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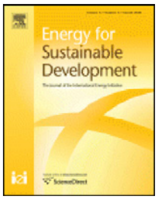

# History and future of domestic biogas plants in the developing world

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ABSTRACT

Technologies which recover biogas do so by harnessing anaerobic degradation pathways controlled by a suite of microorganisms. The biogas released acts as an environmentally sustainable energy source, while providing a method for disposal of various wastes. Biogas contains 50–70% methane and 30–50% carbon dioxide, as well as small amounts of other gases and typically has a calorific value of 21–24 MJ/m$^3$. Various appliances can be fuelled by biogas, with stoves offering an application appropriate for deployment in developing countries. Widespread dissemination of biogas digesters in developing countries stems from the 1970s and there are now around four and 27 million biogas plants in India and China respectively. These are typically small systems in rural areas fed by animal manure. However, in many other countries technology spread has foundered and/or up to 50% of plants are non-functional. This is linked to inadequate emphasis on maintenance and repair of existing facilities. Hence for biogas recovery technology to thrive in the future, operational support networks need to be established. There appear to be opportunities for biogas stoves to contribute to projects introducing cleaner cookstoves, such as the Global Alliance for Clean Cookstoves. Beyond this, there remains potential for domestic plants to utilise currently underexploited biogas substrates such as kitchen waste, weeds and crop residues. Thus there is a need for research into reactors and processes which enable efficient anaerobic biodegradation of these resources.

## Introduction to Biogas

Microbially-controlled production of biogas is an important part of the global carbon cycle. Every year, natural biodegradation of organic matter under anaerobic conditions is estimated to release 590–800 million tons of methane into the atmosphere (ISAT/GTZ, 1999a). Biogas recovery systems exploit these biochemical processes to decompose various types of biomass, with the liberated biogas potentially providing an energy source. There is a distinction between anthropogenic anaerobic processes which recover the energy within biogas and those which do not. Examples of the first category are bioreactors designed specifically for substrates, including sewage, agricultural, industrial and municipal waste, containing a high proportion of anaerobically-degradable biomass. In developing countries the expansion of biogas recovery systems has been based upon small-scale reactors designed for digestion of cattle, pig and poultry excreta. Meanwhile, landfill sites and municipal wastewater treatment plants where anaerobic processes produce biogas which is released into the atmosphere, either before or after combustion, belong to the second category. Biogas contains 50–70% methane and 30–50% carbon dioxide, depending on the substrate (Sasse, 1988) as well as small amounts of other gases including hydrogen sulphide. Methane is the component chiefly responsible for a typical calorific value of 21–24 MJ/m$^3$ (Dimpl, 2010) or around 6 kWh/m$^3$. Biogas is often used for cooking, heating, lighting or electricity generation. Larger plants can feed biogas into gas supply networks. The activities of at least three bacterial communities are required by the biochemical chain which releases methane. Firstly, during hydrolysis, extracellular enzymes degrade complex carbohydrates, proteins and lipids into their constituent units. Next is acidogenesis (or fermentation) where hydrolysis products are converted to acetic acid, hydrogen and carbon dioxide. The facultative bacteria mediating these reactions exhaust residual oxygen in the digester, thus producing suitable conditions for the final step: methanogensis, where obligate anaerobic bacteria control methane production from acidogenesis products. Anaerobic digesters are typically designed to operate in the mesophilic (20–40 °C) or thermophilic (above 40 °C) temperature zones. Sludge produced from the anaerobic digestion of liquid biomass is often used as a fertiliser. Biogas recovery technologies have been failures in many developing countries, with low rates of technology transfer and longevity and a reputation for being difficult to operate and maintain. Thus the objectives of this review were to identify the factors underlying successful and unsuccessful operation of domestic biogas plants and to investigate the future challenges, which, once overcome, would enable sustained expansion of biogas technology.

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## History of biogas production

There are suggestions that biogas was used for heating bath water in Assyria as long ago as the 10th century B.C. and that anaerobic digestion of solid waste may well have been applied in ancient China (He, 2010). However, well documented attempts to harness the anaerobic digestion of biomass by humans date from the mid-nineteenth century, when digesters were in constructed in New Zealand and India, with a sewage sludge digester built in Exeter, UK to fuel street lamps in the 1890s (University of Adelaide, 2010). In Guangdong Province, China, commercial use of biogas has been attributed to Guorui Luo. In 1921, he constructed an 8 $m^3$ biogas tank fed with household waste and later that decade founded a company to popularise the technology (He, 2010). The first German sewage treatment plant to feed biogas into the public gas supply began to do so in 1920, while in the same country the first large agricultural biogas plant began operating in 1950. The spread of biogas technology gained momentum in the 1970s, when high oil prices motivated research into alternative energy sources. The fastest growth of biogas use in many Asian, Latin American and African countries was in the 1970s and the first half of the 1980s (Ni and Nyns, 1996). During that period the Chinese government promoted “biogas use in every rural family” and facilitated the installation of more than seven million digesters (He, 2010) (Fig. 1). From the second half of the 1980s, while biogas technology found more applications in industrial and urban waste treatment and energy conservation, its dispersion into rural areas slowed. In China, by the end of 1988, only 4.7 million household biogas digesters were reported (Ni and Nyns, 1996). Particularly since the turn of this century there has been another rapid increase in the number of plants (Fig. 1) (He, 2010) and in 2007 there were 26.5 million biogas plants (Chen et al., 2010) the overwhelming majority household systems with volumes from 6 to 10 $m^3$. Meanwhile, in 1999 there were over three million family-sized biogas plants in India (Fig. 2) and by the end of 2007, the Indian government had provided subsidy for the construction of nearly four million family-sized biogas plants (Indian Government, 2007). The National Project on Biogas Development (NPBD) has run since 1981–1982 and promotes its own digester designs while providing financial support and various training and development programmes. Subsidies from state and central governments to install household bioreactors ranged from 30% to 100% in the 1980s–1990s (Tomar, 1995).

## Biogas appliances and the need for clean cookstoves

In developing countries, cookers/stoves, lamps, refrigerators and engines are appliances commonly fuelled by biogas (ISAT/GTZ, 1999a). Biogas can be converted into electricity using a fuel cell, though this is still considered a research area due to the need for very clean gas and the cost of fuel cells (Dimpl, 2010). In contrast, using biogas to fuel a combustion engine and in turn an electric generator is a proven means of producing electricity, given the wide availability of suitable generators. For example, in Pura, India a well-studied community biogas digester was used to fuel a modified diesel engine and run an electrical generator (Reddy, 2004). As hydrogen sulphide can corrode engine components it is typical to control its presence in the outlet flow from the digester. Contacting biogas with ferrous salts in a closed filter is a common method to achieve this. Alternatively a small amount of air can be injected into the digester headspace in order to facilitate biochemical hydrogen sulphide oxidation (Dimpl, 2010). Biogas burns with a clean, blue flame and stoves have been considered the best means of exploiting biogas in rural areas of developing countries (ISAT/GTZ, 1999b) (Fig. 3). Due to the physiochemical properties of biogas, commercial butane and propane burners are not suitable for biogas without modification. Since six litres of air are required to combust one litre of biogas, assuming a methane composition of 60%, compared with 31 L and 24 L of air for butane and propane respectively, commercial appliances need larger gas jets when burning biogas. Removing water is achieved by cooling, such as in an underground pipe, to condense the moisture.

The efficiency of biogas stoves has been quoted as 20%–56% (Itodo et al., 2007; ISAT/GTZ, 1999b), though such figures are strongly affected by operating conditions and stove design. Moreover, many health benefits can result from the switch from traditional to cleaner fuels. According to the World Health Organisation (WHO) over three billion people worldwide continue to use solid fuels, including wood, dung, agricultural residues and coal, to supply their energy needs (WHO, 2011). Cooking with solid fuels on open fires or with traditional stoves results in high levels of air pollution, due to pollutants such as small particles and carbon monoxide. Indoor air pollution, a significant proportion generated from traditional cooking stoves, is thought to be responsible for 2.7% of the total global burden of disease (WHO, 2011).

The prevalence of traditional fuels is illustrated by figures from Bangladesh where mud-constructed stoves are used by over 90% of

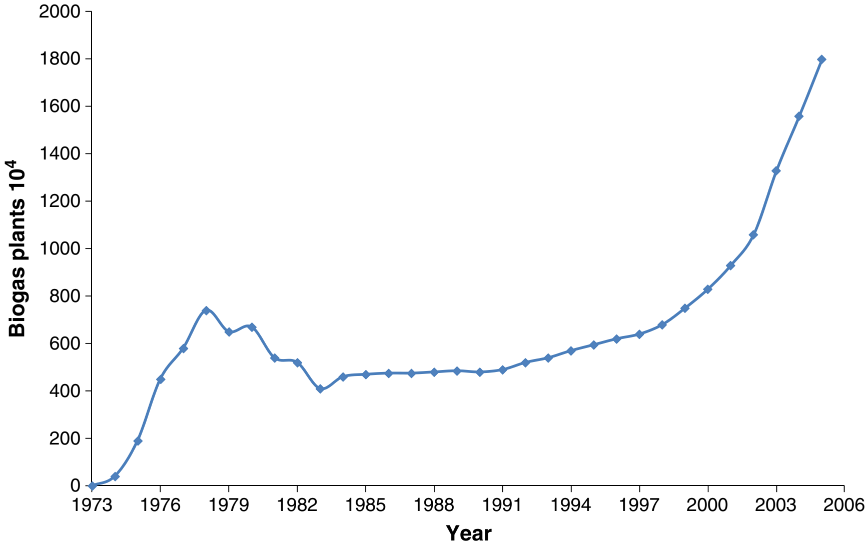

**Fig. 1.** Number of biogas plants in China (Chen et al., 2010; Zeng et al., 2007).

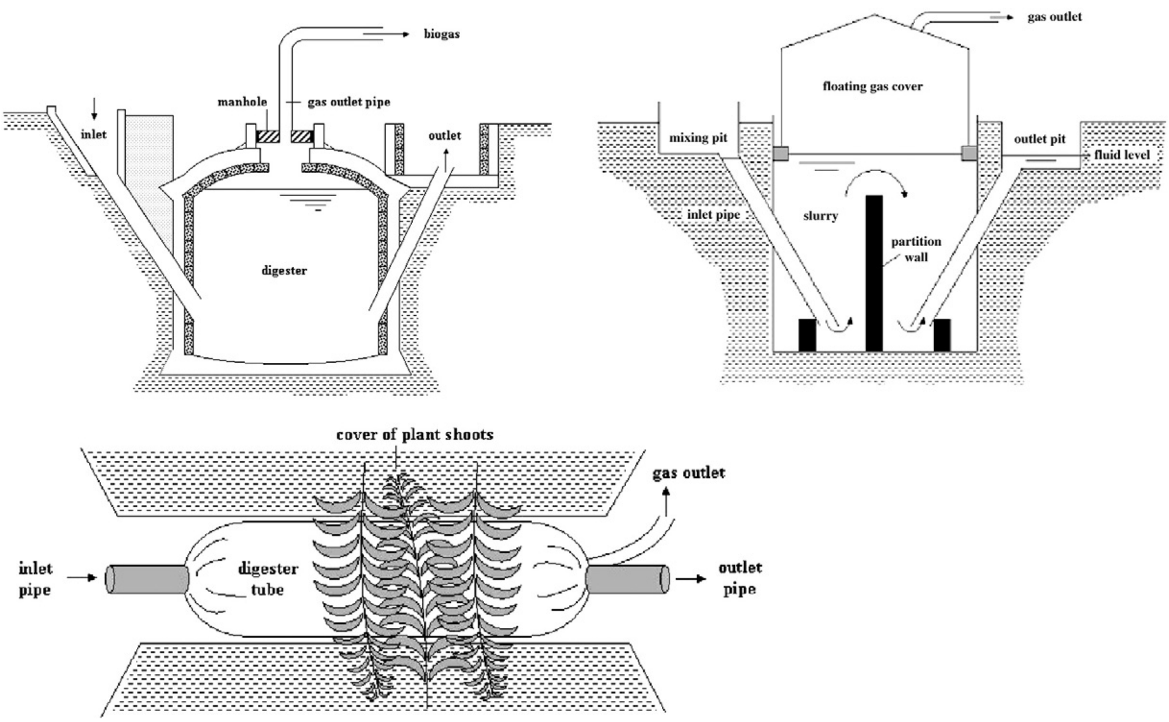

**Fig. 2.** Common digester designs in the developing world. Top left: fixed dome digester (Chinese type). Top right: floating cover digester (Indian type). Below: balloon or tube digester. Source: Plöchl and Heiermann (2006), based on Gunnerson and Stuckey (1986).

all families and have a thermal efficiency of only 5–15% (Hossain, 2003), compared with 29% for an improved biomass stove and 58% for an improved natural gas stove developed in the same country (Akter Lucky and Hossain, 2001). In rural India cooking is estimated to comprise 60% of overall energy consumption (Ravindranath and Hall, 1995). Various programmes have developed more efficient and cleaner cooking stoves (for example, Bailis et al., 2007; Dutta et al., 2007) and this area is currently subject to increasing research momentum. India recently launched the National Biomass Cookstoves Initiative (NCI), with the aim of providing cleaner biomass cookstoves, of comparable cleanliness and efficiency to those run on fuels such as liquefied petroleum gas (LPG), to all households currently using traditional cookstoves (Venkataraman et al., 2010). Furthermore, in September 2010, the United Nations announced the Global Alliance for Clean Cookstoves, which has the target of delivering 100 million clean cookstoves by 2020 (Smith, 2010). To achieve these goals, formidable technological and dissemination challenges will need to be overcome (Venkataraman et al., 2010; Smith, 2010). Although the principal strategy of these schemes is to introduce improved cookstoves to combust traditional biomass fuels they appear to represent an opportunity for renewed interest in biogas stoves and by extension domestic digesters.

**Fig. 3.** Biogas stove, Java, Indonesia (picture: Elisa Roma, University of KwaZulu-Natal, South Africa).

## Design of biogas plants

Many different types of biogas reactors are used throughout the world. In general designs used in developing countries for digestion of livestock waste are classified as low-rate digesters, being simpler than those in more temperate regions and lacking heating and stirring capability. This is also related to climate, since unheated plants and those without insulation do not work satisfactorily when the mean temperature is below 15 °C (ISAT/GTZ, 1999a). Three major types of digesters are used in developing countries for livestock waste: the Chinese fixed dome digester, the Indian floating drum digester and balloon (or tube) digesters (Plöchl and Heiermann, 2006) (Fig. 1). Such digesters are usually sized to be fed by human and animal waste from one household and to deliver the energy demand of the household. In practice this means digester volumes are between 2 and 10 m³ and that they produce around 0.5 m³ biogas per m³ digester volume (Dutta et al., 1997; Akinbami et al., 2001; Omer and Fadalla, 2003). Floating drum digesters are normally made from concrete and steel, whereas fixed dome digester are constructed with various available materials, such as bricks. Balloon (or tube) digesters are fabricated from folded polyethylene foils, with porcelain pipes as inlet and outlet. The principle behind these digester designs is very much the same. Feedstock enters through the inlet pipe either directly or after a mixing pit. Substrate retention times of 20–100 days are used with such mesophilic digesters (Sasse, 1988). Biogas is collected above the slurry before leaving through an outlet pipe for utilisation. Even a pit in the ground can be used as a digester provided the biogas can be captured. There have been efforts to promote low-cost batch-fed digesters fed by weeds and various biomass sources which use a gas-proof membrane above a pit and a 120 day substrate retention period (Lichtman et al., 1996).

## Biogas substrates

Although in theory any type of biomass can be degraded to biogas, the dramatic growth in biogas technology in China and India has been based upon pig and cow manure, respectively. Cattle dung is especially suitable as a substrate due to the presence of methanogenic bacteria in the stomachs of ruminants. Biogas production to provide a five-member family with two cooked meals a day is 1500–2400 L (ISAT/GTZ, 1999b). Taking the lower value, this indicates a minimum of one pig, five cows, 130 chicken or 35 people are required to provide enough biogas to cook for a family of five (Table 1). This correlates with practical experience, as it has been reported rural households in India require four to five cattle to feed a 2 m$^3$ biogas plant, around the smallest available (Dutta et al., 1997).

**Table 1**
Biogas production from selected substrates (Amon et al., 2004; Chanakya et al., 2005; Gunaseelan, 2004; Heiermann and Plöchl, 2004; Linke et al., 2003; Maramba, 1978; Oechsner et al., 2003; Plöchl and Heiermann, 2006; Sasse, 1988; Sathianathan, 1975).

| Substrate | Daily production (kg/animal) | % DM | Biogas yield (m$^3$/kg DM) | Biogas yield (m$^3$/animal/day)$^a$ |
|---|---|---|---|---|
| Pig manure | 2 | 17 | 3.6–4.8 | 1.43 |
| Cow manure | 8 | 16 | 0.2–0.3 | 0.32 |
| Chicken manure | 0.08 | 25 | 0.35–0.8 | 0.01 |
| Human excrement/sewage | 0.5 | 20 | 0.35–0.5 | 0.04 |
| Straw, grass | | ~80 | 0.35–0.4 | |
| Water hyacinth | | 7 | 0.17–0.25 | |
| Maize | | 20–48 | 0.25–0.40$^b$ | |
| Barley | | 25–38 | 0.62–0.86 | |
| Rye | | 33–46 | 0.67–0.68 | |
| Triticale | | 27–41 | 0.68–0.77 | |
| Sugar beet | | 22 | 0.76 | |
| Hemp | | 28–36 | 0.25–0.27$^b$ | |
| Alfafa | | 14–35 | 0.43–0.65 | |
| Rice straw | | 87 | 0.18 | |
| Rice straw hull (husks) | | 86 | 0.014–0.018 | |
| Baggase | | | 0.165 (m$^3$/kg organic DM) | |
| Leaf litter | | | 0.06 (m$^3$/kg) | |

DM = dry matter. a = based on mean biogas yield (m$^3$/kg DM). b = calculated from methane yield based on biogas of 55% methane.

**Table 2**
Advantages and disadvantages of biogas technology, based on ISAT/GTZ (1999c).

| Advantages | Disadvantages |
|---|---|
| Improved sanitation | Laborious operation and maintenance |
| –Reduced pathogens | Limited lifespan (~20 years for many plants) |
| –Reduced disease transmission | Construction costly |
| Low cost energy source: cooking, lighting etc. | Less suitable in cold regions |
| Low cost fertiliser: improved crop yields | Less suitable in arid regions |
| Improved living conditions | Negative perception where low functionality of existing plants |
| Improved air quality | Requires reliable feed source |
| Reduced greenhouse emissions | Requires reliable outlet for treated sludge |
| Reduced nitrous oxide emissions | Poor hygiene of sludge from mesophilic digestion |
| Less demand for alternative fuels | High construction costs relative to income of many potential users |
| –Conservation of woodland | |
| –Less soil erosion | |
| –Time saved collecting firewood | |

Biomass with a carbon: nitrogen ratio between 20 and 30 has been reported to produce optimised biogas composition (das Neves et al., 2009). Substrates with either excessive carbon or nitrogen can result in poor bioreactor performance and biogas with high carbon dioxide content. Straw and urine are examples of biomass resources with high carbon and nitrogen levels respectively. Particularly in Europe there has been interest in cultivated energy crops as biogas substrates. These include maize (*Zea mays*), rye (*Secale cereale*), triticale (*Triticum X Secale*), sugar beet (*Beta vulgaris*) and barley (*Hordeum vulgare*), while hemp (*Cannabis sativa*) and alfalfa (*Medicago sativa*) also show promise (Plöchl and Heiermann, 2006) (Table 1). As can be seen, plants such as barley and maize have biogas yields similar to animal waste. However, yields from rice straw and rice straw hull, both potentially useful substrates in the developing world, are lower at 0.18 and 0.014–0.018 m$^3$/kg DM (dry matter) respectively.

It is believed that fresh human excreta is suitable for biogas production, whereas sludge collected from septic tanks, pit latrines, etc. is not (Klingel et al., 2002). This is most likely because both aerobic and anaerobic processes contribute to the decomposition of biodegradable waste in pit latrines, leaving a residual of biologically-inert solids after a certain residence time (Foxon et al., 2009). Another important property is solids content. Slurry with a solids content of 5% to 10% is appropriate for use in low-rate domestic digesters (Sasse, 1988). Because of this, where cow manure is the feedstock, an equal amount of water is normally added to the digester simultaneously (ISAT/GTZ, 1999b). When public toilets supply digesters, water used for flushing or cleaning should be limited to 0.5–1.0 L per bowl (ISAT/GTZ, 1999b). Several studies have found that the use of multiple substrates often has synergistic effects in that biogas production is higher than would be expected on the basis on methane potential of feedstock components (Shah, 1997). This is illustrated by data showing biogas yields for cattle manure, sewage and a 50:50 mix of cattle manure and sewage were 0.380, 0.265 and 0.407 m$^3$/kg DM respectively after 40 days' digestion (Shah, 1997). Consequently, co-digestion is often beneficial and the focus of much recent research activity, often with combinations of sewage, municipal waste and industrial waste (Dereli et al., 2010; Lee et al., 2009; Shanmugam and Horan, 2009; El-Mashad and Zhang, 2010).

## Advantages and disadvantages of biogas technology

Anaerobic digestion of human and animal waste provides sanitation by reducing the pathogenic content of substrate materials (Table 2). Hence biogas installation can dramatically improve the health of users. This is particularly the case where biogas plants are linked to public toilets and/or where waste is no longer stored openly. Rapid public health improvements following biogas implementation have been observed in rural China, with reductions in schistosomiasis and tapeworm of 90–99% and 13% respectively (ISAT/GTZ, 1999c; Remais et al., 2009). Solid retention times of 3 weeks at mesophilic conditions are enough to kill pathogens leading to typhoid, cholera, dysentery, schistosomiasis and hookworm (Sasse, 1988). However, for eliminating other pathogens mesophilic anaerobic processes are rather ineffective, with typically 50% inactivation of helminth eggs and modest reductions of tapeworm, roundworm, *E. coli* and *Enterococci* (Feachem et al., 1983; Sasse, 1988; Gantzer et al., 2001). Thus, the WHO suggests pathogen reduction by mesophilic anaerobic digestion is insufficient to allow subsequent use of human excreta as fertiliser (WHO, 2006). Moreover, pervasive health benefits are associated with a switch to a cleaner cooking fuel. In Guatemala, an association between domestic use of wood fuel and reduced birth weight, independent of key maternal, social, and economic confounding factors has been documented (Boy et al., 2002). Of over 1,700 women and newborn children, the percentage of low birth weights was 19.9% for open fire users, compared with 16.0% for those using electricity or gas.

However, while the construction costs of biogas plants vary between different countries they are often high relative to the income of farmers and other potential users. Recent studies undertaken in Thailand (Limmeechokchai and Chawana, 2007) and Kenya (Mwirigi et al., 2009) identified the high investment costs as a major barrier to technology uptake and in seven Asian and African countries farmers classified as medium or high income comprised nearly 95% of those adopting biogas technology (Ni and Nyns, 1996). In Kenya it has been suggested that without alternative financial capital it was difficult for farmers to fund biogas systems and respectively 46% and 57% of fixed-dome and flexible-bag plant owners received subsidies covering over 25% of the construction costs (Mwirigi et al., 2009).

Assessing the economic impact of biogas systems can be complex, since it often requires allocating a monetary cost to fuels without a defined market value. Nevertheless, one of the main drivers for the spread of biogas technology in Asia has been to reduce pressure on woodland as a fuel source. The success of such strategies is illustrated by a study in Sichuan province, China, where installation of biogas systems decreased household usage of coal and wood by 68% and 74% respectively (Remais et al., 2009). These energy savings were sufficient to recoup the construction costs within 2–3 years. It is though worth noting that no new biogas systems were installed without government subsidies. Similarly, surveys undertaken in the Southern Province of Sri Lanka have found that the introduction of biogas for cooking has resulted in an 84% fall in firewood consumption (de Alwis, 2002). Such reduced burning of wood is also likely to have health benefits (see above). Increased agricultural yields of 6–10% and sometimes up to 20% have been recorded through use of biogas slurry as fertiliser (ISAT/GTZ, 1999c). An agricultural disposal route also provides a means to utilise nutrients, notably nitrogen and phosphorus, which would be wasted without reuse. Although rarely evaluated, with lower dependence of fossil fuels and wood come environmental benefits in terms of reduced deforestation, soil erosion and greenhouse gas emissions. Methane is the second most important greenhouse gas (after carbon dioxide). Over 100 years it has a global warming potential over 20 times that of carbon dioxide (USEPA, 2010). Hence, through combustion of methane and its conversion to carbon dioxide, less global warming results. Agricultural production contributes around 33% of total anthropogenic methane emissions, mostly from ruminant animals and rice cultivation. It has been estimated biogas technology could potentially reduce global anthropogenic methane emissions by around 4% (ISAT/GTZ, 1999c). Another possibility is reduced emissions of nitrous oxide ($N_2O$) (Table 2), now regarded as the biggest manmade threat to the ozone layer (Ravishankara et al., 2009) and which has a global warming potential over 300 times that of carbon dioxide. Recent estimates indicate food production (60%) is the largest anthropogenic source of $N_2O$, with synthetic fertiliser and animal waste management being the largest individual contributors to this category (Syakila and Kroeze, 2011). Nitrous oxide can be formed during both nitrification and denitrification processes, with nitrite a precursor in both cases. Anaerobic digestion of animal waste is believed to be a feasible strategy to mitigate $N_2O$ emissions, although insufficient to reverse the increasing emissions arising from animal production (Oenema et al., 2005). Certainly anaerobic digestion of animal manure can be expected to reduce emissions from biological oxidation of ammonia (i.e. nitrification pathway). Furthermore, reduced demand for synthetic fertilisers caused by increased use of digested biomass as fertiliser could reduce emissions. However, discussing the impact of greenhouse gas emissions is complex, as ideally emissions for the complete disposal/treatment/reuse cycle need comparing across relevant scenarios for disposal of animal waste (including digestion, burning as a fuel and no anthropogenic disposal). For example, during digestion of cattle slurry, it was observed that greenhouse gas emissions (comprising $CH_4$, $N_2O$ and $NH_3$) from slurry stores were more important than after field application of digested manure (Clemens et al., 2006).

## Experience with domestic biogas technology

### *Asia*

Worldwide, effective and widespread implementation of domestic biogas technology has occurred in countries where governments have been involved in the subsidy, planning, design, construction, operation and maintenance of biogas plants. There are several such countries in Asia, where in particular China and India have seen massive campaigns to popularise the technology. Surveys in various regions of India have found the proportion of functional plants to be from 40% to 81% (Dutta et al., 1997; Bhat et al., 2001). It should be noted that, although not always stated, digester age is a significant factor in performance, with, on average, higher functionality being associated with younger digesters as well as more recent designs (Tomar, 1995). In Madhya Pradesh state digesters surveyed at various times were built from 1974–93, with a major installation push in 1981–1982 driven by the NPBD. In 1981–1982 functionality was found to be only 30% improving to 81% in 1985–1986. An analysis of several studies considered overall around 60% of biogas plants in the mid-1990s were functional, though that figure rose to over 80% if only recently installed plants were considered (Tomar, 1995). In the mid-1990s a large survey of 24,501 plants in Madhya Pradesh found 53% of plants were functional; 48% of defects were technical, the majority in the digester foundations, inlet–outlet chambers and digester walls, with 13% of defects operational and 21% resulting from incomplete installation (Tomar, 1995). Floating drum plants had a higher proportion of functionality relative to fixed dome plants, while only a very small number of community plants were operating effectively. One of a limited number of areas experiencing a higher degree of functionality is the Sirsi block of the Uttara Kannada district, Karnataka state, southern India. Here, of 187 household plants in eight villages, 100% were found to be operating satisfactorily (Bhat et al., 2001). In the study area, 37% of digesters were installed in 1985–1989, 36% in

1990–1994 and 27% in 1995–1999, thus age was not the key determinant of efficacy. Reasons given for the success of biogas dissemination were free servicing and the presence of competing entrepreneurs who assisted householders in all phases of plant construction and installation, including the procurement of subsidies. Other relevant factors, some particular to the Sirsi block, were a demand for biogas plants (i.e. more applicant households than administered subsidies), warranties for plant performance, while availability of cattle manure, household incomes and literacy rates were above the national average.

Over 60,000 biogas plants had been installed in Nepal by 1999 (Singh and Maharjan, 2003), while a total of 24,000 domestic biogas plants were installed in Bangladesh from 1971 to 2005 (Alam, 2008), while there are also over 2000 biogas plants sited on poultry farms (Dimpl, 2010). The Bangladeshi government has been heavily involved in the dissemination of biogas plants through the country, with subsidies offered for plant construction. A survey of 66 plants in the country found that 3% were functioning without defect, 76% were defective but functioning and 21% were defective and not functioning (Alam, 2008). In Sri Lanka it is believed there are up to 5000 biogas plants (de Alwis, 2002). A survey in 1986 found that 61% of plants were functional. However, by 1996 another investigation found that only around 29% of household plants were operational, with a multitude of reasons given for failure (de Alwis, 2002). There was also a large degree of geographical variability: the percentage of operational (household and other) plants was between 34% and 65% in districts where over 10 plants were surveyed, though underlying causes were not discussed. In Pakistan, the Ministry of Petroleum and Natural Resources commissioned 4137 biogas plants between 1974 and 1987 (Mirza et al., 2008). However, after the government withdrew financial support the program essentially failed. As well as the lack of subsidies, a lack of technical training, high cost and inadequate community participation were identified as contributory factors to this decline (Mirza et al., 2008). In another scheme, the Pakistan Council of Renewable Energy Technologies (PCRET) installed 1200 biogas plants from 2001 with 50% of the cost borne by the user. It is reported that presently there are 5357 biogas units installed in the country. By 1982, there were already 1000 biogas plants in Thailand, with the Ministry of Public Health central to their propagation. However, by 2000 these activities had largely ceased, with the diffusion of various designs proving unsuccessful (ISAT/GTZ, 1999d), although subsequently larger biogas systems have become popular in livestock farms as a means to treat wastewater or slurry, with a total of capacity of 60,210 m$^3$ installed in 2001 (Limmeechokchai and Chawana, 2007).

By 2007, there were 26.5 million biogas plants in China (Chen et al., 2010). Household biogas digesters are especially prevalent in the Yangtze River Basin, with Sichuan Province having the largest number of biogas plants, at 2.94 million. The rapid development of biogas through the country is linked to accumulated technical knowledge, the availability of fermentation materials, and strong state support, including financial. Nonetheless, of the seven million household biogas tanks installed during the 1970s, around half had already been abandoned by 1980. Various technical issues were cited for their failure, such as gas leakage, insufficient feedstock, blockages and lack of maintenance (He, 2010). Some 60% of biogas digesters in China's rural areas were believed to be operating normally in 2007 (Chen et al., 2010). The lack of attention paid to plant maintenance is a major reason for failure, while qualified technical support is in short supply. Such trends reflect an emphasis on plant construction rather than operation, maintenance or repair (Chen et al., 2010).

### *Other developing countries*

Elsewhere in the world, the situation is mixed. As with Asia it is not straightforward to quantify and compare causes of digester failure (e.g. technical, economic, lack of feedstock) between countries owing to the incomplete reporting of these parameters. Moreover, in many countries the number of plants constructed is under 1000, therefore the availability of operational and technical support is much less than in those Asian countries with more widespread experience of the technology. One review found the number of operational rural digesters was 50–75% of the total in various developing countries and in Latin America the number of plants installed from 1985 to 1992 was only one-seventh of those installed from 1982 to 1985 (Ni and Nyns, 1996). In the Ivory Coast, Tanzania and Costa Rica non-technical reasons comprised respectively 69%, 25% and 50% of total failures (Ni and Nyns, 1996). Part of the explanation is that the routine operation and maintenance of the digesters is usually laborious. In particular it has been noted that biogas technology has had very little success in sub- Saharan Africa, except Tanzania and Burundi where some hundreds of plants have been constructed (Akinbami et al., 2001). Figures from 1993 indicate the African countries with the highest numbers of biogas plants were Zimbabwe (>100), Burundi (>136), Kenya (>140) and Tanzania (>600) (Akinbami et al., 2001). Meanwhile, a survey in Kenya in 1995 estimated that about 850 domestic biogas plants were installed (Gitonga). However, only 25% of installed plants were operational, with many abandoned plants, giving a negative image of biogas technology. In Tunisia, governmental bodies, with French and German involvement, made efforts to promote biogas technology in the Sejenane region from 1982. After one of the partners withdrew its support in 1992, despite continued support from state organisations, biogas dissemination almost completely halted (ISAT/GTZ, 1999d).

## Applicability of biogas plants in the developing world

Based on the above, some recommendations can be made regarding suitable circumstances for installation of biogas plants. Particularly relevant here are factors listed by Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), the German government technical assistance agency, which constrain effective implementation of biogas plants in the developing world (ISAT/GTZ, 1999c) (Table 3). Conversely it is possible to define a set of conditions comprising an ideal situation for biogas systems fed by animal manure (ISAT/GTZ, 1999c). Low rate digesters work best in tropical regions, especially where the temperature is above 20 °C year round. As seen, the methane generating potential of various substrates imposes limits on biogas production and consequently digester sizing (Table 1), with 1500–2400 L of biogas considered sufficient to supply cooking requirements for a family of five. Thus ideal conditions for a household-digester comprise a daily supply of at least 30 kg/day of dung, with full stabling of animals on concrete floors (facilitating transfer of

**Table 3**
Factors constraining successful implementation of biogas technology ISAT/GTZ (1999c).

| Excluding factors | Critical factors |
|---|---|
| Climate too cold or too dry | Low income of the target group |
| Irregular or low gas demand | Unfavourable macro- and micro-economics |
| Under 20 kg dung/day available or under 1000 kg live weight of animals per household in indoor stabling or 2000 kg in night stabling | Good supply of energy throughout the year, therefore only moderate economic incentives for biogas technology |
|  | Irregular gas demand |
| No stabling or livestock in large pens | Gas appliances not available |
| No building materials available | High building costs |
| No or very little water available | Low qualification of builders |
| Integration of biogas plant into the household and farm routines not possible | Institution has only limited access to the target group |
| No suitable institution can be found for dissemination | No substantial government interest |

dung to the digester) and perhaps supplemented by other substrates. The equivalent requirement if human excreta were the substrate would be with a daily supply of at least 14 kg human faeces (equivalent to 28 people, calculation using data in Table 1). Other ideal conditions are that the use of organic fertiliser is already established, the biogas plant can be located close to the stable and point of gas consumption, the cost is moderate relative to income of the target group, that financing is secure and that efficient dissemination and support networks exist, including government support (ISAT/GTZ, 1999c). Overall this suggests household biogas plants are most advantageous in rural areas, with both reliable feedstock and an established outlet for produced sludge and a sustainable support network for users.

## Potential for spread of domestic digesters

Even in those countries with an established record in installing small-scale livestock digesters there remains potential for continued spread of these systems. While the introduction of biogas technology can have a multitude of environmental and public health benefits (Table 2) those arising from biogas stoves appear especially relevant as an avenue to promote biogas technology in the near future. In particular, biogas stoves can make an important contribution to those high-profile projects which aim to reduce air pollution through the accelerated introduction of cleaner cookstoves—the Global Alliance for Clean Cookstoves and NCI. The potential maximum number of household livestock digesters in India has been estimated as 12–17 million, based on the availability of cow manure (Ravindranath and Hall, 1995; MNES, 1999); compared with current levels of around four million. Meanwhile, in Bangladesh since it is thought 80% of the manure from the 22 million cattle in the country could be made available for biogas production (Hossain, 2003), this indicates a potential maximum of around 3.5 million household plants based on the value of five cows per digester. This would represent a massive increase from the current number of over 25,000 biogas plants in Bangladesh (Dimpl, 2010). Similarly, given the number of cattle and buffalo in the country, it was estimated that the 60,000 plants installed in Nepal by 1999 represented only 4% of the total potential (Singh and Maharjan, 2003). Meanwhile, in Nigeria it was calculated that biogas production from the 12 million cattle in the country could potentially reach 3.3 million $m^3$/day (Itodo et al., 2007). In China the current rapid expansion of rural biogas plants shows no sign of slowing (Fig. 1) (He, 2010). Since the annual production of dry livestock and poultry excrement in the country is estimated at 1467 million tons, of which 1023 million can be collected (Chen et al., 2010), this suggests considerable scope for continued expansion based on existing designs and government support. Indeed, it has been calculated that only 19% of biogas potential has been utilised in rural China (Chen et al., 2010).

However, for the long-term spread of biogas recovery technologies reliance on animal manure will need to be overcome. Thus a reoccurring theme of recent literature is the need for small-scale plants which digest alternative substrates. In China, there is demand for household anaerobic systems which allow efficient digestion of crop residues and straw (Chen et al., 2010). Although the high carbon: nitrogen ration of straw, specifically in the form of lignocelluloses, is thought to make straw rather resistant to anaerobic digestion, laboratory tests have found a biogas yield of 0.35–0.4 $m^3$/kg DM (Table 1). Only 0.5% of total crop residues in China are currently utilised for biogas generation (Liu et al., 2008) and when co-digested with other substrates such as animal manure they are normally limited to under one-third of the total substrate mass. Alternatively, pre-silage and fermentation are sometimes used to raise biogas generation. There has also been interest in additives or digester designs which promote efficient biodegradation of straw. Furthermore, designs incorporating solar-powered heating and water saving devices have been proposed to allow dissemination into colder and more arid regions of China (Chen et al., 2010). The digestion of weeds in a plug-flow-like plant designed to produce 6–8 $m^3$/day of biogas with a retention time of 36 d has been investigated in India (Chanakya et al., 2005). However, while the design was an engineering success in the sense it produced an adequate amount of biogas, the women feeding the digester were required to spend 1.3–2 h per day collecting vegetation, compared with 2.5–3 h per week when gathering firewood for cooking. In India, wastes such as sewage, municipal solid waste, and crop residues such as rice husks and bagasse (sugarcane waste) have potential for biogas generation. However, while biogas yields from some tropical plant residues approach those of energy crops, Table 1 shows yields from rice straw, rice straw husks and bagasse are relatively low at 0.18, ~0.018 and 0.165 respectively (Plöchl and Heiermann, 2006). Hence, these crop residues may have a limited usefulness as biogas sources.

Meanwhile, one potential barrier to digestion of sewage and animal excreta is that mesophilic anaerobic digestion does not by itself produce sludge of suitable hygienic quality for use as fertiliser, if that is to be the disposal/reuse route. The WHO suggests post treatment is required to meet its health guidelines for reuse of human excreta in agriculture (WHO, 2006). European legislation is stricter and states that anaerobic digestion of animal waste must include pasteurisation for 1 h at 70 °C if sludge is being applied to land subsequently (EC, 2002). As indicated by this regulation, thermophilic digestion of sewage sludge provides a good level of hygiene (Gantzer et al., 2001). Consequently, for biogas digesters to deliver improved sanitation, designs incorporating additional treatment stages may be required. Municipal solid waste (MSW) in developing countries is typically rich in organic material (up to 70%) and thus a suitable biogas substrate (Müller, 2007; Vögeli and Zurbrügg, 2008). The digestion of MSW has attracted attention in Southern India, where kitchen waste from households and restaurants, market waste and waste from slaughterhouses is utilised in urban digesters of various sizes (domestic and larger). A few systems co-digest toilet waste (Vögeli and Zurbrügg, 2008).

## Conclusions

Biogas technology offers a unique set of benefits. It can improve the health of users, is a sustainable source of energy, benefits the environment and provides a way to treat and reuse various wastes—human, animal, agricultural, industrial and municipal. It has come a long way since the 1970s, with China and India supplying models of how to disseminate small biogas plants in rural areas. In other developing countries, the proportion of functional plants is often 50% or less. This reflects a need for investment in operational validation, maintenance and repair if the technology is to thrive. Experience suggests considerable government involvement is requested for these support networks to be continued over time. The current drive to reduce indoor air pollution by promoting cleaner cookstoves would appear to present biogas stoves with renewed development opportunities. At the same time, domestic biogas digesters have number of challenges to overcome for continued proliferation in the 21st century. Designs which deliver lower cost, improved robustness, functionality, ease of construction, operation and maintenance would aid the market penetration of biogas plants. Furthermore, to move beyond a dependence on livestock manure there is a need for small-scale bioreactors which efficiently digest available substrates in both rural and urban situations. On a domestic level these include kitchen waste, human excreta, weeds and crop residues.

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