Evolving biomass-based biogas plants: The ASTRA experience

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Anaerobic digestion of animal waste in biogas plants for energy, manure and sanitation has made a significant impact in quality of rural life wherever it has been deployed. Insufficiency of animal dung resources limits the use of this technology to only an eighth of the overall Indian rural population. Yet the convenience of a biogas plant in rural households has led R&D efforts to extend the use of biogas plants to other non-animal dung biomass feedstock and rural residues. Fermenting typical biomass residues in conventional slurry-based biogas plants has been far from successful. Most attempts to convert rural biomass residues into 'flowable' slurries like animal dung have rarely been successful. Alternative concepts were required. Achieving successful quasi-continuous fermentation of biomass residues has come through a break away from the 'slurry' fixation and animal dung digester designs of the past. A better understanding of the underlying processes has greatly helped evolve new fermentation concepts. Success has emerged only through use of multi-stage processes, where key fermentation properties of biomass feedstock have been acknowledged and digesters designed accordingly. Here, a 25-year effort in understanding the processes of biogas and biomass fermentation, developing new techniques and technologies to ferment biomass feedstock and efforts at simplifying the technology to enable sustainability carried out at the Centre for Sustainable Technologies, IISc, Bangalore is described. Finally, integration of the two or three fermentation steps into a single reactor configuration has enabled evolving simple-to-use digester designs for biomass feedstock, namely the plug-flow and the solid-state stratified bed digesters.

BIOGAS has been a reasonably successful renewable-energy technology developed and widely disseminated in India. Close to 4 million cattle dung biogas plants have been built against a potential of 12 million plants (estimation based on cattle ownership) – thus tapping a third of the potential. The results achieved are good when compared to a simpler-to-disseminate energy device like LPG (about 7 million in rural India). Yet the biogas programme has not been a runaway success as dreamt of earlier[1]. The gaps between expected levels of success and reality seem to arise from an insufficient appraisal of the grass-roots situation as well as due to technological and dissemination gaps. Behind this success lies the effort of a large body of scientists and technologists, which has relentlessly put development causes first and addressed frequent changes in development perspectives to come out with science and technology inputs. Elsewhere, it was reported that this field was largely technology-driven and potential for multiple end-uses was created. The R&D inputs and focus have constantly shifted with priorities accorded to these end-uses[2]. Here we attempt to understand R&D efforts made by the ASTRA Centre (currently named as Centre for Sustainable Technologies), IISc, Bangalore with regard to bridging some of the scientific and technological gaps.

Biogas usage in India, technologies for biogas plant construction and R&D in anaerobic digestion in India are now a little over a century old. R&D and construction of biogas plants have been carried out with various objectives and end-uses during the different periods. This has strongly influenced the direction and focus of R&D groups. Using stated achievements or main outputs as the key objective and thereby indirectly identifying the driving force(s) for developing biogas science/technology, it is possible to demarcate 4–5 clear periods of shifting focus of R&D in this field.

1. Biogas was initiated in India as an alternative to piped natural gas – mantle lamp based home lighting (c.1897)[3] was the main attraction – obviously home illumination was the driving force.
2. Better sanitation arising from safe disposal of human/animal waste appears to be the driving force early into the 20th century. Fermentation studies on agro-residues[4,5] is a case in point. Biogas plants served the dual purpose of providing gas-based illumination and safe human (less often animal) waste treatment. Around this time, research began on the 'fermentation' of cellulosic materials and 'sanitary' treatment of human, animal and agro-wastes[4].
3. The need for N-rich manure for higher crop yields resulted in attempting biogas plants from animal wastes. Providing good quality manure, conservation of nutrients and domestic illumination seemed to be the major benefits accrued.
4. The National Programme on Biogas Development focused on the energy angle; domestic cooking gas and manure in that order became the deliverables. Perceptions of

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*For correspondence. (e-mail: chanakya@astra.iisc.ernet.in) energy crises driven by the 1973/75 oil crises shaped the programme significantly. As a result, organic-matter conversion and material-use efficiencies became important criteria in R&D goals. ASTRA's R&D effort began during this period and was thus strongly influenced by the energy crises, especially rural energy crisis described in early rural energy studies by ASTRA[6,7]. Expanding the biogas potential[8] by the use of non-dung biomass feedstock[9] became an important driving force.

5. In recent years, in addition to biogas for cooking, lighting and shaft power, water purification/pollutant removal, urban solid waste (USW), organic farming labels, sustainability issues and even global warming issues are being addressed with anaerobic digestion process/biogas plants being central to these objectives. This has brought a greater number of researchers and interactions into the fold and consequently more applications have benefited from it.

Early biogas R&D at ASTRA Centre

Biogas was listed as a priority R&D area of ASTRA from the time of the Centre's initiation in 1974. At this stage only two versions of biogas plants were available: the Khadi and Village Industries Commission (KVIC) and Janata – both of which did not carry adequate technical information support either in published literature or archival. To bring about technology improvements, there was a dearth of science and engineering information on this type of reactors. ASTRA then initiated studies on the conventional Indian design biogas plants and underlying process. Results from these long-term studies suggested that neither the process nor the civil engineering involved needed narrow and deep digester designs being followed at that time. Over 60% of the gas production potential could be extracted within 35 d hydraulic retention time (HRT). The temperature of the digesting slurry in the reactor below a 45 cm depth did not fluctuate much on a daily basis and it followed the seasonal average temperature. In addition to this, a closer look at the existing designs and plant construction led to an optimization theory for biogas plants. Biogas plant designs could be optimized for the overall costs rather than merely for the cost of the mild-steel biogas floating-drum, as was being done earlier[10]. Other studies carried out along with the above[10] led to three sister publications in the same volume – it was thus possible to look at the underlying processes, conversion efficiencies, physico-chemical changes, mass balance, heat balance, nutrient conservation, microbial changes, etc. Such efforts were continued and enabled reduction in the civil construction costs and using amongst others, a depth-to-diameter ratio close to 1 in all future constructions. The resulting design changes were accepted rapidly and it brought down the biogas plant costs by 40% and made it an important contribution at that time.

The Indian biogas programme was founded on a seemingly unlimited availability of cattle dung supply in villages[3]. Measurements of daily animal dung production carried out on stall-fed animals showed a daily output of 15–25 kg dung/animal/d. A per animal output of 15 kg/head/d has been used to determine if a family had sufficient cattle dung to run a biogas plant effectively. Owning three adult cattle per family was thus sufficient for benefiting from a family-size biogas plant. Soon it was found that with available family biogas plant technology, not all the families in a village could afford a biogas either due to unaffordable biogas plant cost[11] or because the families did not own sufficient number of cattle to meet a minimum daily availability of cattle dung feedstock. This understanding led to two distinct directions driven by two approaches, namely:

1. Spreading biogas benefits uniformly within a village (biogas-led development).
2. Technology development to bring a larger range of rural residues under the umbrella of biogas feedstock.

Village-level data[7] collected since 1978 showed that cattle ownership was skewed such that only a third of the village households had cattle in numbers large enough to run family-sized biogas plants. In a community-based biogas plant approach, all families of the village could have biogas for their daily needs if all the dung resources of the village were pooled. Apart from setting up large community biogas plant systems, there were no successful models on how to run these in a viable manner. Devising innovative and field-tested methods to run them formed the goal and challenge of one part of the biogas R&D of ASTRA[12]. This required an innovative resource-handling and management system that was both transparent and acceptable to local people. In biogas plants, cattle dung is mixed 1 : 1 with water and the resultant slurry is fed to the digester. The digested dung slurry (also called spent slurry) loses its original semi-solid form and becomes unacceptable to people who have 'lent' the dung for enrichment in a biogas plant. This required the development of a sand-bed filter-based slurry dewatering system capable of village-level operation[13]. Even when all the dung resources of the village are made available for conversion to biogas, they can meet only 50–70% of the total cooking energy needs in typical Indian villages. Alternatively, villagers involved in the planning stages opted to use this for providing domestic water supply along with home illumination as a means to enhance the revenue contribution and make such systems meet all running costs[12]. Many of these resource and common utility management methods were developed in a participatory manner with women at the core of the system. Much later, such techniques have been emulated elsewhere in other areas of rural development.

Although the overall biogas-yielding reaction is mildly exothermic, the conventional digesters do not heat up. On the contrary, they lose heat and remain near the annual average temperature (22°C for Bangalore). The conversion rates are slow, resulting in a yield of 35l biogas/kg dung for a 35 d HRT. A greater extent of gas could be extracted if the digester is operated at 35°C and could solve two problems, namely low gas production rates and overcoming dung shortage in villages. Heat-balance studies indicate that > 60% of heat loss in a floating drum plant occurred from the gas-holder roof and operating digesters above ambient would require a net input of heat, e.g. solar heating[10]. Solar heating using a transparent cover on the gas holder is an obvious choice to increase the heat absorbed from the sun as well as to lower the heat lost from the gas-holder roof at night[14]. Such solar-heated plants did not increase the operating temperature beyond 32–35°C, but greatly increased the gas yields (from 35 to 50 l/kg dung) at the same retention time and digester volume. The total solids conversion rose from 23 to 31%, thus explaining the increased gas yields. The increased yields did not match the expected per family need of daily gas. The solar-assisted biogas plants did not overcome the problem of dung shortage in typical villages, but helped in using them in colder areas where low winter temperatures impede normal functioning of biogas plants. The use of other biomass feedstock, e.g. water hyacinth appeared to bridge the shortfall, and developing digesters capable of fermenting water weeds to biogas became a promising avenue[14]. By the use of commonly available herbaceous biomass feedstock[14,15], it was reported that in addition to the existing potential of 12 million biogas plants[8] operating on cattle dung, it is possible to meet the cooking energy needs of the rest of the rural families. About 120 million tons of herbaceous biomass of the net annual generation of 1150 million tons, would be adequate to bridge this gap. Today, with gradually decreasing cattle population, a significant quantity of herbaceous biomass is becoming available for conversion to biogas.

Biogas technology for biomass feedstock

The need to use alternative biomass feedstock in the national biogas programme is a means to widen the range of 'beneficiaries'. Many laboratory scale studies have been carried out to determine feasibility of producing biogas from biomass. Reviews and papers published were quick to point out that biomass residues available in India could produce high levels of biogas[16,17] and possibly solve the dung shortage problem[18]. However, switching to non-dung biomass feedstock has proven to be far from simple. Most of the early efforts in this area involved powdering biomass feedstock, rendering them into slurries, operating typical dung plants with these slurries – in short emulate the cow-dung feedstock in a cow-dung-type biogas plant. In reality, such powdered biomass slurries inevitably stratified into a matted floating layer and a clear digester liquid. Studies at ASTRA led to some key observations and conclusions that changed the way the Centre approached this problem. Powdered biomass rarely emulated cow-dung slurry feedstock physically, chemically or microbiologically[14]. The major problems, observations and conclusions are grouped as follows:

1. Unfavourable physical properties: Biomass particles generally have a lower density than the digester liquid or acquire it as soon as biogas bubbles adhere to them. As a result they float throughout their useful stay in a reactor. When not continuously stirred, powdered or pulverized, biomass feedstock always segregated into distinct liquid and solid phases (floating) in typical fermentors, leading to incomplete or cessation of fermentation. Developing or adapting fermentors to the physico-chemical and microbiological properties of biomass (floating and bulk) could only promise results rather than modifying biomass feedstock to suit a limited variety of digester configuration.
2. Pre-treatment zone within a digester enabling bacteria to reach the decomposition site within the biomass rather than feeding pre-treated/pre-inoculated feedstock appeared an efficient strategy. Creating an additional pre-treatment step would, however, make the biogas plant operation less attractive[19].
3. Feedstock suitability: Adapting the process to complex and widely varying biomass composition as well as decomposition patterns while using mixed feedstock ensured process stability and functioning of the plants throughout the year. In the field, year-round availability of a single type of defined feedstock is unlikely and hence fermentors need to work a wide range of physico-chemical and decomposition properties of feedstock.
4. Fastidiousness of fermentor geometry and properties of materials used in construction (skill/technology/material-based limitations) imposed a great restraint on the shape and the method by which a fermentor could be built or operated.

Preliminary studies

The limitations and resources of villages were clearly imprinted among ASTRA scientists so as not to attempt biogas production with powdered biomass residues. The argument was: 'Where is the power to powder the biomass?' For biogas generation, it has been difficult to break away from the fixation of slurry-based reactors, irrespective of the feedstock. It is interesting to note that almost all the groups that have worked on biomass-based biogas production have, in their early efforts, attempted to render biomass feedstock into slurry using physico-chemical pretreatment to finally enable slurry-based fermentation in typical or partially-modified cattle-dung-type biogas reactors. At ASTRA, having had a poor experience with mechanical (size reduction) pre-treatment, it became obvious that an alternative low-energy method was needed.

The floating property of the biomass (initial or acquired during biogas fermentation) became the critical issue and thus required new fermentation processes that did not attempt to fight this seemingly 'inviolable' floating property of the biomass feedstock[14].

All pre-treatment methods tried so far required sacrifice/offset of an appreciable portion of the net harvestable energy from the overall process – sometimes even leading to a negative energy balance! Even the use of high cellulase-producing microbes (rumen isolates of buffalo, goat, camel, deer, etc.) was tried without achieving any significant breakthrough(s) in terms of simple-to-operate digesters. Biological pre-treatment (anaerobic composting) carried out on water hyacinth provided a clue that in case the pre-treatment step could be integrated with the reactor design, there was a potential process option to overcome the difficulties faced thus far by improving physical properties, easily handling volatile fatty acid (VFA) fluxes and enhancing microbial access[19]. The experience of using pulverized water hyacinth had then given two research directions, namely to either operate a reactor without using too much water and thus escape any chances of floating or operate a reactor where a pre-processing step is incorporated into the reactor design and floating becomes inconsequential in the fermentation process. During this period, two novel approaches were tested and are described below. Emerging from these initial efforts was first a clear definition of the problem and second, a need for radically new fermentation concepts that were required to overcome these barriers.

Solid-phase stratified bed fermentation

Attempts at minimizing digester liquid to remove the root cause of floating (first) and the anaerobic pre-treatment approach (1983) threw up key process questions, namely the role of digester liquid in a biomass-based biogas reactor. This is especially true for feedstock such as water hyacinth with high water content (> 93%) and when > 70% of it remains afloat. It was also known that fermentation in landfills needed little water, and also with no water content there can be no stratification, scum or floating. A landfill-type process thus escapes floating and scum formation with biomass feedstock. The major issue, however, was how to increase the slow reaction rates of a landfill, i.e. bring down the solid residence time (SRT) from 5000 to about 35d. Laboratory studies were carried out with leachate recirculation to enhance the rate of colonization and to flush out VFA accumulation pockets[20]. This initial success triggered the solid-state, two-stage diphasic and finally the stratified bed approaches to biomass fermentation[20–25].

The first obvious affliction was to attempt a two-stage process wherein acidogenesis (partially aerobic or anaerobic) was carried out in a separate digester and only the hydrolysis products, namely VFA dissolved in the leachate were to be fermented in a simple digester. Separating the two phases, acidogenesis and methanogenesis using pH, redox and HRT differentials became crucial to this mode of thinking and proved to be control intensive and unsuitable to rural areas. Soon it was realized that partially digested biomass could be used as methanogen support systems[25] – methanogens were found to strongly colonize green and herbaceous biomass feedstock after it underwent a certain level of decomposition[26]. The need for a second reactor was obviated[24,25]. During the first part of the reaction (acidogenesis), the freshly fed biomass on the top produced a lot of VFA intermediates that accumulated in the bed. A daily sprinkling of the bed once on one side introduced acidogenic organisms onto the upper regions of the biomass bed and it also carried down VFA intermediates to lower regions of the bed. The partially decomposed feedstock of > 12 d fermentation itself becomes the immobilized bed for methanogens, exhibiting a total methanogenic rate exceeding 30–50 times the output of a cattle dung reactor[25,26]. Thus when these two stages are placed one above the other, transition of decomposing biomass from the predominantly acidogenic (top) to the predominantly methanogenic stage (lower end) can occur gradually or quickly, without affecting the process stability or performance capabilities. By feeding fresh feedstock at the top and removing digested material from below, a continuous operation was conceived and achieved on a long-term basis (> 3 years)[24].

Biogas plants operated on this basis gave an output of about 0.4–0.5 volume gas/volume reactor/d. Laboratory-scale plants (0.5–6 l), pilot plants (100–500 l) and field-scale plants (1–3 m^3) have been operated for periods up to three years to confirm their performance (Figures 1 and 2). The solid-state stratified bed (SSB) biogas fermentation process overcomes most of the problems faced by batch-operated solid-state or diphasic processes and has multi-feed options. The solid-state and diphasic processes rely on an accurately predicted match of acidogenic and methanogenic stages. However, in the SSB mode, the transition from predominantly acidogenesis to methanogenesis is a loose horizontal boundary that could range from 3 to 30 d SRT, with the total SRT varying between 30 and 65 d without significantly affecting the gas production rates[24]. In this mode the reactor could remain unfed for over eight months and could reach design feed rate within a period of 7 d of restarting. Over the years, several important civil engineering inputs have improved the design and material substitution efforts have been made to render such reactors affordable.

Plug-flow digestion approach

Another stream pursued at ASTRA was whether pre-treatment steps can be integrated into the biogas plant design or the operation technique itself to overcome several problems. This led to the concept of shallow and horizontal 'plug-flow' like biogas digesters with inlets modified to carry out the biological pre-treatment found successful earlier. For this approach, about 25 major and minor design modifications were tried. Coupled with better insights of 'dry/SSB' fermentation, plug-flow process became easier to visualize and tackle. Biological pre-treatment approach greatly reduced problems related to VFA overproduction at the early stages of biomass decomposition[19]. This simultaneously rendered better physical properties to feedstock (namely higher density) using forces of buoyancy rather than gravity-assisted methods of compaction. It then took R&D along a direction where attempts were made to integrate this successful pre-treatment into the reactor design/operation method itself. Various experimental reactors were built and operated to determine the stage of decomposition of biomass feedstock at which the acidogenic rate (VFA production) matched the methanogenic rate (VFA/H_2 utilization). Pre-treatment efforts[19] and later on experiments of fermentation under forced submergence revealed that most of the biomass feedstock suffered a rapid initial decomposition phase lasting 3–5d[14]. During this rapid fermentation stage, over 30% of the organic matter (measured as volatile solids, VS) is converted to produce a collection of simple 2–6 carbon-containing VFA intermediates. In these systems, concentrations of VFA at greater than 6 g/l inhibit their subsequent conversion to biogas[21,22]. In case the biomass feedstock was forcibly placed under digester liquid for this period, VFA overproduction quickly diffused into the digester liquid surrounding it, without seriously suppressing methanogen colonization on this feedstock as well as achieving normal biogas production rates in the latter stages of decomposition[27].

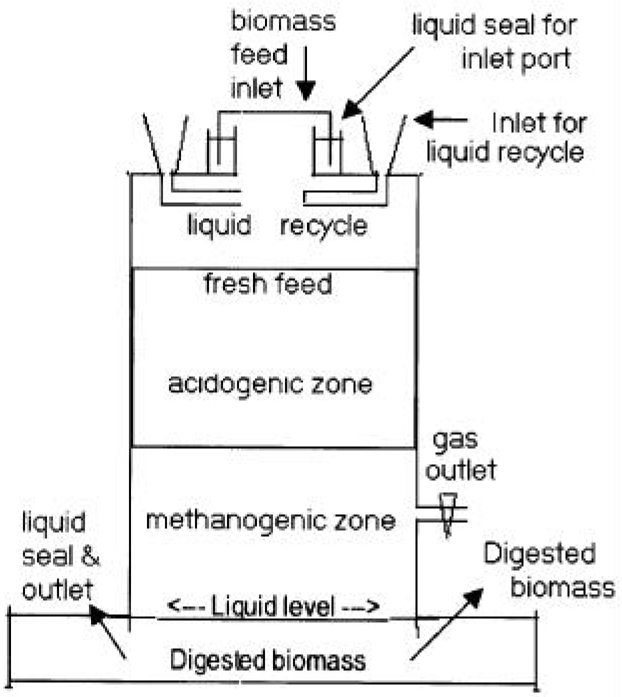

Figure 1. Sketch of a solid-state stratified bed biogas digester. Fresh biomass feed added to the top of the decomposing biomass bed becomes the acidogenic zone. Digested biomass is withdrawn from the outlet below. As a result, partially digested biomass between 10 and 35 d SRT becomes the methanogenic zone. Fresh biomass undergoes significant compaction to reach wet densities of 600 kg/m^3 within a short period.

After this initial decomposition stage, the biomass feedstock acquires higher methanogenic rates that match or exceed acidogenic rates[25,26] and therefore biogas is produced without serious impediments. This happens even in the absence of the feedstock being submerged in digester liquid[15,26]. In the case of fermenting urban solid wastes in plug-flow-type reactors, VFA overproduction

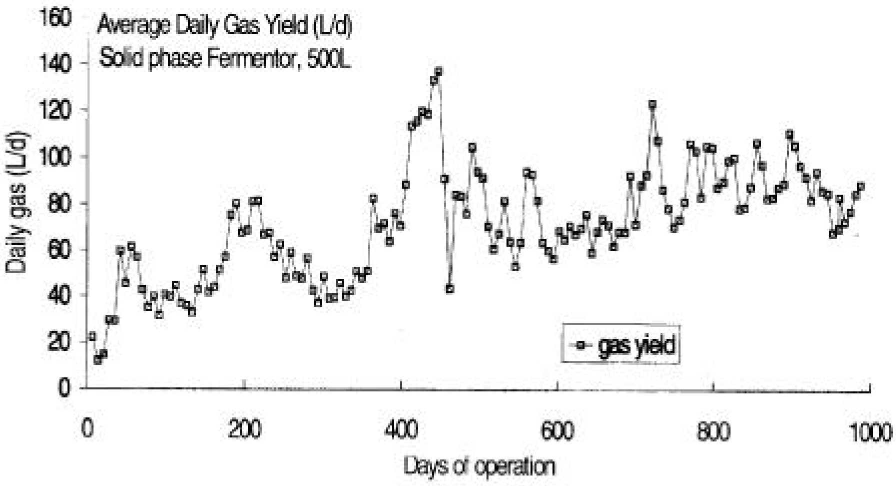

Figure 2. Long-term gas-production pattern in an SSB pilot plant. Feed rate employed was 1, 2 and 2.5 kg fresh/d equivalent between 1 and 200, 201 and 500 and 500 and 1000 d respectively.

significantly exceeded the diffusion and conversion rates mentioned above. As a result of accumulating VFA levels near the inlet, pH levels around 5 were often noticed and required simple solutions to overcome the problem[26]. These observations gave the explanations necessary to design and operate larger fermentors to hold biomass feedstock submerged only for an initial period of 3–4 d, after which feedstock were free to move horizontally, in a partially floating state, towards an outlet placed at the opposite end. During this second phase, decomposition rates gradually fell, while feedstock acquired densities of up to 0.95 g/cc within a fermentation period of 30–35 d. However, it remained afloat throughout its useful stay in the digester. Studies of the biomass profile recorded during normal operation or while using biomass fed in marked bags bore out this flow pattern. This then necessitated designing wide outlets for manual removal of spent feedstock[15]. Partial pre-composting followed by compaction of biomass with or without added clay showed good promise. The successful adaptation of masonry vaults on shallow masonry tanks gave the final breakthrough and maturity for this technology for dissemination. Many plants working on this principle have now been built and are being operated over a long period (Figures 3 and 4). New construction techniques are also being developed to facilitate easy dissemination and to overcome field problems.

Adaptations of biogas technology concepts

Adaptation to urban solid waste

In tropical sub-humid and per-humid climates, USW components ferment faster than the rate at which they dry. USW is held up to 24 h prior to being dumped in street bins, by which time active fermentation is normally initiated. When USW is not removed from street bins within the next few hours, ensuing fermentation renders it malodorous and offensive. Even more offensive is the transport of fermenting wastes from street bins in leaky open vehicles. On the other hand, if these are immediately fed to decentralized small anaerobic fermentors, the transport and odour issues are quickly tackled. Biogas produced in the process is a bonus and the small quantity of digested USW removed from this reactor is only marginally offensive, dries rapidly and is rendered into powdered compost within a few days, without being malodorous. While a significant portion of the organic matter is decomposed, recalcitrant plastics that have escaped household-level segregation remain behind in the digested mass[27]. At this stage, the two are easy to separate out using only a coarse sieve. Large anaerobic digesters have now been operated in Europe. Such fermentors are uneconomic at levels below 100 tons per day of operation. In a city from a developing country, where

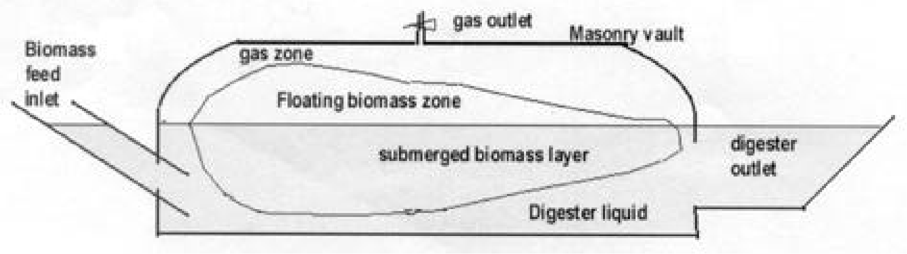

Figure 3. Sketch of plug-flow biogas digester showing a layer of floating biomass feedstock.

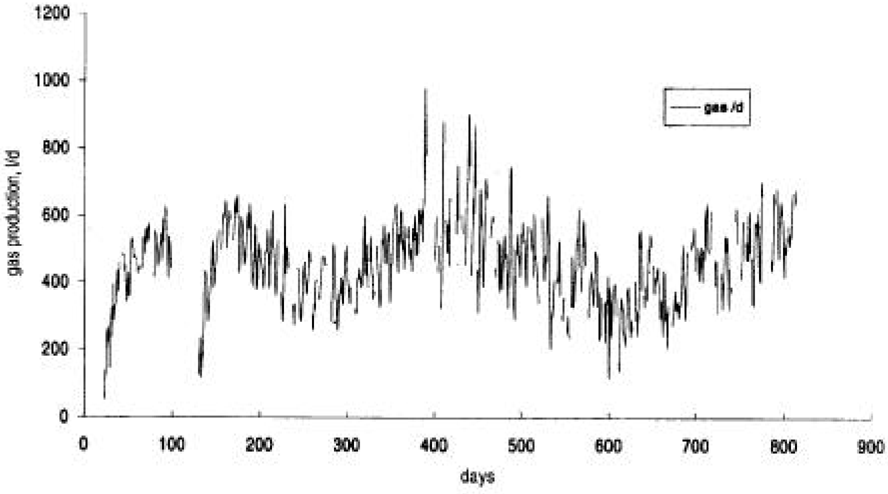

Figure 4. Long-range performance of plug-flow pilot plant at a daily feed rate of 10 kg fresh weight/d.

carrying such solid wastes could cost between Rs 350 and 1000/t, small-scale anaerobic reactors that do away with this cost could be of great help, especially if biogas is sold nearby. In such situations both the plug-flow and SSB fermentors lend themselves to operation with USW. The plant-nutrient-rich powdery manure returned to local users, the combustible gas sold to nearby restaurants and the collection charges put together are expected to make economic sense (meeting all O&M costs)[28]. Only the recalcitrant plastics and metallics need to be carted away at fortnightly intervals from these decentralized units. This concept is being tried in small towns.

Adaptation to high rate biogas production from liquid wastes – The coffee bioreactor

During anaerobic digestion of the biomass feedstock, a large number of methanogens colonize the inside of typical plant cells at a stage when all other exposed simple feedstock constituents have been digested, converted to gas and only a partially exposed ligno-cellulose complex is available for decomposition. This stage is reached between 10 and 30 d in the SSB fermentor depending upon the feedstock characteristics. This ligno-cellulosic skeleton with methanogenic bacteria attached to it was used as a whole-cell immobilized system to determine its capability to digest liquid waste with moderate suspended solids content (simulating sewage and agro-industrial wastes). Laboratory results with agro-industry wastes showed[26] that compared to a 0.5 kg VS converted/l/d to gas in a typical dung reactor, it was possible to convert around 10 kg VS/l/d at 24 h retention time. The biomass support typically exhibited a half-life of about 120 d[26,29]. This reactor functioned well and could be operated without any moving parts in a pulse-fed down-flow mode, where the incoming feedstock could disperse the biomass particles-based microbial support on a daily basis.

When this concept was adapted to coffee-processing effluents in the field, the performance fell to about 40% due to two reasons, namely low ambient temperature (10–12°C) and inability to create high-velocity pulse feed with available natural slopes in the field. Nevertheless, these reactors accept up to 2.5–4 kg COD (2.8–3.6 kg BOD)/m^3/d under horizontal flow through biomass support – a level that is a 100 times higher than what is achieved in an anaerobic lagoon under identical conditions[29]. This reactor has worked well for over four years and has provided a breakthrough in coffee-effluent treatment and resource recovery. There is thus a good potential for combined use of USW and sewage in simple-to-operate bioreactors for small-town needs.

Getting more from biogas plants

Cooking gas and nitrogen-rich manure are the two valuable outputs from an anaerobic digestor (biogas plant) and these are expected to substitute:

1. Wood-based cooking (leading to an improved quality of life).
2. Synthetic fertilizer (promoting self-reliance and ecological soundness).

There are instances where one or both of these are either in surplus or out of context. Here then arise other options for the conversion of gas to electricity services and/or illumination as also conversion of digested material to products valued higher than organic manure – mushrooms, vermicompost, pest repellents, etc. ASTRA has had long-term experience and successful demonstration of village-level systems of biogas-electricity[12].

Alternative options for digested feedstock

The current trend of dissemination indirectly emphasizes multiple end-uses and value-addition options as indices for potential end-user acceptability. In line with this thought, many value-added products/options were developed for a biomass-based biogas plant. While the key end-use of digested biomass is manure to crops, value-added products can be extracted from gas and digested manure without affecting this end-use. Two potential products were developed, tried and tested, namely vermicompost and oyster-mushrooms.

Vermicompost from digested biomass

Most earthworm species used in vermicompost operation are secondary feeders of decomposing organic matter and prefer consuming it only after a certain extent of decomposition has taken place. Normally, aerobic composting is carried out prior to introducing earthworms to substrates. Initial decomposition in a biogas plant extracts the calorific value (biogas) of the easily decomposable fraction lost during aerobic pre-composting. The digested biomass from a biogas plant, drained for 24 h to reduce moisture, is immediately colonized by earthworms and converted to a fine powder within the next 21d. Nitrogen levels (as per cent N) are retained from digested biomass to vermicompost, while mass throughput ranges widely, 10–30% of the pre-digested mass, depending upon the degradability of the feedstock being used. Vermicompost makes economic sense only where vermicompost to manure cost ratios exceed 4. Vermicompost is also an excellent option for terminal treatment of USW used as a biogas plant feedstock – USW containing plastics can be fed to biogas plants and then subject to vermicomposting. All organic matter is converted to a fine powder which is gradually dried, sieved and separated from plastics coming along with USW. Anaerobic digestion followed by vermicomposting and finally opting for segregation greatly reduces the burden for stringent segregation specifications required for all other USW treatment processes.

Mushroom production on digested biomass

Mushroom fungi are generally secondary colonizers of digested biomass residues in nature. In this case, digested biomass from biogas plant is first colonized by anaerobic bacteria, which leave behind high levels of nitrogen, phosphorous and organic nutrient fraction that will undergo slow decomposition under normal conditions. When this material is sun-dried to reduce moisture and contamination and mixed with steamed paddy straw (1 : 3–9), mushroom yield increases 2–3 times the normal, compared to paddy straw alone. Simple cultivation techniques for this modification were evolved and tested over three years. From 1 kg paddy straw + digested biomass mixtures, up to 3 kg mushrooms can be raised. This can greatly enhance cash flow in the system and make biomass-based biogas plants repay within a year of operation[30].

Biogas into the future

The biogas programme in India has evolved over a significantly long learning period spanning several decades, national and international crises. While there have been pockets of poor performance, there are also pockets of good performance. Studies in the Uttara Kannada district, Karnataka show high dissemination levels (30–60% of possible households) and biogas plant functionality (> 98%) – where fuel wood is not a crisis and LPG is easily available[31]. The need for organic manure to sustain soil fertility is an important driving force. Concerns of falling soil fertility, a search for people-driven technologies to sustain and even boost it and also efficient resource-use methods leading to endogenous empowerment will be the focus of development in the immediate future. A growing appreciation for organic agricultural products will place a high demand for biogas manure and digester liquid use as pest repellent and methods for its production at household level will be important in the future. However, as manure is not an easily transportable or tradable commodity in rural India, higher demands for it will be met through efficient manure production processes, namely anaerobic digestion. A gradually rising fuel cost, awareness for cleaner cooking, existing successful biogas plants, national dissemination programme, etc. will provide a constant demand for biogas plants and place it continuously in the minds of the rural user. It is expected that when these biomass-based biogas plants are inducted to the national biogas programme, they will not need long learning times and will be quickly adopted by users to meet the 'green' and organic farming wave of the future. R&D efforts that lead to improved efficiency of biomass transformation and energy recovery, adaptation to local conditions, feedstock and ease of operation will be needed to provide the vital push to make this technology widespread. Establishing and extending the new uses for biogas, digester slurry and digested feedstock will now be an important R&D area which will finally make the overall technology broad based. Finally, digested leaf biomass is a good anaerobic biofilm support that can be used with a variety of liquid wastes, especially the emerging need for sustainable methods for wastewater disposal in small towns and villages.

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