the Kohlrabi bulbs, weight was measured. The weight of single bulbs fertilized with B and with the other SF were significantly higher, 27.9 and 29.2 percent respectively, than those with urea. There were no significant yield differences between B and the synthetic fertilizer.

N-uptake and yield by rice and sugar cane with B lower than with SF

The N-uptake by crops is an important growth parameter. Ghoneim (2008) showed a vastly lower level of N-uptake by rice after B application than after synthetic fertilizer application (containing N, K, P). However, despite the higher uptake of the latter, synthetic fertilizer gave only a slightly higher rice grain yield (24.6 g) compared to B (23.1 g). This pattern was also seen in sugar cane in Singh *et al* (2007). The N-uptake by the plant with synthetic fertilizer (306 kg/ha) was higher compared to B (199.5 kg/ha) but plant yield was only slightly higher with synthetic fertilizer than with B (76.1 t/ha to 71.9 t/ha).

Tomato yield lower with B, however tomato quality higher

Yu *et al* (2010) showed that B significantly improved contents of soil-available N, P, and K as compared to the control (no fertilizer) and conventional methods (SF containing N, K, P). Application of B significantly increased contents of 13 kinds of amino acids, proteins, ß-carotene, soluble sugar, and vitamin C in tomato fruit. However, the mean weight of B treated tomato fruit was lower (123g) than that with SF (132g). This shows that B application effectively improved tomato quality but not the yield.

Best rice yield after combined application of B and SF

B and its combinations with SF (containing N, K, P) were studied by Gnanamani and Kasturi Bai (1992) in India. The combined application of SF with B performed better than separated application of either SF or B: A 36 percent increase compared to B alone, and a 52 percent increase compared to SF application alone.

TABLE 2.

Comparison of grain, vegetable and fruit yield between bioslurry (B) treatment, synthetic fertilizer (SF) treatment (N-fertilizer and NKP fertilizer) or a combination of both (B+SF): higher yield (=); lower yield (-); equal yields (=).

	B	SF		B+SF	References
Yield		**N**	**NKP**		
Rice	+		-		Gnanamani and Kasturi Bai, 1992
Rice	-		+		Ghonheim, 2008
Rice	=		=		Bharde, 2003
Rice	-			+	Gnanamani and Kasturi Bai, 1992
Lettuce	+	-			Wenke, 2009
Sugar cane	-	+			Singh, 2007
Kohlrabi	=		=		Lošák *et al*, 2011
Tomato	-		+		Yu *et al*, 2010

2.1.2 Bioslurry as fertilizer for fish ponds

In a string of articles relating to an experiment with B fertilization of fish ponds, Kaur *et al* (1987) and Seghal *et al* (1991 & 1992) analysed various effects of B as a fish pond fertilizer. First and foremost, Kaur *et al* (1987) showed a significant increase in growth rates of carp when ponds were fertilized with B. Secondly, and just as importantly, the study reports no fish death pertaining to this fertilization regime, as reported from studies using raw dung. Seghal *et al* (1991 & 1992) showed that both phyto- and zooplankton populations increased with addition of B, compared to the control, into the ponds. The growth rate was further increased when B was supplemented with a high protein feed (in this case, rice bran and groundnut-oil cake).

Edwards *et al* (1987) experimented with composted B, derived from a mixture of night soil (i.e. human faeces), water hyacinth (*Eichhornia crassipes*) and rice straw. The composted B was fed into three fishponds, from low to high loading rates. There was an increase in both the rate of growth of stocked fish and their mean size. However, the production of fish from B was more efficient at lower than at higher loading rates.

In India, Balasubramanian & Kasturi Bai (1994) assessed the effect of B, control (pond with water only) and conventional (pond with chemical fertilizer) feed when given as fish pond fertilizer. Results showed a 10-fold increase of B over the control and a 3.6-fold increase of B over the conventional feed in fish yield. Balasubramanian and Kasturi Bai worked on a similar investigation in 1995 and found similar results.

Concerning fish production, B seems to be a promising replacement for chemical fish pond fertilizers. The peer-reviewed articles that were found all showed an increase in phyto-, zooplankton and fish population. The studies are rather limited in scope however and as such, there should be potentials for optimization. As Seghal *et al* (1991 & 1992) show, there is quite a big surplus of various species of plankton that could be utilized for fish feed by growing different species at once, instead of carp alone. This should be explored in greater detail.

2.2 BIOSLURRY AS FEED FOR LIVESTOCK

Feeding animals with animal waste is a common practice. Feeding of animal wastes results in reducing feed cost and a lower price of animal products; it contributes to self-sufficiency in protein, phosphorus and other expensive nutrients in feed rations (FAO, 1980). In theory, using B for animal feed follows the same logic, yet studies on this particular topic are scarce.

Monogastrics

Sikka (2006) experimented with substituting 10 percent and 20 percent of the feed for pigs with B. The results showed a negative linear correlation between the addition of B and the weight gain for the swine, when compared to a diet of maize, rice bran, groundnut extraction and fishmeal. The authors therefore concluded that B cannot be recommended as feed for pigs.

Ruminants

Saxena *et al* (1988) recommends that in times of fodder scarcity, B could be used as emergency feed. His study found weight maintenance of crossbred bulls who were partially fed with B for 21 days.

2.3 BIOSLURRY AS PESTICIDE AND FUNGICIDE

Pesticide

Jothi *et al* (2003) compared the use of B to the use of a commercial pesticide in a controlled infection of root knot nematode in tomatoes. At a 10 percent dose of soil weight, B controlled the nematode infection more efficiently than the commercial pesticide. Even at 5 percent, B fared slightly better than the pesticide.

Xiao *et al*. (2007) assessed the effect of anaerobically digested swine manure on soybean cyst nematode (SCN) egg control. SCN is a known problem that affects soybean yields and causes many root diseases that interfere with nutrient uptake by the crop. The researchers focused their analysis on two components of swine B derived from proteins in the raw manure, namely volatile fatty acids (VFAs), and ammonium (NH4 +), which are reported to be biocidal to pathogens.

The authors found that the anaerobic digestion process can be used to enrich both VFA and NH_4^+ in swine manure. The optimal incubation times to reach the highest levels for these two ingredients are 17-18 days for VFA (about 17 percent increase) and 28 days for NH_4^+ (about 23 percent increase), respectively. They further concluded that for soil samples collected 35 days after receiving the manure treatments (raw, VFA-enriched, and NH_4^+-enriched manure), the SCN egg counts decreased as the manure doses increased, with the VFA-enriched treatment demonstrating the lowest egg counts at all application rates. The NH_4^+-enriched manure showed the least effect on the reduction of SCN eggs for all the rates tested, which was even worse than raw manure and water treatments. Xiao *et al*. recommend that for the best treatment result, the VFA-enriched manure should be applied to soybean fields every 35 days in order to effectively suppress SCN egg production.

Fungicide

Kupper *et al* (2006) studied the potential of B use compared to the standard fungicide treatment (copper oxychloride and *carbendazim + mancozeb*) for the control of *Phyllosticta citricarpa*, the causal agent of citrus black spot. The B from a digester fed by cattle manure was sprayed on Natal Orange trees (B was added to water and sprayed on the trees). B had a significant effect in controlling citrus black spot, at a concentration of 10 percent to 20 percent doses in water. However, the standard fungicide was more effective than B application, which resulted in 95 percent of the fruits having no symptoms of black spots (B numbers not given). The author stated that the results indicate that the B may have potential as an alternative for the fungicide in citrus black spot control but more studies are needed to determine the ideal B dose and application interval.

Shi *et al*. (2002) studied the effect of B on wheat scab (*Fusarium graminearum*). They found that when B is sprayed during full-bloom stage, the disease incidence decreased by 20.7 percent. The extent of biocontrol by the effluent was similar to the effect of the fungicide Benomyl.

2.4 BIOSLURRY FOR SOIL REMEDIATION

Kadian *et al* (2008) studied the degradation of the herbicide atrazine in soil amended with B. The results showed that when B was added as soil amendment, it accelerates the breakdown of atrazine to 34 percent in 21 days, compared to the control. B seems to support maximum microbial growth resulting in highest dissipation of atrazine.

In a different study, Kandian *et al* (2012) examined the suppressing effect of organic amendments on the insecticide chlorpyrifos (CPF) in agricultural soils. CPF is known to inhibit the microbial activity in soil. B proved to be able to reduce this inhibitory effect of CPF, considerably enhancing the microbial activity of the soil again.

2.5 ANAEROBIC DIGESTION AND ITS EFFECTS ON PATHOGENS AND SEED VIABILITY

Livestock faeces can be significantly contaminated with pathogens and many outbreaks of gastroenteritis related to livestock have been reported (Massè *et al.* 2011). The anaerobic digestion process may inactivate bacteria, viruses, fungi and parasites in the feedstock, which is crucial prerequisite if B is to be directly applied to crops. If treated appropriately, B reduces the risk of contaminating crops with harmful pathogens as opposed to undigested farmyard manure (e.g. Yen-Phil *et al*, 2008). Else, pathogens can be directly transmitted to vegetables, animals and/or agricultural workers, and groundwater or surface water may be contaminated with faecal material deriving from field runoff.

The sanitation of the end product depends on the quality of the substrates fed into the digester, and on the digester performance, such as previous pasteurisation, digestion temperature, slurry retention time, pH and ammonium concentration, among others (Sahlström, 2003 and Ottoson *et al.*, 2008).

Bacteria

The process of anaerobic digestion in biogas plants usually takes place either under thermophilic (53 to 58 °C) or mesophilic (30 to 42 °C) conditions. Anaerobic degradation using thermophilic temperatures significantly reduces the number of bacteria; mesophilic digestion is not as effective in this regard (Slana *et al*, 2011). This particularly concerns smallholder biogas digesters which usually only work at mesophilic conditions.

Bacterial pathogens from livestock residues provoking human and/ or animal health issues include *Salmonella spp., Campylobacter ssp. and Yersinia enterocolitica*, *Listeria monocytogenes, E. coli* O157, *Mycobacterium avium* subsp. *Paratuberculosis*, *Clostridium spp. and Bacillus spp* (Bagge *et al*. 2005; Slana *et al*, 2011).

At an experimental site in Austria, Governa *et al*. (2011) found that anaerobic digestion at mesophilic temperatures (37 °C for 60 days) completely eliminated *E. coli* and *Salmonella* from the samples, but not *Listeria ssp.*. *Listeria monocytogenes* can survive and even proliferate at 1–45 °C in digested residues (Junttila *et al.*, 1988). *L. monocytgenes* is the causative agent of listeriosis, which is one of the most virulent food-borne pathogens for both human and animals (Ramaswamy *et al*, 2007).

In a second stage of the experiment, the researchers incorporated the B into the soil. When they analysed the soil after three months, the numbers of cultivable potential pathogens in the amended soils did not exceed those in the control soils. Governa *et al.* (2011) therefore conclude that 90 days could be a reasonable period of delay between land-spreading organic amendments and crop harvesting.

Bonetta *et al.* (2011) investigated the microbiological contamination of B from bovine manure and agricultural by-products in Italy. They found that the hygienic quality of B was better than that of the raw bovine manure (range of reduction 1.6-3.1 log $_{10}$). In the treated sample, they found no *Escherichia coli* O157:H7 and *Yersinia. Salmonella* sp. and *Listeria monocytogenes* were detected in the samples, yet in small quantities. *Salmonella* spp. is common in manure and can under favourable conditions survive for more than one year in the environment (Mitscherlich and Marth, 1984). *Salmonella* spp. causes serious infections in both man and domestic animals.

In the same study, *Enterococci* and *Clostridium perfringens* showed similar counts before and after anaerobic digestion. The quantity of *Enterococci* exceeded the standard for *Enterococcaceae* reported in the European regulation on animal by-products (Commission Regulation EC, no. 208/2006). The study concludes that while the prevalence of *Enterococcaceae* was reduced after storage of 120 days, *C. perfringens* could pose a hygienic problem when B is spread on land. The presence of *C. Perfringens* in food is a common cause of food poisoning.

Badge *et al.* (2005) found similar results. They analysed B after both prepasteurisation and anaerobic digestion, and found that the spore-forming bacteria *Clostridium spp.* and *Bacillus spp.* still persisted after the pasteurisation and digestion. They concluded that this may be a risk when using digested residues on arable land. *Bacillus anthracis and Bacillus cereus* cause infections in humans (Ray and Ryan, 2003).

In Canada, Massé *et al.* (2011) did a similar experiment using psychrophilic anaerobic digesters, which work at low temperatures (20-25 °C). They found that digestion of 7 or 14 days reduced the concentrations of *E. coli, Salmonella, Campylobacter* spp. and *Y. enterocolitica* to undetectable levels in most samples, while *C. perfringens* did not decrease significantly during the treatment.

Slana *et al.* (2011) examined cattle-derived B obtained from digestion at mesophilic temperatures for survival of *Mycobacterium avium* subsp. *Paratuberculosis* at an experimental site in the Czech Republic. *The bacteria* is known for its ability to survive in the environment for a long time and to cause paratuberculosis (Slana *et al.*, 2011). The researchers detected viable *M. avium subsp. paratuberculosis* cells in the fermenter up to two months after initiating the digestion process. After this period, no viable *M. avium subsp. paratuberculosis* cells were found. Accordingly, the researchers recommend to use B for land fertilization or animal bedding and feeding only after two months.

Viruses

Only few studies have analysed the viability of viruses found in animal manure during anaerobic digestion; even less is known about the survival of viruses under standard operational conditions (Lund *et al.* 1996).

In Canada, Derbyshire *et al.* (1986) compared samples of raw liquid pig manure with B at monthly intervals for nine months at mesophilic conditions. They found porcine enteroviruses in the raw manure, while they were found significantly less frequently in B. They concluded that the anaerobic digestion system resulted in significant, but incomplete, reductions in viral infectivity. The authors therefore suggest that longer retention times or temperatures would be necessary to completely eliminate the virus. A Canadian study using bovine manure found similar results (Monteith, 1986). Enteroviruses are associated with several human and mammalian diseases.

A laboratory study assessed the effect of heat treatment at 55°C and at 70 °C on the survival of the enteroviruses Porcine parvovirus (PPV) and Swine vesicular disease virus (SVDV) from a large-scale biogas plant in Sweden (Sahlstroem *et al*, 2008). The authors concluded that PPV was not reduced sufficiently, even at 70 °C at a retention time of 60 min.

Nematodes

The same Swedish study (Sahlstroem *et al*, 2008) also examined B for *Ascaris suum* eggs. However, no developed larvae of *A. suum* could be detected in the samples treated for 15 min, 30 min or 60 min at 55 °C and at 70 °C. *A. suum* causes ascariasis in pigs.

Yongabi *et al.* (2009) assessed the survival of nematodes in rotting plantain compost after anaerobic digestion in Nigeria. The samples were digested for five weeks in a plastic tubular digester. Out of the seven species of soil pathogenic nematodes causing plant diseases - Meloidogyne spp, *Pratylenchus goodeyi, Helicotylenchus dihystera*, *Helicotylenchus multicinctus*, unknown Helicotylenchus, *Hopiolaimus pararobustus, and Radophlus similes* – none were detected after the treatment.

Weed seeds

Schrade *et al* (2003) investigated the effects of digestion on the viability of seeds, including weed seeds present in raw manures. They found that the operating temperature of the digester and the time of digestion played a significant role in reducing the germination potential of the analysed seeds. Seeds of winter wheat, canola, foxtail and wild mustard were completely immobilized after 24 hours in the digester under mesophilic temperatures. By contrast, seeds of tomatoes, white goosefoot, and yellow dock root required thermophilic temperatures to stop germination after 24 hours. Further factors that influenced the results were assumed to be the microbacterial activity, the emissions from the decomposing organic matter and the moisture content of the seeds.

2.6 ACCUMULATION OF HEAVY METALS IN BIOSLURRY

Animal manures can contain heavy metal impurities. They may accumulate in the soil with repeated fertilizer applications and thus increase heavy metals in soils, raising concern about the entry of these metals in the human food chain and related health implications (Mortvedt, 1996). This might have health implications as crops for human consumption accumulate these metals in their tissue. In recent years, livestock production systems, especially those common in intensive swine farming, have been utilizing heavy metals as growth promoters. Tulayakul *et al* (2010) found that Zn, Cd and Pb levels in biogas covered lagoon wastewater samples were higher than in non-biogas wastewater samples. Despite the fact that the differences were not significant, the researchers recommend that these results should be considered for future evaluations.

Hongmei & Chang (2010) collected B samples from 21 large-scale anaerobic digestion plants (digestion reactor volume >500 m^3) to analyse the chemical fractions of Zn, Cu and As in pig and dairy B. Total concentrations of Zn, Cu, and As in B were much lower than those in the sludge, the solid fraction of the digestate. A possible explanation is that since most of the heavy metals associated with suspended solids sink to the bottom of the digester during a relatively long period, it results in a larger accumulation amount of heavy metals in solid matter.

2.7 OVER-FERTILIZATION THROUGH SLURRY APPLICATION

Over-fertilization of crops can be critical if too much fertilizer is applied to arable lands. Critical concentrations of plant-available P and K that are necessary for maximizing crop yield have been documented for a limited number of soil types and crops worldwide (e.g. Syers *et al*., 2008; Johnston *et al*, 2001). Above these critical P and K levels, there is no additional yield benefit (Zhao *et al*, 2010). To the contrary, high P soil concentrations can lead to significant P losses to drainage waters resulting in eutrophication (Zhao *et al*, 2007).

Likewise, high ammonia emissions from over-fertilization with N may create considerable environmental risks (e.g. Ni *et al*, 2012). Ammonia (NH_3) volatilization from field application of organic slurries not only results in financial loss through fertilizer-N loss, but NH_3 volatilization from agriculture is also considered to be the main source of atmospheric pollution by NH_3 (e.g. Vitousek *et al*, 2009). Subsequent excess NH_3 deposition from the atmosphere causes soil acidification and eutrophication of N-limited natural and semi-natural ecosystems as well as surface water bodies (Dragosits *et al*, 2002; Sanderson *et al*., 2006). As the NH_{4+} content and pH of the bioslurry increase during fermentation of biogas crops (Wulf *et al*., 2002), there is a high potential of NH_3 emissions after bioslurry application to the fields (Ni *et al*, 2012).

Nonetheless, to our best knowledge, there has been no comprehensive quantification of NH_3 volatilization (Ni *et al*, 2012) nor of P and K loss (Zhao *et al*, 2010) from bioslurry in different contexts (e.g. small or large crop and livestock farms), nor of the subsequent risks for soil acidification and eutrophication.

2.8 BIOSLURRY METHODS OF STORAGE

The storage of B is an important issue as sometimes not all of the slurry produced is directly applied to the fields or used as feed. Either there is no need for it at the given moment, or regulations do not allow for spreading slurry at a certain time of the year. A farmer survey in Nepal found that only a few farmers incorporate the B directly into the soil (SNV, 2009). However, leaving B in the open air, exposed to the sun for a long period of time, leads to a significant nitrogen loss, which diminishes the quality of the fertilizer and increases the release of powerful greenhouse gases (e.g. Möller *et al*, 2008 and Möller, 2009). It is therefore crucial to adequately treat the B after the digestion process. This can either be done through the right farm storage facilities, through slurry transportation to another farm where it is directly used, or through the transformation of slurry into compost.

While new storage facilities are readily available in industrialized countries, where initial investment costs do not present a barrier to farmers, the storage of B in developing countries is still one of the major challenges in terms of B management. Even if adequate storage facilities are in place, storage itself still depends on various conditions and on duration, which may affect the characteristics of the stored materials and the separation of nutrients through biological decomposition as well as the amounts of bacteria in the materials through, for example, the growth of bacteria or availability of nutrients (Paavola & Rintala 2008; Bagge *et al*., 2005). Temperature during storage time has strong influence on the chemical composition of the slurry. Sommer *et al*. (2007) reported that during 114 - 138 days storage of fresh cattle slurry, the transformation of organic N to NH_4^+ was slow and insignificant at <15 °C but increased significantly at 20 °C. This is particularly important in the context of slurry storage in tropical countries where temperatures can vary considerably between different regions.

Tran *et al*. (2011) found that the fraction of N loss caused by N emission from covered B storage was 25 to 30 percent of initial N content, while that from uncovered B was 60 to 70 percent. They furthermore found that after 90 days of storage, 1.15 to 1.20 times the initial ammonium-N (NH_4-N) was found in the covered slurry and only 0.40 to 0.50 in the uncovered.

Nutrients can also be lost through leaching when slurry is collected in underground uncemented storage pits, which can be found in India for instance. Gupta *et al* (2003) report that the liquid portion of the slurry is bound to leach in these kinds of storage systems. Their experimental study showed that losses were greatest for Potassium (36.5 percent), Zinc (25 percent) and Nitrogen (21.5 percent).

2.8.1 Bioslurry as material for compost

Since adequate storing facilities are not always in place, composting can be a good alternative. Compost is produced by aerobic micro-organisms and can be used as basal fertilizer when preparing soil or as an additional fertilizer for crops. Some practical tips on how to make compost from B have been published by Gurung (1997) and SNV (2009), for instance.

A special approach is taken by the Gardner Association VACVINA and the Research and Development Center CCRD in Vietnam who train their members on how to compost B as part of their biogas program (Bogdanski *et al*, 2010). The VACVINA composting system requires around 45 days for maturation and requires two biochemical additives, BiOVAC and BiCAT, which add concentrated nutrients and micro-organisms to the slurry mixture and accelerate the composting process (Pham, 2006).

Composted and stored B can serve as an important way of reducing farm operative costs, as it reduces the need for synthetic fertilizer and hence related household expenditures. In Vietnam for instance, the cost of producing composted B with the VACVINA composting system is estimated at roughly US$15 per tonne (Campbell-Copp, 2011), considerably cheaper than the current prices of synthetic fertilizers, which amounted to US$332 per tonne for urea in May 2011, for instance (Vietnam Business Forum, 2011). The comparison of prices must take into consideration the substitution potential between these two types of fertilizers. In this respect VACVINA estimates that the composted B can replace 35 to 50 percent of synthetic fertilizers (Campbell-Copp, 2011), depending on crop type and specific site conditions.

The fact that composted B can be stored and easily transported leads to another important advantage of composted B: *surplus* B can be sold on the market and therefore generate additional household income. Box 3 shows an example from Bangladesh.

BOX 3

INNOVATIVE PAYMENT SCHEMES FOR BIOGAS SYSTEMS THROUGH THE SALE OF BIOSLURRY

A pilot project by the University of Liberal Arts in Bangladesh and the Institute of Sustainable Development (ISD, 2010) is currently testing an innovative payment scheme for those interested in biogas systems. A loan was given by ISD to pay for the digester. Payments are made in the form of dry B that is purchased by ISD at a fixed price and then sold to the Kazi and Kazi Tea Estate (KKTE), a commercial farm based on organic agriculture.

The project is still ongoing, but preliminary calculations indicate that the digester will be paid off after two years. Once the loan is paid off, farmers can sell the dry slurry directly to KKTE. According to the study, a smallholder digester (2 m3) can generate 416 Bangladeshi Taka (BDT) from 378 kg dry B production per week (ISD, 2010). This translates to roughly US$10 for one tonne of dry B. The weekly sale of B generates almost as much as a local worker makes per week, i.e. 420 BDT.

CHAPTER 3

CONCLUSIONS

This review shows that peer-reviewed literature on the use of bioslurry (B) is relatively scarce. Most literature concerns the use of B as a fertilizer for crops. To a lesser extent, research has been conducted on the use of B as a fish-pond fertilizer, as animal feed or as composting material. Only a few articles deal with the effects of B on human health.

Studies on B as fertilizer look at a vast array of parameters. Some studies concentrate on soil nutrients only; others determine nutrient balances of fertilized crops or biomass growth of a given plant in general. Only few studies are of direct relevance for smallholders, as they are ultimately interested in the yield of a given crop, vegetable or fruit.

To determine the effectiveness of a fertilizer, it is important to know its nutritional value as such and the nutritional requirements of the plants. The content of B varies widely however, as it depends on many variables, such as:

1. the type of animal manure used as feedstock for the digester, e.g. from pig, cattle or chicken;
2. additional feedstock for the biogas digester, e.g. different types of crop residues or duckweed;
3. the animal fodder, in terms of quality and quantity;
4. the climate, particularly the temperature, in which the biogas digester is operating, i.e. in warm temperatures the digestion rate is higher than in lower temperatures;
5. the biogas digester technology as such.

The same challenge applies for the nutritional requirements of the plants. Each type of crop, vegetable or fruit has different fertilizer requirements. Not less important is the type of soil (including nutrients, organic matter, soil fauna and flora, etc), the amount of water, and the general climate conditions that the plants ideally need to give maximum yields. The nutrient and organic matter content that fertilizers can provide only represent one of these factors. This makes it difficult to draw generic conclusions about the potential of B use for a specific situation as the exact effects of B application vary from case to case and cannot be determined unless studies are performed locally. However, some general conclusions can be drawn from the reviewed articles:

Nutritional value and physical properties of bioslurry

All studies report a reduced organic matter content of B compared to FYM, as the digestion process leads to the breakdown of organic biomass.

The pH-value of B is usually higher than that of FYM that bears the risk of an elevated release of ammonia. High concentrations of ammonia cause damage to vegetation and lead to acidification and eutrophication of soils. This has adverse effects on ecosystems. In addition, ammonia is an important precursor for the formation of secondary aerosols.

The nutrient composition of B varies widely between studies, always depending on the original substrate, the type of digester and the process applied. All studies report a higher percentage of available nitrogen in B compared to FYM, which accelerates the N-uptake by plants. This is particularly visible in the early part of the growth cycle as the higher ammonium fraction of the B is more easily accessible for the crops (Möller, 2009 and Möller *et al*, 2008). The difference seems to even out over the length of the growth cycle for most of the crops, as the remaining nitrogen mineralizes. The same study found, however, that this could not be concluded for plants with a shorter growth cycle such as spring wheat and potatoes.

Accordingly, the C/N ratio of B is lower than in FYM, which accelerates the N mineralization process. This, in turn, helps the uptake of N in the crops, but also increases ammonia emissions. FYM, by contrast, is oxidized to nitrates and nitrites, which do not bond well with soil particles and therefore leach out faster (Ghoneim 2008).

Crop yield

In general, it can be stated that B has proven to have positive effects on yields compared to not using any soil amendments and fertilizers. In comparison with other organic fertilizers such as FYM or compost, the content of readily available N for plants is higher after bioslurry application. This is particularly important for crops with a relatively short cropping cycle such as spring wheat, which benefit from a quick uptake of N in their early growth.

In terms of yield, it remains fairly unclear how B performs in comparison with other organic fertilizers, as the results vary widely between different experiments, manure types and crops.

The comparison between B and SF is equally ambiguous. In some experiments B outperformed SF, in others SF-treated plants showed better results in terms of yield.

Little research has been done on the combined application of B and SF. However, one study indicates that such combined application can lead to significantly higher yields of grain.

Despite these initial conclusions, it is crucial to stress that it is difficult to compare the results. The specific content of B caused by different types of manure input in the digester, different types of OF and different SF, the nutrient requirements of each respective plant species and the soil conditions on site are all factors which vary widely between studies. It also needs to be noted that the specific experimental design and methodology of each study differs significantly.

There have been no experiments that determine the effects of B use *on long-term* soil fertility compared to both OF and SF.

Crop quality

The protein content of plants (duckweed and cassava leaves) has been shown to be higher when treated with B compared to other OF. Another study showed that tomato quality in terms of amino acid content and macro and micronutrients increased compared to SF treatments.

Fish production

All articles on fish production showed positive results when fish ponds were amended with B. It can be concluded that an increase in fish production with B as fertilizer is possible, without giving any additional protein rich or synthetic fertilizer.

Animal feed

There is only little data on B used for animal feed, which does not allow for general conclusions. The only two scientific studies found on this subject recommended to use B as animal feed only in times of food scarcity, or to use it as an additive to the normal diet.

Pesticides and herbicides

A couple of papers report on the potential of using bioslurry as pesticide. Studies found that bioslurry is a good alternative to synthetic pesticides in order to combat nematode manifestations.

Other papers report on the effects of bioslurry as an alternative to conventional fungicides. The researchers found that the biogas effluent does have fungicidal properties, yet in the studies it did not perform as well as its synthetic counterpart.

Soil remediation

Despite limited research in this field, two studies clearly showed that the organic matter fraction of B has the large potential to reduce or inhibit substances in soils. This has been shown for the herbicide *atrazine* and the insecticide *chlorpyrifos.*

Pathogens

Several studies clearly show that both temperature and retention time are crucial parameters to determine whether B can be used without causing health risks. Yet, the available literature does not give the full image of the risks associated with B use. Contrary to the perception of many biodigester users, B does in many cases still contain a considerable amount of pathogens, although often in smaller quantities than in undigested manure. This is particularly true for the bacteria *Clostridium perfringens, Listeria monocytogenes, Salmonella spp..*

Literature on the effectiveness of anaerobic digestion on nematodes and viruses is very scarce and deserves further attention among the research community.

Weed seeds

Some seeds, including those from undesired weeds, survive the anaerobic digestion process. Studies in this respect are scarce, but available literature indicated that the operating temperature of the digester and the time of digestion play a significant role in reducing the germination potential of seeds.

Heavy metals

There seems to be no indication that B contains more heavy metals than undigested manure. Yet, there might be the risk of heavy metal accumulation in biogas sludge, which is also used for crop fertilization.

Composting

When the available B cannot be used at once, storage of B is needed and composting of B can be a solution. After B is mixed with other biodegradable materials and treated well, the composted fertilizer can be stored for several weeks although the characteristics and nutrients value diminish because of biological decomposition. The composted fertilizer has similar characteristics as manure and can be used as basal fertilizer or as an additive to B. Since composted B can be more easily stored and transported than liquid B, it can be used when actually needed. Surplus B can be sold, and thereby generate additional income. Composted B has the advantage of being considerably cheaper than synthetic fertilizer. A case in Vietnam showed that the cost of B self-production was 20 times less than purchased urea.

3.1 RECOMMENDATIONS

Despite the several academic studies on the effects of B utilization and many technical reports, it is obvious that some crucial questions still remain unanswered. These knowledge gaps can be broadly divided into: (i) specific research needs, (ii) practical, use-oriented guidelines, and (iii) outstanding issues that have not been addressed at all so far. The first one should be addressed by universities and national research institutes, tailored towards the needs and conditions of specific regions and locations. The second one would ideally be taken on by local organizations and extension services jointly with farmers and rural workers.

(i) In **agronomic research**, the main focus of the work should be on:

1. The physical, physicochemical and biochemical properties of B, particularly in order to determine long-term soil fertility implications of utilizing B compared to raw manure and/or SF;
2. Yield implications of substituting SF with B under specific conditions, for various local crops;
3. The viability of digesting field residues together with manure, with particular emphasis on long-term soil fertility;
4. Disease and pest management implications of B utilization, particularly to determine the full potential of bioslurry as pesticide, and fungicide for different pest and fungi species, and to determine the ideal bioslurry dose and application interval;
5. Risks associated with B utilization, with particular emphasis on pathogen transfer from B to crops;
6. Optimization possibilities of utilizing B for aquaculture;
7. Potential of using B for soil remediation;
8. Energy balance of B (see Box 4).

(ii) More **practical, use-oriented studies** should focus on the details of B application in the local context. These studies should include an assessment of existing on-farm resources and a socio-cultural study of local preferences and practices to ensure greater adoption levels of B. Methods could include seasonal calendars and cropping calendars. The key questions should be: how compatible with local agricultural and socio-cultural practices is the use of B? Which farm activities would be best served by the use of B?

Ideally these studies would be combined with locally adopted agronomic research. How should B be applied, what is the correct dose, what is the rate of application? Should it be incorporated into the soil, or sprayed on the respective crop?

In order to be applicable outside of each study region and comparable to other experiments, we suggest to set standardized field trials, which will need thorough guidelines. They should be practical, simple and of low cost in order to allow comprehensive testing throughout the different agro-ecological zones.

In the easiest case, a questionnaire could be developed that gives detailed instructions to farmers to record data on digester input (i.e. the types of manure, animal feed, etc,), the application procedure (when, how, how much etc.) and plant parameters such as yield and biomass growth. Additional parameters such as soil types and climatic conditions would need to be recorded separately by the researcher.

The development of such studies should be undertaken in collaboration with experienced technical institutions that have significant experience in this field.

Based on such research, guidelines could be produced and disseminated to farmers and extension workers.

(iii) **Outstanding issues**: An area that has received no attention in peer-reviewed literature, and hardly any in technical reports, is the **profitability of B use and sale**. Few technical reports indicate that the full or partial replacement of synthetic fertilizer with B on-farm or the sale of surplus, composted B can be very profitable. Data on this issue would make a very strong case for anaerobic digestion in general, and B use in particular.

Another area to be explored is the energy efficiency of bioslurry. To determine an energy balance is the customary method us ed to evaluate and compare the performance of agricultural systems in terms of energy. A central input to consider in the energy balance in agriculture, is the energy spent in the production of fertilizers (i.e. inputs, outputs, and net returns). However, it is difficult to determine a precise energy balance, mainly because there is no universally accepted method for doing so. This causes a great variation in outcomes as can be seen in a literature review on the energy balance of agricultural systems conducted by Zegada-Lizarazu *et al* (2010).

Gross estimations reported in the literature review indicate an energy coefficient for N fertilizers ranging from 32.2 MJ/kg to 99.6 MJ/kg, an energy coefficient for Ammonia fertilizers ranging from 27 MJ/kg to 50.6 MJ/kg, and an energy coefficient for Urea fertilizers ranging from 35.1 MJ/kg to 76 MJ/kg (Zegada-Lizarazu *et al*., 2010). In comparison, organic fertilizers have a much lower energy balance (FAO 2000), for instance 0.35 MJ/kg for fresh manure. According to Hülsbergen *et al*., the general energy cost of 1 kg of manure is equivalent to 0.428 kg of synthetic fertilizer (Hülsbergen *et al*, 2001 as cited in Zegada-Lizarazu *et al*, 2010).

Selling surplus bioslurry in bottles.
© Jaime Marti Herrero

The energy balance of B is not reported. However, it is likely to be closer to the balance of fresh manure than that of synthetic fertilizer. Bearing the uncertainties of determining an energy balance in mind, the energy used to produce one kilogram of SF is around 100 to 300 times larger than for producing one kilogram of fresh manure. Given these very large differences, it seems worthwhile to conduct research on the energy balance of B to determine the potential of reducing GHG emissions and saving fossil fuel energy and related costs. Increasing fossil fuel prices will make fossil fuel based fertilizers' price more and more expensive and volatile, which will directly impact those smallholder farmers that currently depend on them.

Another outstanding item is related to the potential **over-fertilization** of arable lands with bioslurry, which can lead to soil acidification and eutrophication.

FINAL REMARKS

This review leads to the conclusion that there are still significant research gaps as listed above. However, it is important to keep in mind that these gaps present just one of the barriers to effective B use. Numerous technical reports clearly show that the effective use of B also depends on many practical and social issues. Misinformation regarding the benefits of slurry uses among the rural population still presents a large hurdle in many countries. Some practical issues regarding the handling and storage of liquid manure still need to be addressed. Furthermore, the predominance of synthetic fertilizers makes B a fairly attractive option, as supporting policies and subsidies favour the use of these cheap inputs in many areas of the world.

Environmental pollution, climate change and increasing fossil fuel prices leading to higher agricultural input costs make the call for exploring the full potential of B a strong case. This needs adequate support for both scientific and practical research, capacity building and knowledge transfer as well as sound supporting policies.

REFERENCES

Ashden Awards, 2010: *Case study summary Ministry of Agriculture and Rural Development (MARD), Vietnam and Netherlands Development Organisation (SNV)*, http://www.ashdenawards.org/files/reports/MARD-SNVpercent20casepercent20study.pdf, accessed February 16th, 2011

Bagge, E., L. Sahlström, and A. Albihn, 2005: *The Effect of Hygienic Treatment on the Microbial Flora of Biowaste at Biogas Plants.* Water Research 39, vol., pp. 4879–4886.

Balasubramanian P.R & Kasturi Bai, R.K, 1991: *Recycling of Biogas-Plant Effluent through Aquatic Plant (Lemna) Culture,* Bioresource Technology, vol. 41, pp. 213-216

Balasubramnian, P.R. & Kasturi Bai, R., 1994: *Biogas-plant effluent as an organic fertiliser in fish polyculture,* Bioresource Technology 50 (1994), pp. 189-192

Balasubramnian, P.R. & Kasturi Bai, R., 1995: *Biogas-plant effluent as an organic fertiliser in monosex, monoculture of fish (oreochromis mossambicus),* Bioresource Technology 55 (1996), pp. 119-124

Bendixen H.J., 1999: *Hygienic safety – results of scientific investigations in Denmark Sanitation requirements in Danish BGPs.* In: Böhm R, Wellinger A (Eds.), Hygienic and Environmental Aspects of Anaerobic Digestion, Stuttgart, pp. 27-47

Bharde, N.M., Shivay, Y.S. & Singh, S., 2003: *effect of bioslurry and neem oil-treated urea sources in rice (Uryza sativa) – Wheat (Triticum aestivum) cropping system,* Indian Journal of Agronomy, vol. 48(2), pp. 73-75

Bogdanski, A., Dubois, O., Jamieson, C. & Krell, R, 2010: *Making integrated food-energy systems work for people and climate – An overview*, Food and Agriculture Organization of the United Nations, Rome, Italy

Bogdanski, A., 2011: *Introducing Integrated Food-Energy Systems that Work for People and Climate,* Micro perspectives for decentralized energy supply - Proceedings of the International Conference. Technische Universitaet Berlin, 7th-8th of April 2011.

Bonetta, S., E. Ferretti, S. Bonetta, G. Fezia, and E. Carraro, 2011: *Microbiological Contamination of Digested Products from Anaerobic Co-digestion of Bovine Manure and Agricultural By-products.* Letters in Applied Microbiology 53, vol. 5, pp. 552–557.

Bottone, E J, 1997: *Yersinia Enterocolitica: The Charisma Continues.* Clinical Microbiology Reviews 10(2): 257–276.

BP, 2007: *Bio-slurry utilization in Vietnam,* edited by Le Thi Xuan Thu, The Biogas Program for the Animal Husbandry Sector of Vietnam, Vietnam

BP, 2009: *Small-scale CDM programme of activities design document,* http://cdm.unfccc.int/UserManagement/FileStorage/P1GREC6D42V3AZBWH5LITNKOJXU078, accessed February 16th 2011

Campbell-Copp, J., 2011: *The Greenhouse Gas Reduction Potential of Chemical Fertilizer Replacement with Bio-slurry in Vietnam,* MSc Carbon Management, University of Edinburgh, Edinburgh, Scotland.

Chau, Le Ha, 1998a: *Biodigester effluent versus manure from pigs or cattle as fertilizer for production of cassava foliage (Manihot esculenta)*, Livestock research for Rural Development, volume 10, nr. 3, 1998: http://www.lrrd.org/lrrd10/3/chau1.htm/, accessed July 20th 2011

Chau, Le Ha, 1998b: *Biodigester effluent versus manure, from pigs or cattle, as fertilizer for duckweed (Lemna spp.)*, Livestock research for Rural Development, volume 10, nr. 3, 1998: http://www.lrrd.org/lrrd10/3/chau2.htm/, accessed July 20th 2011

Craswell, E.T. & Lefroy, R.D.B., 2001: *The role and function of organic matter in tropical soils,* Nutrient Cycling in Agroecosystems, vol. 61, pp. 7-18

Dahiya, A.K. & Vasudevan, P., 1986: *Biogas plant slurry as an Alternative to chemical fertilizers,* Biomass 9 (1986) pp 67-74

Debnath, G., Jain, M. C., Kumar, S., Sarkar K. & Sinha, S.K., 1996: *Methane emissions from rice fields amended with bioslurry and farm yard manure,* Climatic Change, vol. 33, pp. 97-109

Dragosits, U., Theobald, M. R., Place, C. J., Lord, E., Webb, J., Hill, J., ApSimon, H. M., Sutton, M. A., 2002: *Ammonia emission, deposition and impact assessment at the field scale: a case study of sub-grid spatial variability*. Environ. Pollut. 117, 147–158

Edwards, P., Polprasert, C., Rajput, V.S. & Pacharapraktiti, C., 1987: *Integrated biogas technology in the tropics. 2. Use of slurry for fish culture,* Waste Management & Research (1988) 6, pp. 51-61

EIU, 2008: *Country profile 2008 – Vietnam,* Economist Intelligence Unit, London, UK

El-Hadidi, Y. M. & Al-Turki, A. I., 2007: *Organic fertilizer and biogas production from poultry wastes,* Journal of Food, Agriculture & Environment Vol. 5(1), pp. 228-233

Encyclopaedia Britannica, 2011: *Fornace operation,* http://www.britannica.com/EBchecked/topic/553362/solid-waste-management/72384/Incineration?anchor=ref593307, accessed May 3rd 2011

FAO, 1980: *Feed from animal wastes: state of knowledge*. FAO Animal production and health paper 18, Rome, Italy

FAO, 1996: *Utilization of slurry as feed and fertilizer,* Support for the Development of National Biogas Programme Project, Session Four, by Consolidated Management Services Nepal, Kathmandu, Nepal

FAO, 2000: *The energy and agriculture nexus,* by Jacques Eckebil, Food and Agriculture Organization of the United Nations, Rome, Italy

FAO, 2006: *Plant nutrition for food security - A guide for integrated nutrient management*, by Roy, R.N., Finck A., Blair G.J. & Tandon, H.L.S., Food and Agriculture Organization of the United Nations, Rome, Italy

Faostat, 2011: http://faostat.fao.org/, accessed March 17th 2011

Garfi, M., Gelman, P., Comas, J., Carrasco, W., Ferrer, I., 2011: *Agricultural reuse of the digestate from low-cost tubular digesters in rural Andean communities,* Waste Management, doi:10.1016/j.wasman.2011.08.007

Garg, R. N., Pathak, H., Das, D. K. & Tomar, R. K., 2005: *Use of fly ash and bioslurry for improving wheat yields and physical properties of soil,* Environmental Monitoring and Assessment, vol. 107, pp. 1-9

Gebrezgabher, S.A., Meuwissen, M.P.M., Prins, B.A.M., Oude Lansink, A.G.J.M., 2010: *Economic analysis of anaerobic digestion – A case of Green power biogas plant in The Netherlands,* NJAS, 57 (2010) pp. 109-115

Ghoneim, A.M., 2008: *Nitrogen dynamics and fertilizer use efficiency in rice using the nitrogen-15 isotope techniques,* World Applied Sciences Journal, vol. 3(6), pp. 869-874

GM, 2008: *Country Profile of China,* Global Methane, http://www.globalmethane.org/documents/ag_cap_china.pdf, accessed March 7th 2011

Gnanamani, A. & Kasturi Bai, R., 1991: *Influence of Biodigested Slurry on Rice-Gram Cultivation,* Bioresource technology 41 (1992), pp. 217-221

Goberna, M., Podmirseg, S.M., Waldhuber, S., Knapp, B.A., Garcia, C., Insam., H., 2011: *Pathogenic bacteria and mineral N in soils following the land spreading of biogas digestates and fresh manure,* Applied Soil Ecology, 49 , pp. 18-25

Gunaseelan, V.N, 1997: *Anaerobic digestion of biomass for methane production: A Review,* Biomass and Bioenergy Vol. 13, Nos. l/2, pp. 83311

Gupta, A. P., Gupta, V. K., Antil, R. S., Jagan Nath, 1985: *Possible losses from bioslurry,* Agricultural Wastes vol. 12, pp. 317-320

Gurung, B., 1997: *Training Manual Proper utilization of bio-slurry*, obtained from CD 'Domestic Biogas in Developing Countries, 20 years of key documents', version 1.0, October 2009

Gurung, J., 1997: *Review of Literature on Effects of Slurry Use on Crop production*, http://s3.amazonaws.com/zanran_storage/www.snvworld.org/ContentPages/48612287.pdf, accessed June 7th 2011

Hongmei, J. & Chang, Z., 2010: *Distribution of Heavy Metal Contents and Chemical Fractions in Anaerobically Digested manure Slurry,* Applied Biochemical Biotechnology (2011) 164, pp. 268-282

IPCC, 2006: *Emission factor database:* http://www.ipcc-ggip.iges.or.jp/EFDB/find_ef_main.php, accessed April 15th 2011

ISD, 2010: *Increasing access to homestead biogas in Tentulia: Pilot Project*: http://www.snvworld.org/en/Documents/Inreasing_access_to_homestead_biogas_in_Tentulia_Bangladesh_2010.pdf, accessed September 21st 2011

Jothi, G., Pugalendhi, S., Poornima, K. & Rajendran G., 2003: *Management of root-knot nematode in tomato Lycopersicon esculentum, Mill., with bioslurry,* Bioresource Technology, vol. 89, pp. 169-170

Johnston, A.E. 2001: Principles of crop nutrition for sustainable food production. Proc. Int. Fertiliser Soc. 459:1–38

Kadian, N., Gupta, A., Satya, S., Metha, R.K., Malik, A., 2008: *Biodegradation of herbicide (atrazine) in contaminated soil using various bioprocessed materials,* Bioresourcetechnology, vol. 99 (11), pp. 4642-4647

Kadian, N. Malik, A., Satya, S., Durejab, P., 2012: *Effect of organic amendments on microbial activity in chlorpyrifos contaminated soil*, Journal of Environmental Management, vol. 95, pp.199–202

Karch, Helge, Phillip I. Tarr, and Martina Bielaszewska, 2005: *Enterohaemorrhagic Escherichia*

Coli in Human Medicine. International Journal of Medical Microbiology 295, vol. 6-7: 405–418

Kaur, K., Sehgal, G.K. & Sehgal, H. S., 1987: *Efficacy of Bioslurry in Carp, Cyprinus carpio Var. communis (Linn.), Culture Effects on Survival and Growth,* Biological Wastes, vol. 22, pp. 139-146

Kudva, I.T., K. Blanch, and C.J. Hovde, 1998: *Analysis of Escherichia Coli O157:H7 Survival in Ovine or Bovine Manure and Manure Slurry*. Applied and Environmental Microbiology, vol. 64 (9), pp. 3166–3174

Kupper, K.C., Bettoil, W., de Goes, A., de Souza, P.S., Bellotte, J.A.M., 2006: *Biofertilizer for control of Guignardia citricarpa, the causal agent of citrus black spot,* Crop Protection 25 (2006), pp. 569-573

Lallai, A., Mura, G. & Onnis, N., 2001: *The effect of certain antibiotics on biogas production in the anaerobic digestion of pig waste slurry,* Bioresource Technology 82 (2002), pp. 205-208

Liu, W. K., Yang, Q.-C.,& Du, L., 2009: *Soilless cultivation for high-quality vegetables with biogas manure in China: Feasibility and benefit analysis.* Renewable Agriculture and Food Systems: Vol. 24(4), pp. 300-307

Lošák, T., Zatloukalová, A., Szostková, M., Hlušek, J., Fryč, J., Vítoz, T., 2011: *Comparison of the effectiveness of digestate and mineral fertilisers on yields and quality of kohlrabi (Brassica Oleracea, L.),* Acta univ. agric. et silvic. Mendel. Brun., 2011 LIX, No. 3, pp. 177-122

LTA (Landwirtschaftliches Technologiezentrum Augustenberg), 2008: *Inhaltsstoffe von Gaerprodukten und Moeglichkeiten zu ihrer pflanzenbaulichen Verwertung.* Projecktbericht 2008. Minsterium fuer Ernaehrung und Laendlichen Raum Baden Wuertemberg

Mitscherlich, E. and E. H. Marth, 1985: *Microbial Survival in the Environment.* In: Bacteria and Rickettsiae Important in Human and Animal Health. Pp. 802-854. Springer Verlag, New York.

Möller, K., Stinner, W., Deuker, A. & Leithold, G., 2008: *Effects of different manuring systems with and without biogas digestion on nitrogen cycle and crop yield in mixed organic dairy farming systems,* Nutrient Cycling in Agroecosystems, vol 82, pp. 209-232

Mortvedt, J. J., 1996: *Heavy metal contaminants in inorganic and organic fertilizers.* Nutrient Cycling in Agroecosystems, vol 43, pp. 55-61

Ni, K., Pacholski, A., Gericke, D., & Kage, H.: 2012. *Analysis of ammonia losses after field application of biogas slurries by an empirical model.* Journal of Plant Nutrition and Soil Science, 175(2), pp. 253–264

NNFCC, 2011: *Anaerobic digestion*: http://www.biogas-info.co.uk/index.php/standards-and-quality-control.html, accessed August 2nd 2011

Olsen, J.E., Larsen, H.E., 1987: *Bacterial decimation times in anaerobic digestions of animal slurries*, Biological wastes 21 (1987), pp. 153-168

Ottoson, J.R., A. Schnürer, and B. Vinnerås, 2008: *In Situ Ammonia Production as a Sanitation Agent During Anaerobic Digestion at Mesophilic Temperature*. Letters in Applied Microbiology 46, vol. 3, pp. 325–330

Paavola, T., Rintala, J., 2008: *Effects of storage on characteristics and hygienic quality of digestates from four co-digestion concepts of manure and biowaste*, Bioresource Technology 99 (2008), pp. 7041-7050

Pham, V. T.; Nguyen, D. T., 2006: *Bio-Fertilizer produced at Household scale by recycling agricultural waste and biodigester slurry for sustainable agriculture development.* Center for Rural Communities Research and Development, August 2006

Phiny, C., Borin, K., Preston, T.R.& Ty, C., 2009: *Effect of level of effluent from biodigesters loaded with pig manure on the growth of mulberry (Morus alba) trees,* Livestock Research for Rural Development, vol. 21(7)

Ramaswamy, Vidhya, Vincent Mary Cresence, Jayan S Rejitha, *et al*., 2007: *Listeria--review of Epidemiology and Pathogenesis.* Journal of Microbiology, Immunology, and Infection = Wei Mian Yu Gan Ran Za Zhi 40, vol. 1, pp. 4–13

Ray, C., and Kenneth J. Ryan, 2003: *Sherris Medical Microbiology : An Introduction to Infectious Diseases.* 4th edition. McGraw-Hill Medical

Sahlström, L., 2003: *A review of survival of pathogenic bacteria in organic waste used in biogas plants*, Bioresource Technology 87, pp. 161-166

Sanderson, M. G., Collins, W. J., Johnson, C. E., Derwent, R. G., 2006: Present and future acid deposition to ecosystems: The effect of climate change. Atmos. Environ. 40, pp. 1275–1283

Saxena, K. K., Nath K. & Srivastava, S. K., 1988: *The Effect of Using Dung from Cattle Fed High-,Low-or No-Concentrate Rations, on the Quality and Nutritive Value of Slurry from a Biogas Plant,* Biological Wastes, vol. 28, pp. 73-79

Sauerwein R., Bisseling J., Horrevorts A., 1993: *Septic abortion associated with Campylobacter fetus subspecies fetus infection: case report and review of the literature*. *Infection* 21, vol. 5, pp. 331–3

Schrade, S., Pekrun, C. Oechsner, Claupein, W., 2003: *Untersuchungen zum Einfluss der Biogasgärung auf die Keimfähigkeit von Unkraut- und Kulturpflanzensamen unter besonderer Berücksichtigung des Stumpfblättrigen Ampfers (Rumex obtusifolius L.).* In: Freyer B (ed) Proceedings of 7. Wissenschaftstagungzum Oekologischen Landbau, Wien, Austria, 24-26 March 2003, pp 531-532. http://orgprints.org/8989/1/P.Schrade.pdf. accessed April 13th 2012

Sehgal, H.S., Kaur, K. & Sehgal, G.K., 1991: *Phytoplankton Response to Bioslurry in Carp Ponds,* Bioresource Technology, vol. 37, pp. 229-234

Sehgal, H.S., Kaur, K. & Sehgal, G.K., 1992: *Zooplankton Response to Bioslurry in Carp Ponds,* Bioresource Technology, vol. 41, pp. 111-116

Shen, D., 2001: Beneficial Microorganisms and Metabolites Derived from Agriculture Wastes in Improving Plant Health and Protection. Journal of Crop Production, vol 3, pp. 349–366

SNV, 2007: International Workshop on Use of Bio-slurry from Domestic Biogas Plant. http://www.snvworld.org/en/Documents/International_workshop_on_use_of_bio-slurry_Thailand_2007.pdf, accessed May 7th 2011

SNV, 2008: *Dong for Dung: Utilization for bio-slurry in crop production and animal production.* Film compilation of SNV-supported domestic biogas programmes in developing countries, version 1.0. SNV

SNV, 2009: *Domestic Biogas in Developing Countries, 20 years of key documents*, CD version 1.0, October 2009

SNV, 2011: http://www.snvworld.org/en/aboutus/news/Pages/NewsPage1101002.aspx, accessed March 15th 2011

Shi, Y.J, Lu, Y.L. & Liang, D., 2002: *Application of anaerobic digested residues on safe food production,* Journal of Environmental Science and Health, Part A, vol 37(4), pp. 725-735

Sikka, S.S., 2006: *Effect of incorporating biogas slurry on the growth performance and carcass traits of growing pigs,* Livestock Research for Rural Development, vol. 18(5)

Singh, K. P., Suman A., Singh P. N. & Srivastava T. K., 2007: *Improving quality of sugarcane-growing soils by organic amendments under subtropical climatic conditions of India,* Biology and Fertility of Soils, vol. 44, pp. 367-376

Slana, I., R. Pribylova, A. Kralova, and I. Pavlik, 2011: *Persistence of Mycobacterium Avium Subsp. Paratuberculosis at a Farm-Scale Biogas Plant Supplied with Manure from Paratuberculosis-Affected Dairy Cattle.* Applied and Environmental Microbiology 77, vol. 9, pp. 3115–3119

Syers, J.K., A.E. Johnston and D. Curtin. 2008. Efficiency of soil and fertilizer phosphorus use. Fertilizer Plant Nutr. Bull. No. 18. FAO, Rome, Italy

Sommer, S. G., Dalsgaard, A., Roepstorf, A., Jensen L. S., Luxhøi J., Tran, T. S., Tran, M. T., Tran, T. H. Dang, T. T. S., Vu, C. C., Vu, T. K. V., Undated: *Livestock production, manure management and plant nutrient recycling on animal farms in Vietnam,* http://www.susane.info/bantin/25Oct08/Proceeding.pdf, accessed March 15th 2011

Tambone, F., Scaglia, B., D'Imporzano, G., Schievano, A., Orzi, V., Salati, S., Adani, F., 2010: *Assessing amendment and fertilizing properties of digestates from anaerobic digestion through a comparative study with digested sludge and compost,* Chemosphere 81, pp. 577-583

Teune, 2007: *The Biogas Programme in Vietnam; Amazing results in poverty reduction and economic development,* Boiling Point No 53, pp. 11-13

Thanh, P.V., 2011: Personal communication, 25th March 2011

Tran, M.T., Vu, T.K.V., Sommer, S.G., Jensen, L.S., 2011: *Nitrogen turnover and loss during storage of slurry and composting of solid manure under typical Vietnamese farming conditions*, Journal of agricultural science vol.149 (3), pp. 285-296

Tulayakul, P., Boonsoongnern, A., kasemsuwan, A., Wiriyarampa, S., Pankumnoed, J., Tippayaluck, S., Hanananatachai, H., Mingkhwan, R., Netvichian, R., Khaodhiar, S., 2010: *Comparative study of heavy metal and pathogenic bacterial contamination in sludge and manure in biogas and non-biogas swine farms,* Journal of Environmental Sciences 2011, 23(6), pp 991-997

Vietnam Business Week, 2011: *Imported Urea Prices in Vietnam Soar to Record High:* http://vccinews.com/news_detail.asp?news_id=4171, accessed September 21st 2011

Vinnerås, B., Schönning, C., 2011: *Microbial risks associated with biogas and biodigester sludge.* In: Nriagu JO (ed.) *Encyclopedia of Environmental Health, volume 3,* pp. 757–764 Burlington: Elsevier

Vitousek, P. M., Naylor, R., Crews, T., David, M. B., Drinkwater, L. E., Holland, E., Johnes, P. J., Katzenberger, J., Martinelli, L. A., Matson, P. A., Nziguheba, G., Ojima, D., Palm, C. A., Robertson, G. P., Sanchez, P. A., Townsend, A. R., Zhang, F. S., 2009: *Nutrient Imbalances in agricultural development.* Science 324, 1519–1520

Vu, T.K.V., Tran, M.T., Dang, T.T.S., 2007: *A survey of manure management on pig farms in Northern Vietnam,* Livestock Science 112 (2007), pp. 288-297

VWA, 2011: http://www.vwa.nl/onderwerpen/wet-en-regelgeving/dossier/verordening-eg-nr-1069-2009-basisverordening-dierlijke-bijproducten, accessed September 20th 2011

Wenke, L., Lianfeng, D & Qichang, Y., 2009: *Biogas slurry added amino acids decreased nitrate concentrations of lettuce in sand culture,* Acta Agriculturae Scandinavica Section B -Soil and Plant Science, vol. 59, pp. 260-264

Wilkinson., K.G., 2011: *A comparison of the drivers influencing adoption of on-farm anaerobic digestion in Germany and Australia*, Biomass & Bioenergy, 35 (2011) pp. 1613-1622

Wulf, S., Maeting, M., Clemens, J., 2002: Application technique and slurry co-fermentation effects on ammonia, nitrous oxide, and methane emissions after spreading: I. Ammonia volatilization. J. Environ. Qual. 31, pp. 1789–1794

Yen-Phil, V., Clemens, J., Rechenburg1, A., Vinneras, B. & Kistemann, T., 2008: *Pathogen Reduction in Small-Scale Biogas Plants in a Tropical Region - Bench-Scale Experiments,* http://www.ramiran.net/doc08/RAMIRAN_2008/Yen-Phi.pdf

Yu, F.B, Luo, X.P, Song, C.F., Zhang, M.X. & Shan, S.D, 2010: *Concentrated biogas slurry enhanced soil fertility and tomato quality,* Acta Agriculturae Scandinavica Section B - Soil and Plant Science, vol. 60, pp. 262-268

Zhao, X.R., X.Y. Zhong, H.J. Bao, H.H. Li, G.T. Li, D.B. Tuo, Q.M. Lin, and P.C.

Brookes, 2007: *Relating soil P concentrations at which P movement occurs to soil properties in Chinese agricultural soils*. Geoderma 142:237–244

Zhao, B.-Q., Li, X.-Y., Li, X.-P., Shi, X.-J., Huang, S.-M., Wang, B.-R., … R. Payne, 2010: *Long-term fertilizer experiment network in China: Crop yields and soil nutrient trends*. Agronomy Journal, 102(1), pp. 216–230

Zegada-Lizarazu, W., Matteucci, D., Monti, A., 2010: *Critical review on energy balance of agricultural systems,* Biofuels, Bioproduct and Biorefining, vol. 4, pp. 423-446

FAO ENVIRONMENT AND NATURAL RESOURCES MANAGEMENT WORKING PAPER

1. Inventory and monitoring of shrimp farms in Sri Lanka by ERS SAR data, 1999 (E)
2. Solar photovoltaic for sustainable agriculture and rural development, 2000 (E)
3. Energía solar fotovoltaica para la agricultura y el desarrollo rural sostenibles, 2000 (S)
4. The energy and agriculture nexus, 2000 (E)
5. World wide agroclimatic database, FAOCLIM CD-ROM v. 2.01, 2001 (E)
6. Preparation of a land cover database of Bulgaria through remote sensing and GIS, 2001 (E)
7. GIS and spatial analysis for poverty and food insecurity, 2002 (E)
8. Environmental monitoring and natural resources management for food security and sustainable development, CD-ROM, 2002 (E)
9. Local climate estimator, LocClim 1.0 CD-ROM, 2002 (E)
10. Toward a GIS-based analysis of mountain environments and populations, 2003 (E)
11. TERRASTAT: Global land resources GIS models and databases for poverty and food insecurity mapping, CD-ROM, 2003 (E)
12. FAO & climate change, CD-ROM, 2003 (E)
13. Groundwater search by remote sensing, a methodological approach, 2003 (E)
14. Geo-information for agriculture development. A selection of applications, 2003 (E)
15. Guidelines for establishing audits of agricultural-environmental hotspots, 2003 (E)
16. Integrated natural resources management to enhance food security. The case for community-based approaches in Ethiopia, 2003 (E)
17. Towards sustainable agriculture and rural development in the Ethiopian highlands. Proceedings of the technical workshop on improving the natural resources base of rural well-being, 2004 (E)
18. The scope of organic agriculture, sustainable forest management and ecoforestry in protected area management, 2004 (E)
19. An inventory and comparison of globally consistent geospatial databases and libraries, 2005 (E)
20. New LocClim, Local Climate Estimator CD-ROM, 2005 (E)
21. AgroMet Shell: A toolbox for agrometeorological crop monitoring and forecasting CD-ROM (E)**
22. Agriculture atlas of the Union of Myanmar (agriculture year 2001-2002), 2005 (E)
23. Better understanding livelihood strategies and poverty through the mapping of livelihood assets: A pilot study in Kenya, 2005 (E)
24. Mapping global urban and rural population distributions, 2005 (E)
25. A geospatial framework for the analysis of poverty and environment links, 2006 (E)
26. Food Insecurity, Poverty and Environment Global GIS Database (FGGD) and Digital Atlas for the Year 2000, 2006 (E)
27. Wood-energy supply/demand scenarios in the context of the poverty mapping, 2006 (E)
28. Policies, Institutions and Markets Shaping Biofuel Expansion: The case of ethanol and biodiesel in Brazil, in preparation (E)
29. Geoinformation in Socio-Economic Development Determination of Fundamental Datasets for Africa, 2009 (E, F)
30. Assessment of energy and greenhouse gas inventories of sweet sorghum for first and second generation bioethanol, 2009 (E)
31. Small scale Bioenergy Initiatives: Brief description and preliminary lessons on livelihood impacts from case studies in Asia, Latin America and Africa, 2009 (E)
32. Review of Evidence on Dryland Pastoral Systems and Climate Change: Implications and opportunities for mitigation and adaptation, 2009 (E)
33. Algae Based Biofuels: A Review of Challenges and Opportunities for Developing Countries, 2009 (E)

34. **Carbon finance possibilities for agriculture, forestry and other land use projects in a smallholder context, 2010 (E, F, S)**
35. **Bioenergy and Food Security: The BEFS analysis for Tanzania, 2010 (E)**
36. **Technical Compendium: Description of agricultural trade policies in Peru, Tanzania and Thailand, 2010 (E)**
37. **Household level impacts of increasing food prices in Cambodia, 2010 (E)**
38. **Agricultural based livelihood systems in drylands in the context of climate change: Inventory of adaptation practices and technologies of Ethiopia. in preparation (E)**
39. **Bioenergy and Food Security: The BEFS Analysis for Peru, Technical Compendium Volume 1: Results and Conclusions; Volume 2: Methodologies, 2010 (S)**
40. **Bioenergy and Food Security: The BEFS Analysis for Peru, Supporting the policy machinery in Peru, 2010 (E, S)**
41. **Analysis of climate change and variability risks in the smallholder sector: Case studies of the Laikipia and Narok districts representing major agro ecological zones in Kenya, 2010 (E)**
42. **Bioenergy and Food Security: The BEFS analysis for Thailand, 2010 (E)**
43. **BEFS Thailand: Key results and policy recommendations for future bioenergy development, 2010 (E)**
44. **Algae-based biofuels: Applications and co-products, 2010 (E)**
45. **Making Integrated Food-Energy Systems Work for People and Climate. An Overview (E)**
46. **Bioenergy Environmental Impact Analysis (BIAS): Analytical Framework (E)**
47. **Bioenergy Environmental Impact Analysis (BIAS) of Ethanol: Production from Sugar Cane in Tanzania Case Study: SEKAB/Bagamoyo (E)**
48. **Strengthening Capacity for Climate Change Adaptation in the Agriculture Sector in Ethiopia (E)**
49. **Good Environmental Practices in Bioenergy Feedstock Production – Making Bioenergy Work for Climate and Food Security (E)**
50. **Smallholders in Global Bioenergy Value Chains and Certification – Evidence from Three Case Studies (E)**
51. **A Compilation of Tools and Methodologies to Assess the Sustainability of Modern Bioenergy (E)**
52. **Impacts of Bioenergy on Food Security – Guidance for Assessment and Response at National and Project Levels (E)**
53. **Energy-Smart Food at FAO: An Overview (E)**
54. **Bioenergy and Food Security: The BEFS analysis for Tanzania - Sunflower Biodiesel, Water, and Household Food Security (E)**
55. **Bioslurry=Brown Gold. A review of scientific literature on the co-product of biogas production (E)**

Ar	Arabic	**F**	French	**Multil**	Multilingual
C	Chinese	**P**	Portuguese	*	Out of print
E	English	**S**	Spanish	**	In preparation

The FAO Technical Papers
are available through the authorized
FAO Sales Agents or directly from:

Sales and Marketing Group – FAO
Viale delle Terme di Caracalla
00153 Rome – Italy

ENVIRONMENT – CLIMATE CHANGE – BIOENERGY – MONITORING AND ASSESSMENT

FAO - ENVIRONMENT AND NATURAL RESOURCES MANAGEMENT WORKING PAPER

In recent years, there has been an increasing interest in anaerobic digestion of farm and household residues in many parts of the world. Smallholder biogas digesters and community biogas plants can be found all throughout Asia, but also progressively in Latin America and Africa.

Anaerobic digestion produces two main outputs: biogas and bioslurry, the digestate or digester effluent. While biogas is used to produce energy, the potential of bioslurry has often been overlooked. A large part of both the scientific and grey literature focuses on the production of energy alone, but does not venture into the multiple uses and intricacies of bioslurry use. Technical organizations such as NGOs, extension services and local universities and, last but not least, smallholders themselves, are often not fully aware of the multiple benefits of bioslurry use, nor do they know of the risks associated with handling and applying it on their farm.

This review therefore attempts to synthesize the findings of the growing peer-reviewed literature on bioslurry to provide a sound and scientific basis for bioslurry use. At the same time, it sets out to identify the various research gaps related to bioslurry.




Climate, Energy and Tenure Division (NRC) publications
Series: www.fao.org/climatechange/61878
Working papers: www.fao.org/climatechange/61879

NRC Contact: NRC-Director@fao.org

Food and Agriculture Organization of the United Nations (FAO)
www.fao.org

I3441E/1/09.13