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

ENVIRONMENT AND NATURAL RESOURCES MANAGEMENT WORKING PAPER

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

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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.

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

CONTENTS

CHAPTER 1

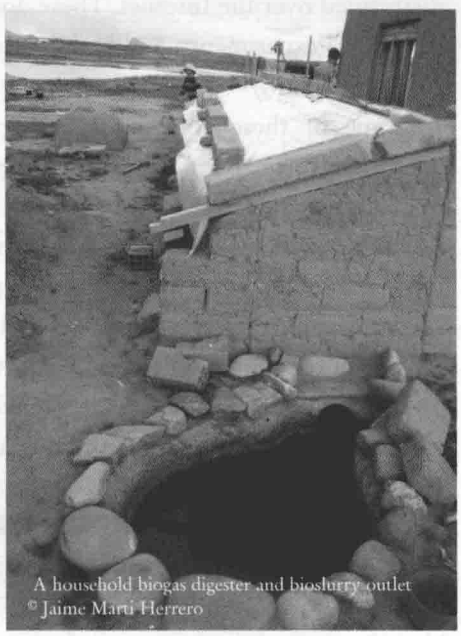
INTRODUCTION

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 Martí 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.

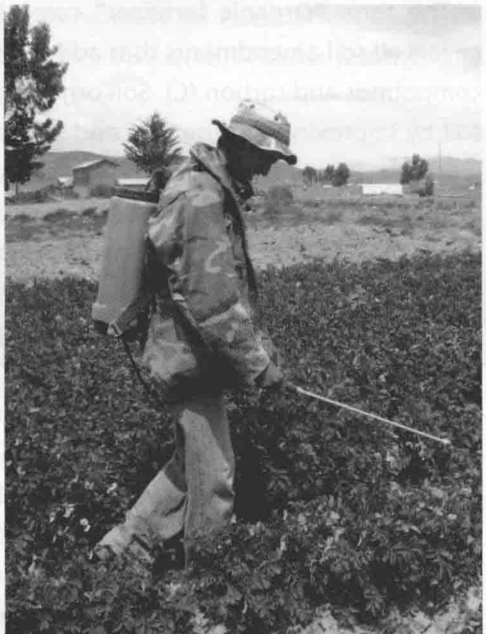
3 Both kerosene and fuelwood

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 Martí 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.