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Anaerobic Digestion for Bioenergy from Agro-Residues and Other Solid Wastes—An Overview of Science, Technology and Sustainability

H.N. Chanakya and Sreesha Malayil*

Abstract | In the quest for a simple technology to realize the goal of 'sustainable energy for all', the conversion of non-lignified 'soft' non-woody biomass to biogas in modern anaerobic digesters is an important component. Firstly, agro-residues, agro-industrial wastes, terrestrial/aquatic weeds form a major source of sustainably raised bio-resources. Anaerobically converting them to biogas provides a sustainable energy source to a large number of users and simultaneously facilitates nutrient recycling (nutrient-rich compost) permitting nutrient-starved agricultural systems in India to become more sustainable. When processed through biogas plants, over 95% of all plant nutrients within can be recycled making India's fragile agricultural soils more sustainable while also producing an energy source, biogas. While a lot of science and technology experience exists with regards to animal waste fed biogas plants, understanding of the underlying science, technology and sustainability of anaerobic digestion of agro-residues, weeds and leaf litter ('non-dung' soft biomass) for biogas/byproducts is poor. This potential has been inadequately tapped. In this paper, an attempt is made to review the microbiology of anaerobic digestion of various biomass residues, the conversion processes that are being developed/in use and finally to examine methods to make them attractive, provide multiple outputs and services than what was possible through animal dung biogas plants. The micro-organisms responsible, physico-chemical environment process and therefore the technology of digestion of biomass residues are not similar or as simple as that found for animal dung or food wastes. Therefore, novel fermentation concepts and modern digesters being developed for biomass residues are required to make this concept feasible and viable. Many more end-products, other than compost and biogas, as was done in the past, are required if the digesters have to be economically attractive to use and socially justifiable as well as sustainable in the long run. The sustainability issues that have and will shape this field are discussed. In this paper we show that simultaneous anaerobic digestion of biomass residues to biogas and multiple by-products could be an answer to the search for alternatives to achieve sustainable energy for all in this decade.

Centre for Sustainable Technologies (CST), Indian Institute of Science, Bangalore, India.
**chanakya@astra.iisc.ernet.in, srisha@astra.iisc.ernet.in*

1 Introduction

Anaerobic digestion (AD) technology and the underlying science has had a long history in India beginning with the first biogas plant that was established in Matunga in 1897 (Mumbai).[1,2] Anaerobic digestion of agro residues had been a key area of research during the early period of the Indian Institute of Science (circa 1910–1920) wherein research on anaerobic-aerobic processing of agro-residues has been carried out towards achieving a near total recycling of plant nutrients into compost accompanied by low losses during composting. This allowed recycling of crop and animal wastes from one cropping season to the next in coming year, with greater attention to nitrogen returned to crop land.[3] Researchers trained at IISc spread this science to other areas and Institutes in India[4] as well as other parts of the world. Anaerobic digestion of biomass has been considered as a method to provide many outputs wherein the primacy accorded to different output(s) changed with time and the globally important concerns of the period (Figure 1).

Understanding the evolution and the current practices and technologies for anaerobic digestion of biomass feedstocks is also an indirect approach to understand how ‘sustainability’ has been sought through the use of AD over a large time frame extending a little over a century. Although the techniques of having pure cultures of many of the *Archea* and related obligate anaerobic micro-organisms had not been developed until late 60’s (and 80s, respectively) research on AD had been continuously carried out by addressing the underlying transformations. Therefore, AD and bio-gas plants (BGP) have been envisaged to solve problems related to N recovery and reuse, combined with sanitation,[3–6] rural and peri-urban lighting using gas,[1] clean cooking fuel,[7] rural water supply, illumination and sustainable development;[8] GHG emission control and avoidance,[9] non-farm rural livelihoods,[10,11] rural sanitation and even environmental clean up.[1] While a majority of early studies and technology development have focused on AD of animal wastes, the digestion of agro-residues and other fermentable rural residues and solid wastes became important much later, after the 1990s, when the promise of biomass biogas plants as a renewable energy source as well as a method for decentralized treatment of wastes became evident. However, at this stage very little had been studied on the science of AD of biomass residues. AD then became both a scientific and technological challenge, and this paper deals with the emergence of AD technologies to process agro-residues and urban solid wastes (USW) in India.

It is important to note here that the science and technology of AD for biogas production in India has progressed along three paths while attempting to meet three different goals, namely, a. AD of animal wastes (and their admixtures) for rural energy, b. AD of segregated urban solid wastes (USW) and kitchen wastes and c. AD of agro-residues and other herbaceous biomass such as weeds, etc. Much of the early research and technology development using AD has largely been

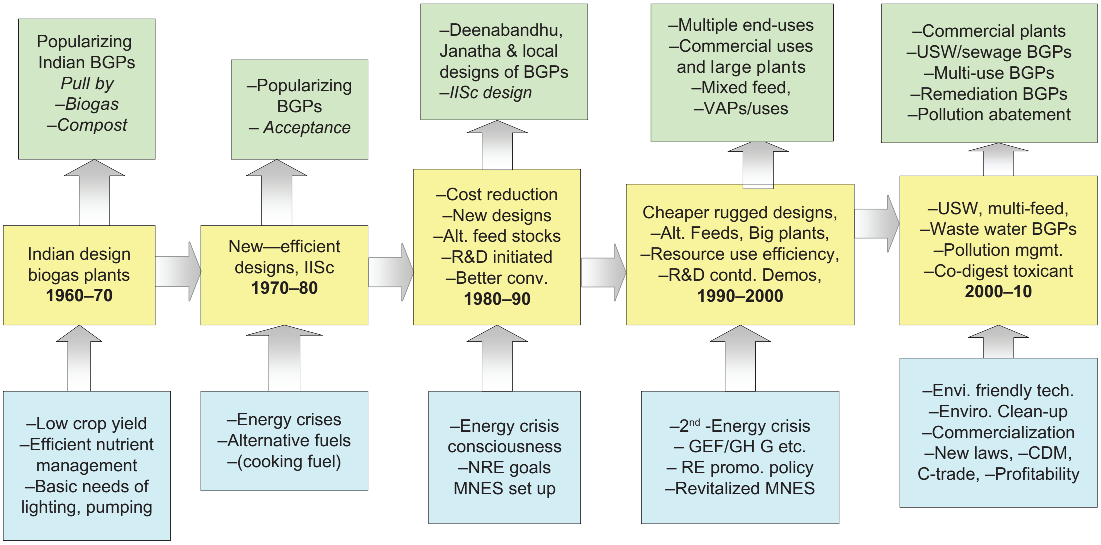

Figure 1: Various forces that have driven the Biogas R&D and dissemination in India. The boxes in the bottom row (blue) indicate the forces and problems that have been being addressed in that period, the boxes in yellow show the types of R&D or issues addressed (middle row) and in the top row shows the outcomes.[10]

on conversion of animal wastes and occasionally for other rural residues. Evolution of biogas plant technology and the spread of biogas technology using animal dung as main feedstock are considered a reasonable success in India (over 4 million plants)[12] and China (26.7 million plants, 2007).[13] Yet, they have a finite reach and did not meet the cooking energy needs of all rural homes as originally envisaged because the availability of animal wastes (cattle dung) has been finite and limiting. Animal waste availability is low and therefore biogas plants (BGP) using animal dung can be feasible only for about 12–17 million homes in India.[14–16] Meeting the cooking needs of all rural families would need use of alternative feedstocks such as agricultural residues[17,18] that is considered to be available in large quantities. If anaerobic digestion of agro-residues can be carried out in modern biomass based biogas plants, it can meet the cooking and energy needs for sustainable development of the remaining households in rural areas.[19–22] The underlying science of anaerobic digestion of several biomass feedstocks available in India, rice straw, sugar cane trash, terrestrial and aquatic weeds have been slow in developing and thereby limiting the evolution of anaerobic digesters that can handle these feedstocks. Therefore there is a need to firstly understand the microbiology of digestion of biomass substrates and develop and disseminate AD technologies that can use various agro-residues, harvestable terrestrial and aquatic weeds, agro-processing solid wastes, segregated urban solid waste usually discarded on village boundaries, etc. Understanding the AD processes for these feedstocks is therefore important for the technology to emerge.[23,24] It is important to acknowledge that much of the science and technology developments outside have occurred in the related field of anaerobic digestion of wastewater (with little emphasis on biogas recovery), especially sewage and industrial wastewater (and to some extent digestion of animal wastes).

The mounting energy costs of aerobic digestion of wastewater using surface aerated treatment systems led to a large scale shift towards adopting the anaerobic-aerobic treatment systems wherein a primary anaerobic digestion of wastewater brought down the organic loads to be digested though aerobic methods by nearly 90% and generated enough surplus energy in the treatment system to run aerobic treatment systems to remove the remaining 10% of the organic loads through conventional aeration systems. However, in spite of such large scale growth of anaerobic treatment systems for wastewater, this resulted in very little impact, in terms of science and technology, on the understanding and improving of process and technology development for anaerobic digestion of agro-residues and other biomass. Firstly, there was very little of soluble material in typical agro-residues and biomass feedstocks[25] and secondly they could rarely be maintained as a stable slurry to enable digestion just as in the case of animal wastes.[23,26]

This paper examines the anaerobic digestion of various non-animal dung biomass residues such as rural agro-residues and urban solid wastes in the Indian context. An attempt is made to study the underlying microbiological and physico-chemical processes, energy potential and issues of sustainability that needs to be addressed in order to use them as a means to achieve the goal of 'sustainable energy for all'. There are therefore three domains to be cognized, namely, science of biomass digestion for process improvement, the emergence of the technologies for digestion of agro residues and biomass, and finally the sustainability issues addressed and achieved. Addressing issues of sustainability and sustainable technology becomes focused when a specific geographical region is specified and for this paper India has been chosen while on the scientific components a global understanding of biomass digestion is attempted.

2 Microbiology and Biochemistry of Biomass Biomethanation

Anaerobic digestion is the use of biological processes to breakdown organic matter found in biomass feedstocks in the absence of oxygen while concomitantly stabilizing these materials against any further rapid decomposition. This conversion process produces a reasonably stable 'anaerobic compost' residue, methane and carbon dioxide (together referred to as biogas). Anaerobic decomposing processes were known as early as the 18th century while in the middle of the 19th century it became clear that anaerobic bacteria are involved in the decomposition process. However, it is now just over a century since anaerobic digestion was used as method for the treatment of sewage[1] and cattle dung slurry (discussed elsewhere in this paper). Ever since, attempts have been made to understand the chemistry and microbiology of the anaerobic digestion process and evolve methods to improve it.

The degradation of organic matter to produce methane (biogas) relies on the complex interaction of several different groups of bacteria. Stable digester operation requires that these bacterial groups remain in dynamic and harmonious equilibrium. Changes in environmental conditions during fermentation strongly affect this equilibrium and often results in the buildup of intermediates which sometimes inhibits the overall process. Therefore it is important to understand the basic microbiological and biochemical processes and pathways in order to ensure uninterrupted digestion processes occur and also to improve the underlying process efficiencies. Although the anaerobic digestion of various liquid wastes such as sewage, industrial and agro-wastes has been studied in depth, there is inadequate information about the digestion of biomass residues, especially of the kind that is available in tropical countries such as India. In this part of the paper while we draw some basic inferences from what is known about the anaerobic fermentation of liquid wastes, we attempt to collate the variation when considering biomass residues. One of earliest description of chemical composition derived prediction of the process products has been summarized by the popular 'Buswell' formula that predicted the stoichiometry of complete anaerobic degradation:[27]

$$C_nH_aO_b + (n - a/4 - b/2)H_2O$$
$$= (n/2 - a/8 + b/4)CO_2 + (n/2 - a/8 - b/4)CH_4$$

The anaerobic digestion of organic material is accomplished by a consortium of microorganisms working synergistically. Digestion is considered to occur in a four-step process, namely, 1) hydrolysis, 2) acidogenesis, 3) acetogenesis and 4) methanogenesis: This is not significantly different from that reported for liquid wastes, animal waste slurry digestion, organic fraction of municipal solid wastes (OFMSW) digestion, etc.[28]

2.1 *Hydrolysis and acidogenesis*

Plant biomass feedstocks are generally rich in various forms of carbohydrates (cellulose, hemicellulose, pectins, starch, etc). In this logically

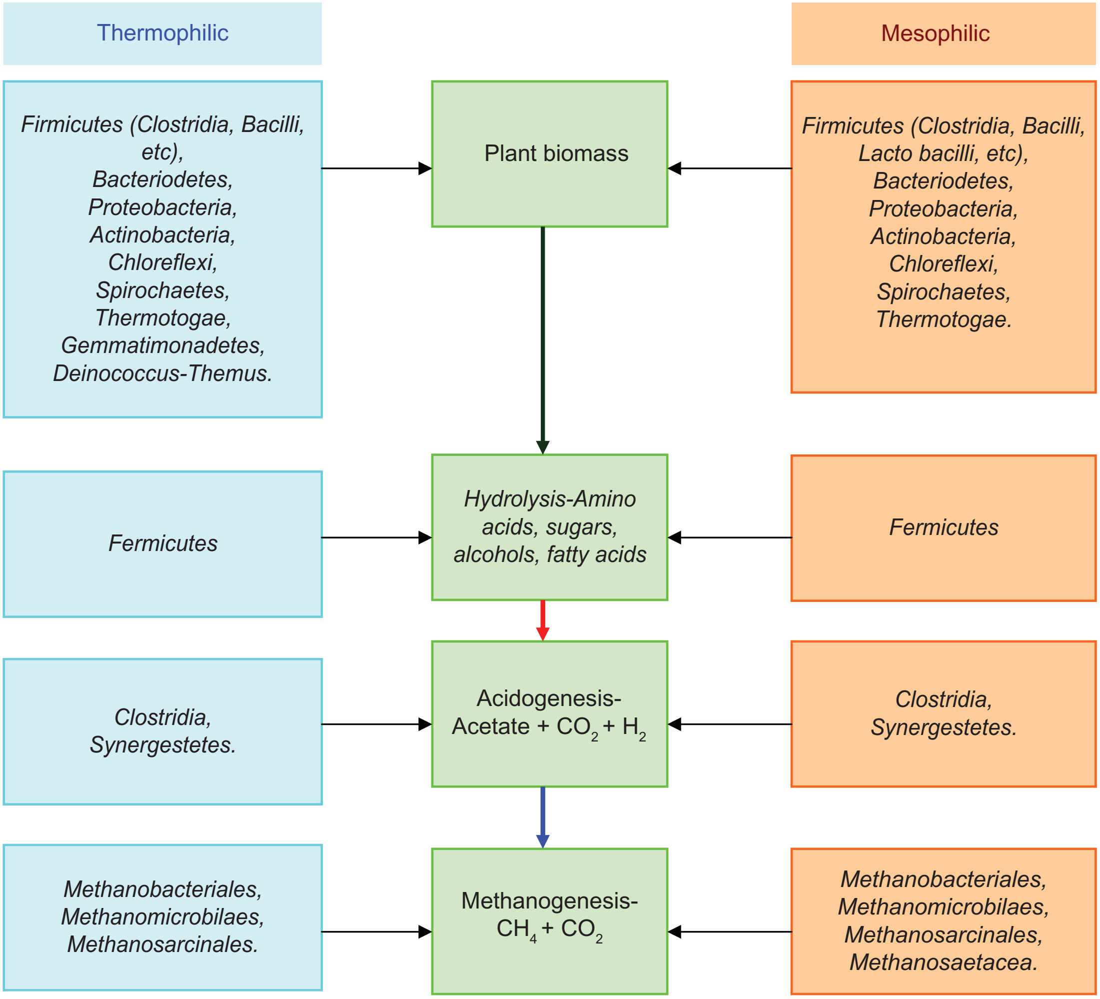

Figure 2: Microorganisms in anaerobic digestion of plant biomass under mesophilic and thermophilic conditions.[30,37–40]

constructed hydrolysis step, large macromolecules such as proteins, fats and carbohydrate polymers (crystalline and amorphous celluloses, etc) are broken down through hydrolysis to amino acids, long-chain fatty acids and sugars, respectively. This process is mediated by the 'hydrolytic and fermenting bacteria that produce a broad spectrum of end products. Lipases convert lipids to long-chain fatty acids. *Clostridia* and *Micrococci* appear to be responsible for most of the extracellular lipase production in the consortia. The long-chain fatty acids produced are further degraded by ß-oxidation to produce acetyl CoA. Proteins are generally hydrolyzed to amino acids by proteases, secreted by *Bacteroides, Butyrivibrio, Clostridium, Fusobacterium, Selenomonas,*and *Streptococcus.* The amino acids produced are then degraded to fatty acids such as acetate, propionate, and butyrate and to ammonia as found in *Clostridium, Peptococcus, Selenomonas, Campylobacter,* and *Bacteroides.*[29–31] Plant cell wall polysaccharides such as cellulose, starch, and pectin are hydrolyzed by cellulases, amylases, and pectinases. The majority of microbial cellulases are composed of three species: (1) endo-l, 4-glucanases; (2) exo-l, 4-glucanases; (3) cellobiase or ß-glucosidase. These enzymes act synergistically on the crystalline structure of cellulose and release glucose.[32]

Hydrolysis of starch to glucose requires amylolytic activity which consists of 5 amylase species: a. α-amylases that endocleave 1–4 bonds; b. ß-amylases that exocleave α 1–4 bonds; c. amyloglucosidases that exocleave α l-4 and α l-6 bonds; d. debranching enzymes that act on α l-6 bonds; e. maltase that acts on maltose liberating glucose. Pectins are degraded by pectinases, including pectin-esterases and depolymerases. Xylans are degraded with α-endo-xylanase and α-xylosidase to produce xylose. Hexoses and pentoses are generally converted to C_2 and C_3 intermediates and to reduced electron carriers (e.g., NADH) via common pathways. Most anaerobic bacteria carry out hexose metabolism via the Emden-Meyerhof-Parnas pathway (EMP) which produces pyruvate as an intermediate along with NADH. The pyruvate and NADH thus generated are transformed into fermentation endo-products such as lactate, propionate, acetate and ethanol by other enzymatic activities which vary tremendously with microbial species.[29,31,33] Although some acetate (20%) and H_2 (4%) are directly produced by acidogenic fermentation of sugars and amino acids, both products are primarily derived from the acetogenesis and dehydrogenation of higher volatile fatty acids (Figures 2 and 3).[31,33]

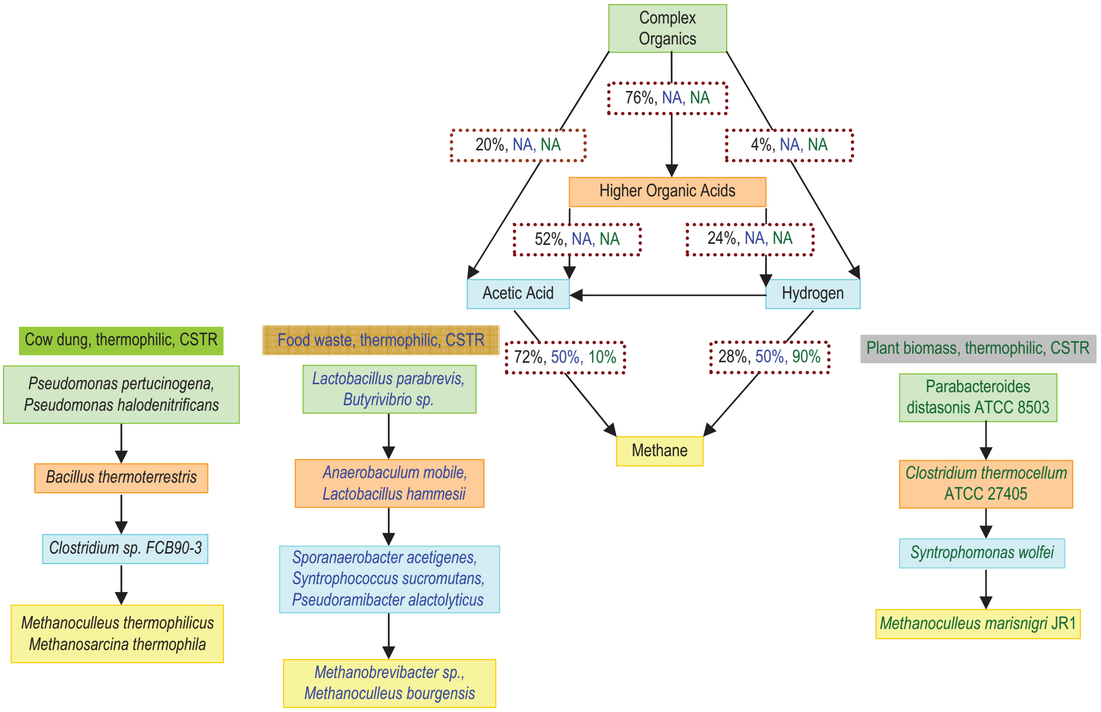

Figure 3: Comparison of the dominant microbial species reported during thermophilic and mesophilic anaerobic digestion of cow dung, food waste and plant biomass in a CSTR and their stoichiometry (colour coding: black = cattle dung, blue = food wastes, green = biomass; numerals indicate the extent of flow of C; NA = not available or reported).[40-42]

2.2 *Acetogenesis*

Obligate H_2-producing acetogenic bacteria are capable of producing acetate and H_2 from higher fatty acids. Only *Syntrophobacter wolinii,* a propionate decomposer and *Sytrophomonos wolfei,* a butyrate decomposer have thus far been isolated due to technical difficulties involved in the isolation of pure strains, since H_2 produced, severely inhibits the growth of these strains. The use of co-culture techniques incorporating H_2 consumers such as methanogens and sulfate-reducing bacteria may therefore facilitate elucidation of the biochemical breakdown of fatty acids.[29,31,33]

The overall breakdown reactions for long-chain fatty acids and H_2 production by acetogens are generally energetically unfavorable due to high free energy requirements. However, with a combination of H_2-consuming bacteria, co-culture systems provide favorable conditions for the decomposition of fatty acids to acetate and CH_4 or H_2S. In addition to the decomposition of long-chain fatty acids, ethanol and lactate are also converted to acetate and H_2 by an acetogen and *Clostridium formicoaceticum,* respectively.[29,31,33,34]

2.3 *Methanogenesis*

Methanogenic organisms consume the acetate, hydrogen and some of the carbon dioxide to produce methane. Methanogens can be divided into two groups: the H_2/CO_2—and the acetate-consumers. Although some of the H_2/CO_2—consumers are capable of utilizing formate, acetate is consumed by a limited number of strains such as *Methanosarcina* spp. and *Methanothrix* spp. (now, *Methanosaeta),* which are incapable of using formate. Since a large quantity of acetate is produced in the natural environment, *Methanosarcina* and *Methanothrix* play an important role in completion of anaerobic digestion and in accumulating H_2, which inhibit acetogens and methanogens. H_2-consuming methanogens are also important in maintaining low H_2 levels.[35] Two dominant (and sometimes a third) biochemical pathways are used by methanogens to produce methane and CO_2.[29,33] The pathways along with the stoichiometry of the overall chemical reactions are

a. Acetotrophic methanogenesis:
$CH_3COOH \rightarrow CO_2 + CH_4$
b. Hydrogenotrophic methanogenesis:
$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$
c. Methylotrophic methanogenesis:
$CH_3OH + H_2 \rightarrow CH_4 + H_2O$

Methanol is shown as the substrate for the methylotrophic pathway, although other methylated substrates can be converted.[36] Sugars and sugar-containing polymers such as starch and cellulose yield three moles of acetate per mole of sugar degraded. Since acetotrophic methanogenesis is the primary pathway reported, theoretical yield calculations are often made using this pathway alone. From the stoichiometry above, it can be seen that the biogas produced would theoretically contain 50% methane and 50% carbon dioxide. However, acetogenesis typically produces some hydrogen. And for every four moles of hydrogen consumed by hydrogenotrophic methanogens a mole of carbon dioxide is converted to methane. Substrates other than sugar such as fats and proteins can yield larger amounts of hydrogen leading to higher methane content for such substrates. Biogas from animal dung more often has 60% methane and 40% carbon dioxide. Furthermore, hydrogen and acetate can be biochemical substrates for a number of other products as well. Therefore, the overall biogas yield and methane content will vary for different substrates, biological consortia and digester conditions.[29,31,33]

2.4 *Breakdown of biomass—hydrolysis, acidogensis and acetogenesis*

In the case of biomass feedstocks represented by agro-residues such as straws and agro-industry wastes such as coffee husk, oilseed husk and terrestrial weeds, the breakdown of biomass is usually slow and can take a long time in anaerobic digesters. This is largely because of the complex way in which cellulosic biomass is organized in plant tissues. In order to speed up the process, a general practice has been to pulverize the biomass into a powder and render them into aqueous slurry for fermentation and sometimes alkali treatment to remove interfering recalcitrant lignin. Much of the laboratory studies utilize this approach in order to facilitate carrying out studies in small digesters while ensuring uniform degradation of the biomass particles.[23] On the other hand, in typical large scale digesters the energy expended to convert dry straw or leaves into a powder would often make the net energy balance negative. Therefore operation of pilot plants and larger scale attempt to focus on studying digestion of intact biomass feedstock on to which energy intensive pre-processing has not been carried out.[23,43–45] This section we use results from both the approaches in order to understand the microbiology and biochemical steps that are to be found and examine the underlying processes. Many reviews are available for digestion of animal wastes, sewage and other soluble wastes of industrial origin.[46,47] While these often indicate how the process is likely to proceed, they do not completely reflect the micro-organisms that are found, the physico-chemical and microbiological limitations thereof. In this part we focus on studies carried out on biomass feedstocks and draw upon experience of animal dung slurry fermentation only when necessary.

In typical plant tissues we expect a wide range of biopolymers, pectin (cementing primary cell walls), hemicellulose in the structural parts of the cell walls, cellulose the dominant part of the cell wall (both in crystalline and amorphous forms) and lignin that forms a matrix and envelopes the two cellulose. Protein components while being found predominantly inside the cell wall, some of it is also detected in primary cell walls. This forms the substrates for anaerobic micro-organisms to degrade and initiate the process through the first step of hydrolysis. Hydrolysis of plant biomass is expected to involve a sequential conversion of the plant constituents (soluble pectin, oxalate- soluble pectin -sometimes referred to as insoluble pectin, hemicellulose, cellulose and lignin) to produce mono and oligosaccharides, short chain fatty acids, alcohols and "hydrolysis gaseous products" that are necessary for the microbial downstream processes towards biogas production (Figures 2 and 3). The typical hydrolytic phyla consisted of *Bacteroidetes*, *Firmicutes* and *Proteobacteria* in all types of fermentors studied.[30] *Firmicutes* and *Proteobacteria* revealed enzyme activities for key retting enzymes viz., xylanase, pectinase and cellulase (Figures 2 and 3).[47]

Beet silage has often been used as substrate for conversion to biogas. Studying the hydrolytic bacteria present,[30] it was found that 50% of the population were proteobacteria, 30% *Bacilli* and 13% *Chloroflexi.* In the mesophilic phase and continuous operation of 650 days the hydrolytic group mainly consisted of *proteobacteria* (19.6%), *Bacteroidetes* (13%), *Actinobacteria* (10.9%) and *Chloroflexi* (6.5%). The same reactor under identical operating conditions at 877 days of operation had *Bacteroidetes* (39.1%) and at 1019 days of operation *Actinobacteria* (36.4%).[30] The same feedstock and a similar reactor operated at thermophillic conditions had *Clostridia* (24%), *Firmicutes* (12%) and *Bacteroidetes* (8%) at 609 days of operation. At 727 days of operation the population of *Clostridia* reduced to 21.1% with an increase in *Firmicutes* to 18% and at 745 days the population of *Clostridia* was high as 40.5%. At 924 and 1249 days the population was dominated by *Proteobacteria* (25–29%). Other studies[37] also gave similar results wherein during the digestion of sugar beet silage *Clostridia, Bacteroidetes, Bacilli*, and unclassified bacteria were dominant. This study was on a continuously stirred tank reactor (CSTR) fed with different crop residues like, straw, grass and sugar beet. The difference in the hydrolytic bacterial species was not much in the case of beet silage and grass whereas straw fed digesters had *Clostridia, Bacteroidetes, Acidobacteria, Deltaproteobacteria* and unclassified bacteria as dominating species. *Clostridia* dominated in both grass (50% of the clones) and straw (53.3% of the clones) feed stocks. Clearly, *Clostridia* are one of the dominant species with a variety of biomass feedstocks. The dominance of other species, especially, *Ruminococcus and Cellulomonas are* visibly absent but generally found in animal waste digesters.[48–50]

The profile of hydrolytic bacteria present during fermentation of maize silage has also been recorded.[51] It was found that *Clostridium thermocellum* was the best degrader of cellulose. From other studies conducted[52] it is evident that *Clostridium thermocellum* and *Clostridium stercorarium* are predominant bacterial species commonly involved in cellulose and hemicellulose degradation during the natural decay of plant biomass in thermophillic phase. While *C. thermocellum* is able to degrade cellulose with high efficiencies it appears that it degrades hemicellulose as a secondary activity of its enzyme complex (cellulosome) as it cannot utilize the pentose sugars released from hemicellulose degradation. *C. stercorarium* is less efficient in cellulose hydrolysis and possesses only two genes for cellulases. On the other hand, it has a great number of genes for the hydrolysis of hemicellulose, hydrolyzes hemicellulose efficiently and utilizes the degradation products. Both these bacteria produce the typical end-products of clostridial fermentation: ethanol, lactate, acetate, butyrate and other short chain products in addition to CO_2 and H_2 gas.[51] It was concluded that hydrolysis of hemicellulose and cellulose is a coupled process and cannot be separated from one another. Zeverlov have also quoted that *C. thermopalmarium* and *C. thermobutyricum* are closely related thermophilic anaerobic species which ferment sugars mainly to butyrate during anaerobic digestion of maize silage. These two OTUs belonging to the *Bacillus* group are considered to be probably saccharolytic but non-cellulolytic bacteria. It is possible that they contribute to the overall hydrolysis of starch, pectin, gums and various hemicelluloses. *Tepidimicrobium* is a thermophilic, peptolytic and strictly non-saccharolytic bacterium related to the *Clostridia. Tepidanaerobacter* is an anaerobic, moderately thermophilic, syntrophic, primary alcohol and lactate degrading bacterium which grows well in co-culture with the hydrogenotrophic methanogen *Methanothermobacter thermautotrophicus.*

Without an externally added electron acceptor it utilizes ethanol, glycerol and lactate syntrophically.

The evolution and succession of hydrolytic bacteria with time of digestion (solids retention time, SRT) of two energy crops (beet silage and grass) has been reported with interesting results.[53] This study provides reasonable understanding to develop strategies to stimulate hydrolysis further and ultimately increasing the methane production rates and yields from reactor-based digestion of these substrates. The digester liquid (leachate) had *Alphaproteobacteria* from 1–10 d, *Betaproteobacteria* from day 3 to 28 d, *Gammaproteobacteria* from day 1 to 28 d, Firmicutes on 15 d, *Actinobacteria* from 3 to 6 d and *Chloroflexi* on 28 d. The loosely attached biomass (floating biomass) in the digester had *Alphaproteobacteria* from day 1–6, *Betaproteobacteria* from day 10 to day 28, *Gammaproteobacteria* from day 1 to 28, *Firmicutes, Actinobacteria* and *Chloroflexi* were absent with beet silage as feedstock and fermented in a reactor configuration consisting of 6 parallel hydrolytic reactors and 1 methanogenic reactor with an upflow membrane filter filled with plastic carriers.

A similar understanding has been obtained from studying decomposition of mixed leaf biomass in different parts of a plug-flow like reactor, from different zones consisting of that floating above the digester liquid and that area that has remained submerged under the digester liquid. Leaf biomass from typical herbaceous plants contain 30–40% lignocellulosic material that digest slowly under anaerobic conditions. Most leaf biomass feedstocks are known to produce tiny biogas bubbles that adhere to the digesting leaf during anaerobic digestion. This phenomenon of adhering gas bubbles to the substrates makes these substrates to float on the digester liquid. As this process could be quite rapid and prolonged, the floating particles remain out of the digester liquid and to quickly become dry. This drying brings down the decomposition rates to low values and often to near zero in some conditions. However, biomass subject to an initial submerged decomposition undergoes a different type of decomposition measured as components of the feedstock decomposed or the specific methanogenic rate. While, plug-flow like digesters tend to allow continued decomposition of fed biomass, other typical slurry digesters suffer stoppages. Efforts to digest large quantities of biomass feedstocks in typical animal dung fed anaerobic digester designs have not been successful in the field since most of the biomass feedstocks tend to float rapidly, then tend to dry, form a scum and make recovery of digested feed not possible.[25,54,55] The understanding of the microbiology involved in such a process where there are two zones, namely floating biomass and that submerged in the digester liquid layer would provide interesting directions for process improvements (*unpublished CST report*).

With grass as the substrate, *Alphaproteobacteria* were found in the digester liquid and was absent on the floating biomass from day 3–28, *Betaproteobacteria* were found in both the digester liquid and the biomass from day 1 to day 28, *Gammaproteobacteria* found in the leachate from day 1 to 28 and were absent in the floating part of the biomass, *Firmicutes* found in leachate from day 3–15 in leachate were absent in biomass, *Actinobacteria* found in liquid layer from day 6 to 26 were found only between day 6 and 10 in the floating biomass while *Chloroflexi* were absent in both the leachate and the biomass. These results on the key activity of the microbiological species as well as that found for composition of the digesting feedstocks suggest that anaerobic digestion of plant biomass follows a pattern of degradation wherein initially pectin and related components are hydrolyzed (the presence of *Proteobacetria* in the first few days of digestion, as *Proteobacteria* is said to have pectinolytic activity), followed by *Firmicutes* (e.g., *Clostridia* species) responsible for hemicellulose and cellulose digestion etc.[40,51–53] This is supported by composition studies conducted on typical feedstocks in India[25,56] where the degradation patterns of various feedstocks are studied with respect to fermentation time (SRT; Figure 4).

Degradation pattern of various commonly found feed stocks (banana peel, cabbage, orange peel, bamboo leaves, teak leaves, and newsprint) have been studied (Figure 4).[25,57] The rate of decomposition of certain feedstocks like banana peel, cabbage and orange peel was high and occurred within 4 days SRT 90% of the components including lignin was solublized and lost from the solids matrix of the feedstock. Bamboo, teak leaves and newsprint showed a different pattern of degradation and wherein the breakdown of components was slow and 90% degradation occurred within 20–30 days SRT. Lignin was recalcitrant in most of these latter feedstocks. Banana peels are largely composed of hot water soluble pectin, cellulose and hemicelluloses, which together constitute nearly 80% of the mass. Their degradation is very rapid (Figure 4), and a majority of the mass of banana peels is solublized by 2 d. There was very little residue left after a 4 d SRT. This degradation is accompanied by loss of lignin fraction as well and is unusual. This pattern of degradation suggested that much of this waste will disintegrate within the inlet or the pre-treatment chamber of the PFR (plug flow reactor) with a potential to generate a large flux of VFA, Cabbage and orange peel waste followed a trend similar to banana peels. On the other hand, the pectin fractions of bamboo leaves are much lower and the leaves are more lignified (Figure 4). Hemicellulose and lignin fractions are much higher relative to the former three feedstocks. The decomposition rates of all fractions (other than lignin) are gradual. About 30% VS decomposition was achieved in 30 d. The lignin fraction remained undecomposed up to a 30 d SRT. Teak leaves had the highest contents of cellulose and lignin (predominant fractions) among the six feedstocks studied: These two feedstocks decomposed slowly, resulting in a 30% decomposition of the cellulose and hemicellulose fractions and 50% of the pectin-1 fraction in 30d. Another feedstock which exhibited a complete different degradation pattern from other feedstocks described earlier was banana leaf.[58] In banana leaf degradation of hot water soluble pectin was slow with 80% removal in 27 d which is not the case with other feedstocks such as banana peel, cabbage or orange peel described earlier. Oxalate soluble

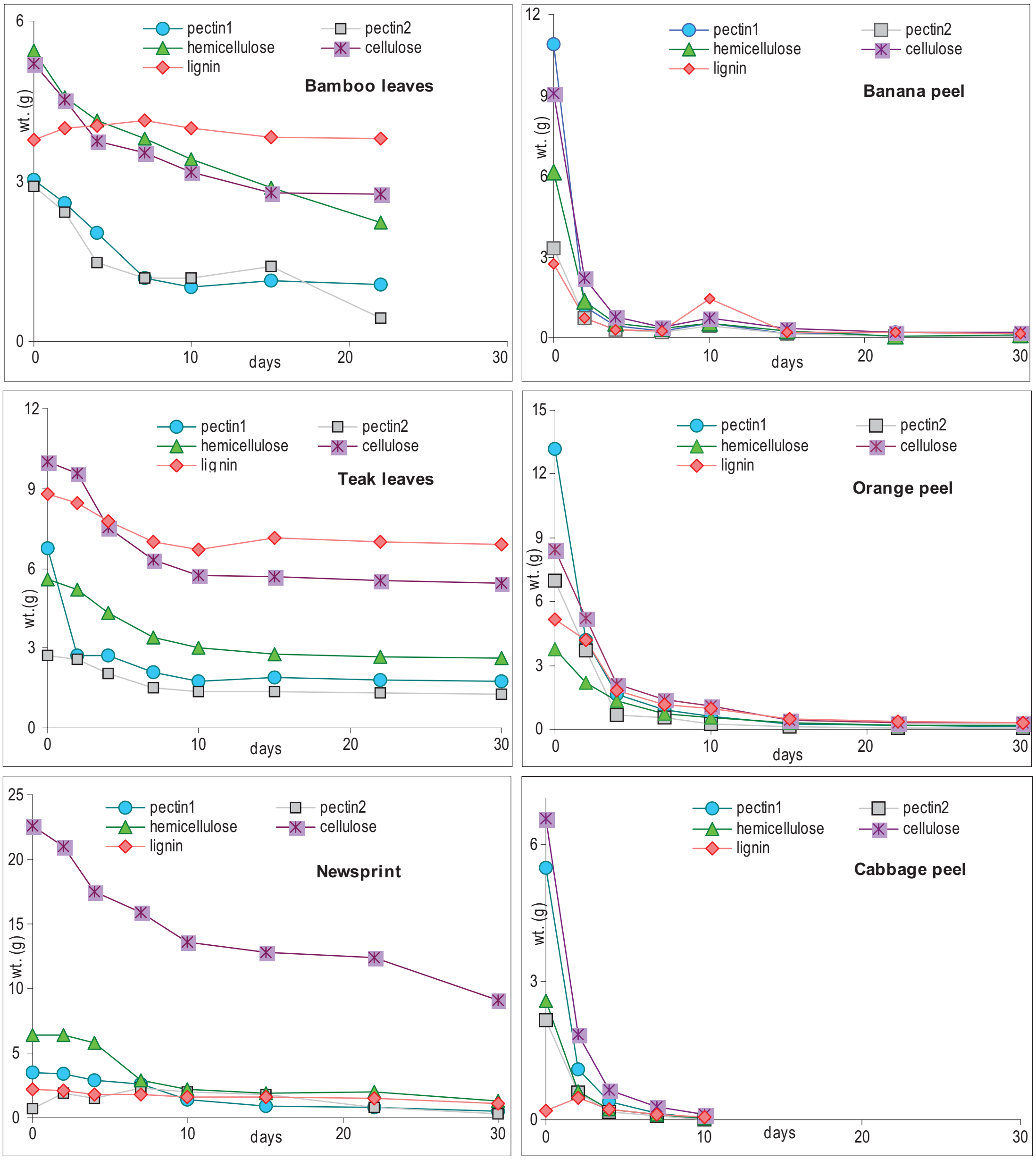

Figure 4: Degradation pattern of typical biomass feedstocks in submerged conditions of a typical plug flow reactor. The components of fruit and vegetable wastes had a rapid loss of TS (especially pectic material) while lignified leafy material such as bamboo and teak leaves exhibit lower decomposition rates even though pectic material is decomposed somewhat quickly.[25]

pectin degraded rapidly like other feedstocks losing 90% in 3 d. Hemicellulose and cellulose degradation was slow and interestingly 40% lignin lost in 30d has not been reported so far.[58]

The decomposition pattern of many of biomass feedstocks have been characterized in terms of the extent of various constituents have been put into two types the rapidly degrading ones and the slow to decompose agro-residues characterized by a higher lignin (Figure 4). However, banana leaves exhibit another peculiar decomposition pattern that may be visually monitored along with changes in composition (Figures 5a–d).[58] This provided a third type of understanding on the physical basis of AD of banana leaf feedstock with a potential to recover fiber. Banana leaves undergoing digestion in a typical PFR digester were extracted in a partially digested state, stained and viewed under light microscope at various periods of fermentation (3, 17 and 30 days). A section of undigested banana leaf is shown in Figure 5a. In banana leaves the vascular bundles are arranged parallel to each other with equal spacing between each vascular bundle. The space between the vascular bundles is characterized

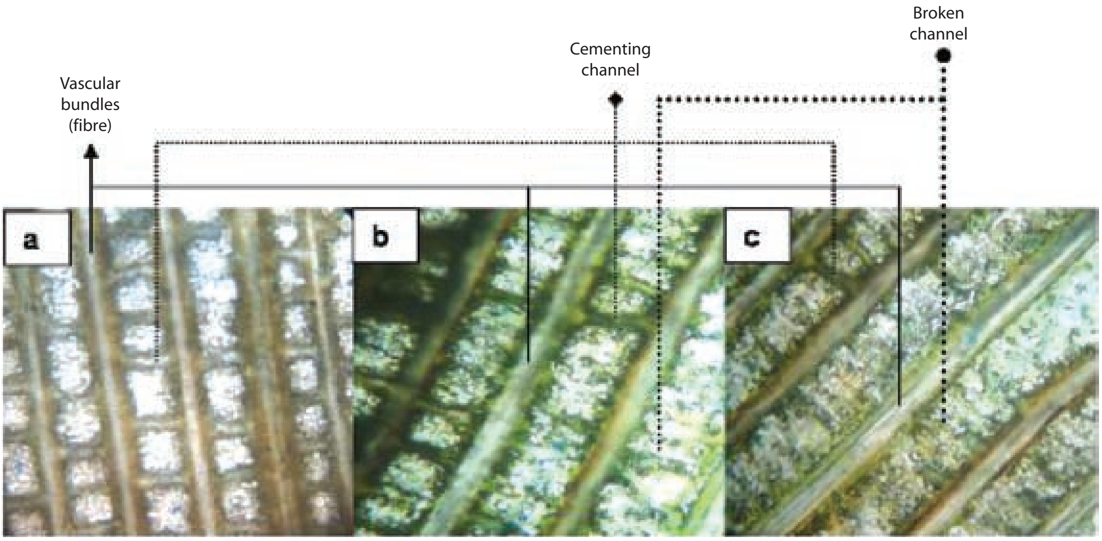

Figure 5a: Cross-section of undigested leaf, 5b: Cross-section of digested leaf (17 d), 5c: Cross-section of digested leaf (30 d).[58]

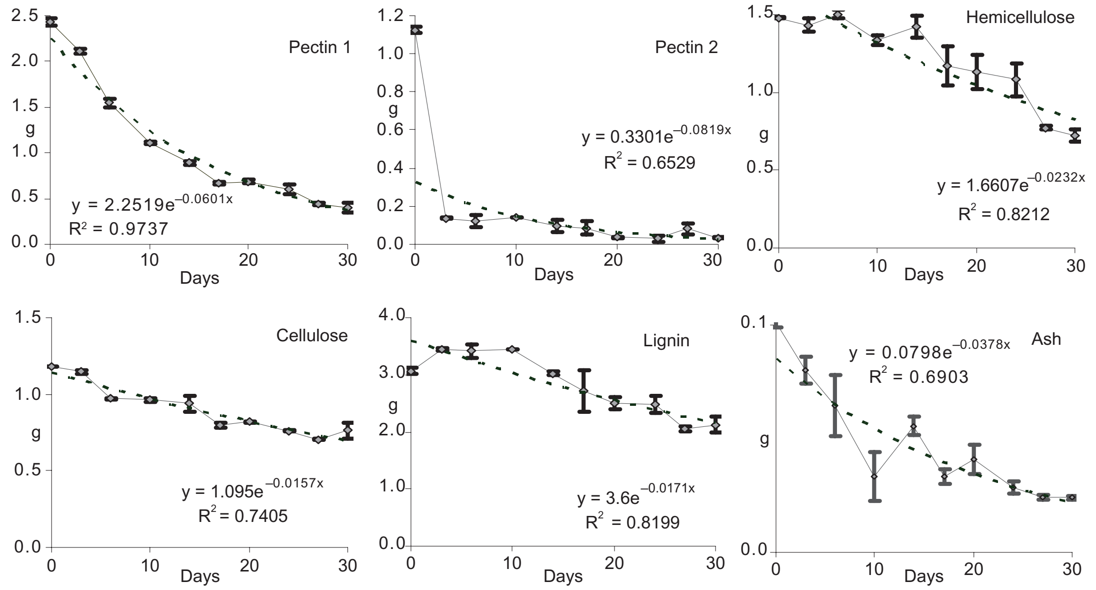

Figure 5d: Decomposition of the constituents of banana leaf (pectin 1 and 2, hemicellulose, cellulose and lignin) with respect to fermentation time.[58]

by channels connecting the bundles. These cementing channels are seen to be spaced equally and are ladder like in appearance. The channels connecting the vascular bundles are similar in length and diameter. The composition of these structures has not yet been identified. A section of the banana leaf after 17 d of decomposition is shown in Figure 5b. Around 50% of channels connecting the vascular bundles were broken and disintegrated. The breaking of the connecting channels were low in 3, 6 10 and 14 d of digestion (data not shown). There was not much noticeable change in the microscopic structure of the digesting leaf till 14 d of fermentation. However, on 30 d of digestion it was observed that over 90% of the connecting channels were lost and presumed to have been digested (Figure 5c). Banana leaves in which these cementing channels were lost were easy to be beaten for the recovery of banana leaf fiber. This suggested a 30 d fermentation period did not bring about damage to the vascular bundles and the vascular bundles (fibre) could be extracted by using a mechanical beater recovering 20% of the dry mass as fibre (discussed earlier). This also suggested a pattern of degradation in which the microbes attacked the outer cementing material between two vascular bundles first while setting the vascular bundles free and has not been reported earlier.[58]

2.5 *Microorganisms involved in methanogenesis of biomass feedstocks*

As discussed earlier the microbial consortia responsible for converting the volatile fatty acids produced after the hydrolysis and acidogenesis steps are mainly acetotrophic methanogens (*Methanosarcinales*), hydrogenotrophic methanogens that use $H_2 + CO_2$ as substrate (*Methanobacteriales* and *Methanomicrobiales*) and methylotrophic methanogens (methanol as substrate, *Methanomethylovorans*). Methanogenic population of bioreactors fed with energy crops and agricultural residues have been studied by various authors (Table 1). It is important to know and monitor the methanogenic *Archaea* in a reactor to optimize the performance as well as to restore the reactors from reaching failing conditions. When the population of methanogenic *Archaea* fall below a threshold or limiting value of the total bacterial population of an anaerobic biogas digester (Microbial Quality Index below 5%, for a stirred fermentor) the overall decomposition process comes to a standstill or stagnates. The volatile fatty acids (VFA) accumulate and the biogas production falls to very low levels. At low concentrations of acetate, normally filamentous *Methanosaeta* species are dominant whereas at higher concentrations of toxic ionic agents, like ammonia, hydrogen sulfide and VFA, *Methanosarcina* species dominate.[59] Thermophilic conditions can favor rod like or coccoid hydrogenotrophic methanogens. Thermophilic *Methanosarcina* species have also been observed, but not thermophilic *Methanosaetae*. Other environmental factors e.g., short or low retention times in a biomass reactor could favor hydrogenotrophic bacteria.

Methanogenic community in a biogas plant fed with maize silage (63%), green rye (35%) and low amounts of chicken manure have been studied[40] using 454-pyrosequencing techniques. It was found that species related to genus *Methanoculleus* (order-*Methanomicrobiales*) play a dominant role in methanogenesis of such a feedstock. The study on mesophilic and thermophilic reactors fed with fodder and beet silage concluded that acetotrophic methanogens (*Methanosarcinales*) represented mostly a minority down to a proportion of only 10% or were not detectable. Hydrogenotrophic methanogens with $H_2 + CO_2$ as substrate (*Methanobacteriales* and *Methanomicrobiales*) clearly dominated the system. Therefore, the methanogenesis of energy crops includes presumably an initial "cold gasification" to $H_2 + CO_2$ and after this a second stage of gas production occur producing $CH_4 + CO_2$. This is in contrast to the common understanding of the anaerobic digestion such as in anaerobic digestion model—ADM-1 where in majority of the methane production is through acetogenic pathway.[30] During thermophilic and slight hyperthermophilic fermentation, the dominance of methanogenic *Archaea*—hydrogenotrophic ones was even more pronounced than under mesophilic temperatures. The percentage of hydrogenotrophic methanogens increased up to 100% *Methanobacteriales*, e.g., on day 609 and 924 after starting the fermenter. They consisted mainly of *Methanothermobacter thermoautotrophicus*. At a fermentation period corresponding to 745 and 1249 day after start, the *Methanosarcinales* consisted only of *Methanosarcina thermophila*, with 1.8–3.5% of the 120 investigated clones. On day 727, the highest number of *Methanosarcinales* was found reaching 9.15%. When day 727 had a temperature of only 55°C some coccoid methanogens were reported through microscopic observations.[30] Similar results were shown by others[38] where *Methanomicrobiales* (*Methanoculleus*) where found to be the major population of the methanogenic community in biogas plant fed with maize silage, green rye and liquid manure. Others[60] studied the methanogenic population of 10 biogas digesters fed with energy crops and found that in nine of the ten biogas

Table 1: Methanogens in different types of anaerobic reactors fed specific biomass feedstocks and assayed by different methods and their potential contribution to technology development.

Sl. no	Type of reactor	Reactor scale up	Biomass feed	Temperature	SRT (days)	Biogas potential (m^3/kg VS)	OUT's	Dominant Species	Method of analysis	Ref	Inference
1	–	Pilot plant	maize silage, green rye and liquid manure	–	–	–	–	*Methanoculleus*	Integrated approach using clone library sequences and metagenome sequence data obtained by 454-pyrosequnecing	38	*Methanomicrobiales* were found to be the most abundant species
2	2 phase leach bed	Lab-scale	triticale silage	38	7	0.387	45	*Methanosarcinales*	PCR-based quantification of 16S rDNA sequences	39	The proportion of acetotrophic to hydrogenotrophic methanogens differed between the laboratory and the pilot scale system. The amount of methane produced by pilot scale plant was lesser than the lab scale
3	Two phase leach bed	Pilot scale	triticale silage	38	14	0.155	17	*Methanoculleus*	PCR-based quantification of 16S rDNA sequences		
4	CSTR	Lab-scale	Beet silages	35	877	–	11	*Methanosarcinales*	RFLP	30	*Methanosaeta* absent at 60°C opens the strategy to prefer industrial scale at 60°C over 55°C to exclude *Methanosaeta*, which is known to be sensitive for acetate, ammonia and H_2S.
					others			*Methanobacteriales*			
				55	-	-	6	*Methanobacteriales*			
				60	-	-	-	*Methanobacteriales*			
5	CSTR	Lab-scale	Maize silage	38	-	0.2	-	*Methanosarcinales*	PCR-SSCP, qPCR	61	Memebers of acetoclastic *Methanosaetaceae* were found only at low acetate con., At higher OLR hydrogentrophic *Methanobacteriales* and *Methanosarcinaceae* were dominating.
					-	0.1	-	*Methanomicrobiales*			
					-	0.2	-	*Methanobacteriales*			
					-	0.3	-	*Methanosarcinales*			
					-	0.5	-	*Methanomicrobiales*			
					-	0.4	-	*Methanobacteriales*			

plants analyzed, hydrogenotrophic methanogens represented by members of the order *Methanomicrobiales* were predominant. Within this order, predominantly members of the genus *Methanoculleus* were detected. Visible numbers of aceticlastic methanogens mainly of genus *Methanosaeta* were found in six of nine biogas plants. However, this genus was predominant only in one of them. These findings point out that hydrogenotrophic methanogenesis based on CO_2 and H_2 conversion as the favored pathway for methane synthesis in majority of biogas plants that use biomass feedstocks, thus contradicting findings made for other simple to degrade feedstocks such as wastewater and other solid wastes in slurry based fermentation.

These results provide the microbiological basis for the long known observations that firstly, hydrolyzing bacteria are the primary limiting step in the decomposition of agricultural residues while methanogenic archaea are weakest in most other fermentations such as food wastes, distillery wastes, etc. Further, hydrogenotrophic, and not aceticlastic, methanogens are dominant forms in energy crop digestion. A preponderance of long chain VFA due to poor VFA movement or acetic acid conversion via syntrophic acetate oxidation to H_2 and CO_2 provides hydrogenotrophic methanogens substrate and possibly supports their high populations and need to be studied in detail. In this pathway of biogas generation, a very small distance between syntrophic bacteria and methanogenic archaea needs to be maintained to render efficiently the syntrophic electron transfer. Typical biomass feedstock when subjected to anaerobic digestion, release an initial flux of VFA that inhibits rapid conversion of VFA and colonization by methanogens. Unless this is addressed with new technologies, digestion rates (hydrolysis) will be limited by the rate at which this VFA generated will be converted to biogas. Once this stage is crossed, the VFA production rates fall to levels where typical methanogens can grow and convert the intermediates to biogas. New technologies could to utilize this phenomenon to evolve simpler processes for anaerobic digestion of biomass (discussed in the following section).[10,23,24]

2.6 *Factors affecting anaerobic digestion*

Biogas production, a microbiological process is affected by various physico-chemical factors such as temperature, pH and composition and biological factors such as the level of inoculum, phages, etc.

2.6.1 Temperature: Anaerobic digestion can occur under two temperature regimes, namely, mesophilic (20–45°C, optimum at 35°C) and thermophilic (50–75°C, optimum 55°C). Anaerobic digestion under pshycrophilic temperatures (<20°C) have also been reported by various authors but not extensively studied as the gas production rates at this temperature (<15°C) is very low and uneconomic. Methanogens are more sensitive to low temperatures and is one of the most common factors affecting methanogenic processes in a biogas digester in other countries. In a large part of India the digester temperature rarely falls below 15°C in spite of long winters. However, the enzyme kinetics, dissociation constants and death rates are greatly affected by small changes in temperature. As temperature rises, enzyme activation increases while at the same time enzyme denaturation also increases. In addition, higher temperatures also increase the irreversible destruction of many of these vital proteins. Such mechanisms cause a typical bacterium to have a range of temperature viability as well as an optimum temperature for growth and functioning. Mesophilic reactors need a gradual start up procedure and methods to prevent heat loss in mild winters. Digesters in south India rarely suffer serious winters and temperatures are generally above 25°C. Many studies have carried out thermal analyses of the floating drum and fixed dome type biogas plants and have provided various solutions.[62] Under mild winter conditions two strategies have been deployed namely, a. to use a longer residence time to compensate for slower decomposition in winter and b. to use a solar assisted digester where a transparent solar envelope traps heat and warms the water used for mixing animal dung.[63]

2.6.2 pH: Changes in pH affects the enzyme activities and only a narrow pH range is suitable for maximum activity. A pH range between 6.7–7.4 is reported suitable for most methanogenic bacteria to function.[33] The rate of methanogenesis decreases when the pH falls below 6.3 or rises above 7.8. Animal dung biogas plants rarely have problems of unsuitable ranges such as the pH being outside the permissible range indicated above. However, in the case of a few biomass feedstocks such as fruit and vegetable discards, fresh leaves, some components of urban solid wastes, there is a rapid initial degradation that produces a VFA flux and lowers pH to levels as low as 5 and methanogenic inhibition sets in.[25,54,55,64–66] On the other hand most agro-residues, especially straws that are stocked over long periods, show an initial rapid degradation (up to 30% TS) and the low pH period is ephemeral. Earlier efforts to use the VFA flux induced low pH to separate the acidogenic and methanogenic stages have not been very successful.[65,67] Thus while VFA induced low pH and concomitant methanogenic suppression has often been found with liquid, agro-industrial and food wastes, this phenomenon has been rare with various biomass feedstocks.

VFA: Volatile Fatty Acids are the typical breakdown products from the early stage of anaerobic digestion. Acetic, propionic and butyric are the commonly found VFAs in an anaerobic digester..

VS: Volatile solids, is an indirect measure of the organic material within a sample.

2.6.3 VFA: As indicated above, many agro-residues and rural feedstocks decompose rapidly to release a large VFA fluxes. Most of the biomass feedstocks are buffered well and therefore in spite of such VFA fluxes arising from about 30% VS lost in the first 2–5 d, the pH is well buffered and does not fall to inhibitory levels. However, when the VFA levels cross about 6 g/L acetic equivalent, methanogenesis appears suppressed. As the VFA levels increase further, the extent of long chain VFA rapidly increases and total VFA in rapidly degrading biomass feedstocks such as leaves can reach up to 20–30 g/L.[65,69] The long chain fatty acids were found to be toxic to various bacteria as they inhibit several kinds of essential reactions in an anaerobic digester. The rate of methane production from hydrogen was lowered by long chain fatty acids even though the pH levels remained within permissible levels. The production of methane from acetate was strongly inhibited with a long lag phase. The VFA accumulation in biodigesters could be controlled by applying various pretreatment steps to the feedstocks. It was also reported that after the VFA flux period, methanogens colonized digesting biomass at such levels that such could be used in place of biofilms supports for wastewater processing and these had specific methanogenic rates up to 10 g VFA/g biomass/d. Of this, in a few plant species both aceticlastic and hydrogenotrophic activities were equal while in many others aceticlastic (9 mL/g/d) and hydrogenotrophic (10–28 mL/g feed biomass/d).[69]

2.6.4 Effect of microbial population: Microbial population in a biogas digester responds quickly to changes in the feeding rates. Acidogens grow faster than methanogens. Thus the potential advantage of stage separation will depend on whether the turnover rate is limited by the degradation of the readily degradable compounds or by polymer hydrolysis. Hydrolysis, being the first step in overall process, normally is the rate-limiting step of the overall anaerobic digestion process when using agro-residues and similar feed stocks with minimal processing. The levels of *Methanosaeta* sp., measured as aceticlastic activity, decreased rapidly as acetate levels build up.[70] The dominant type of methanogenic bacteria changes as the SRT of the methanogenic reactor changes. *Methanosarcina* is dominant at short SRTs while *Methanothrix* is dominant at long SRTs. M*ethanosarcina s*how higher substrate utilization compared to *Methanothrix*.[29,33]

2.6.5 Leachate recirculation: Unlike animal dung feedstocks biomass feedstocks are not premixed with the required decomposing microorganisms such that they are already decomposing to biogas—as is the case with animal dung. Biomass feedstocks do not have the required microbial inoculum that is required to convert the substrates to the desirable end products, namely biogas. Initiation of decomposition therefore becomes slow, especially with most of the dry biomass feedstocks commonly available for biomethanation. Where there is inadequate microbial consortia coming in with the dry biomass feedstocks such as agro-residues and straws, the recirculation of leachate of the digester, rapidly brings close together the degrading micro-organisms to the site of decomposition on the newly fed biomass. In the solid state stratified bed (SSB) reactors developed by CST, recirculation of leachate provides two functions, namely, begins the process of hydrolysis and acidogenesis of the freshly fed feedstock and secondly carries away the VFA accumulated in the bed to lower horizons for conversion to biogas.[24,71]

2.6.6 Ammonia: Ammonia is produced in anaerobic digesters by protein degradation and is toxic to methanogens. The quantity of ammonia that will be generated from an anaerobic biodegradation of organic substrate can be estimated using the following stoichiometric relationship.

$$\begin{aligned} C_aH_bO_cN_d + (4a - b - 2c + 3d)\,4H_2O \\ = (4a - b + 2c + 3d)\,8CO_2 \\ + (4a + b - 2c - 3d)\,8CH_4 + dNH_3 \end{aligned}$$

Small increases in ammonia nitrogen in reactors increase hydrogen and methane production, whereas large increases cause inhibition of hydrogen and in turn methane production. *Methanosarcina barkeri, Methanobacterium thermoautotrophicum, Methanobacterium formicicum and Methanospirillum hungatei* were the most sensitive, being inhibited at 4.2 g/L. The other strains tested were resistant to ammonia levels higher than 10 g/L.

Although a large number of these physicochemical and environmental factors seriously affect the overall process and its functioning, these factors seldom affect biogas plants in most parts of India largely because of the conducive ambient temperatures in most parts of the country and biomass feedstocks seldom suffer ammonia and VFA toxicity when handled properly. Anaerobic digestion of biomass is therefore quite conducive in India for raising biogas as fuel from biomass feedstocks.

3 Emergence of Anaerobic Digestion and Biogas Technology

3.1 *Early research trends*

Much of the early research on anaerobic digestion of farm and animal wastes as well as agro-residues had been directed towards conserving N—an issue that was recognized as vital to sustain crop yields in India between the 1900's and 1960's (related issues also discussed in paper on sustainable soil management in this volume).[5] Therefore the predominant objectives were to maximize the flow through and recovery of N from all rural residues and 'wastes' in the form of anaerobic compost so that a near 100% recycling of N became possible and famines caused by N-limited food shortages could be averted.[1,4,6] Some of the early plant designs emerged as a spin off from this kind of research, especially at the Pusa Institute (now IARI, New Delhi).[1,5,72] The reigning research and developmental objectives that influenced biogas plants in the subsequent periods have been illustrated in Figure 1. Biogas plants that have been conceived in India, especially the ones that convert animal wastes (and sometimes partially mixed with other agro-residues) to biogas and compost have had a varied path of technology development and sustainable development goals as compared to those that emerged in other countries or much later in response to energy crises.[1,14,21,63,71,73] Unless this difference is cognized, the role, the relative importance and the shaping of biogas technology cannot be understood to its fullest extent and compared with the technology development processes in other parts of the world.

The prototype biogas plants and 'anaerobic composters' built between 1930's and 1960's were developed by researchers who were looking for maximization of N and stable organic matter (humus) conservation in the digested material. Even the feed rate and solids concentration was optimized more on the stability of the animal dung slurry and possibly based on its flow-ability.[5,72] Further, although there is very little published record of the reasons for the choice of a 9% TS in the input slurry, it has been followed unchanged even today (CST, unpublished study). This ratio of dung to water has been made as the optimum for operating animal dung based biogas plants.[62] The depth and dimensions and the types of materials chosen for construction of biogas plants, although rationalized for a specific period of time, did not involve extensive engineering and optimization of inputs and appear to have been chosen based on the relative cost of the mild steel (MS) gas holder rather than the biogas plant as a whole.[62,74] The digester designs evolved during that period had remained (in terms of operation and construction in the field) simple, considering that these biogas plants were meant to be built in rural areas using insufficiently trained/skilled masons and technicians. Thus the choice of a 5 m depth and 1.8 m diameter, the 0.23 m (9 inch) thick circular brick wall, the height and diameter of the floating gas holder, etc. greatly reduced the costs of the floating drum, perhaps the highest costing component and thereby an indirect optimization.[62,74] Later as these researchers developed a better method of optimization, it gave way to creating shallow and wide digesters which was claimed to give marginally higher gas yields.[62]

Although biogas plants were spread gradually over nearly 20 years between the 60's and 70's, the strong and widespread need for biogas plants to substitute rural cooking energy requirements and envisaged as long term replacement for the smoky wood based cooking emerged around the energy crises of the seventies.[75] It is after this period that significant research funding had been initiated all over the country and R&D efforts had begun in order to improve biogas plants to provide cooking energy and compost. This approach now reverses the order of priority from primacy to manure to primacy to gas as cooking and 'development' energy. This occurred both as the offshoot of the DST/MNRE's National Program on Biogas Development as well as many research institutions 'mainstreaming' biogas technology as a priority area. Thus the process of biogas technology development and improvement to a significant extent moved out of the ambit of the 'voluntary sector' workers to a much larger and national level S&T based activity. This was indeed pioneered by many of the lead institutions of the country at that period such as IISc, IITs and CSIR laboratories. This, accompanied by the setting up of the Ministry of Non-conventional Energy Sources (MNES, now MNRE) in India, had a strong focus on AD for energy and accompanying rural development. It must be emphasized here that this long and strong history of using animal dung slurries as the main feedstock and designing digesters for it, to some extent, has left an indelible tradition of and tendency towards slurry based reactors. The influence of animal dung 'slurry' based design of the past and fermentation concepts has been so strong that today most of the commonly available biogas plant reactor designs developed even for solid wastes resemble in many ways the slurry based designs or require wastes to be converted to slurries for operation. While this approach provides a more logical incremental development path, it does not recognize better innovations for conversion of solid residues without first powdering them.

Between the years 1980 and 2005, various types of efforts have led to nearly 4 million domestic sized biogas plants being built—all of which use animal dung slurry as the feedstock *(discussed in the paper on Energy Access by Dr Balachandra)*. From the nineties, it was realized that the potential for cattle dung based biogas plants was limited to a level between 12–17 million plants in the country and there would be vast majority of homes (rural and peri-urban) that could not benefit from the biogas plant technology because they do not have enough cattle at home to effectively run biogas plants.[14,76] Thus in the late eighties, a large number of attempts have been made to extend the potential biogas feedstock to other 'waste' biomass such as water hyacinth and terrestrial weeds.[21,63,71,73,77–81]

3.2 *Development of anaerobic digestors in India—the early years*

The general view of anaerobic digester emerges from the popular concept of the "Gobar gas" plant that addresses an important rural energy need of cooking and where the predominant feedstock has been cow-dung mixed with water to make a flowable slurry. Towards achieving this, there has also been a long process of technology development in India. In the early stages between circa 1955–1970,[1] the biogas plants were expected to provide a capability to anaerobically digest animal wastes produced on a daily basis on farmsteads or rural homes, and store the digested feedstock for periods up to 8 months, without loss of N, in such a form so as to be able to recycle this N-rich manure on to the crop land. When the digested slurry from a biogas plant was let into a soil pit or a filter bed of leaves, the water slowly filtered through it leaving behind a solid mass termed anaerobic compost that retained nearly 85% of the original N found in animal dung.[82] The soil system through which the liquid passed captured a significant part of the N present in ammonia form. The net N lost was thus very small and the process therefore, N-wise efficient.[24,25,82] The gas that was produced simultaneously provided an efficient and smokeless cooking fuel in rural and peri-urban India where generally low quality biomass was burnt as fuel (e.g., dried animal dung).[83] The gas also provided lighting (as mantle lamps) in villages where electricity grid did not reach or grid electricity was unreliable.[1,5,8,72,84]

While the early research circa 1935 examined anaerobic digestion as a safe means of conserving nitrogen without carrying over pathogens and as a safe method to handle animal wastes while simultaneously avoiding flies (rural sanitation), the incentive to produce and use 'cooking' gas for a household appeared much later, circa1952–55. The first commercially available biogas plant using animal dung appeared circa 1950 and its improved versions were later adopted by the Khadi and Village Industries Commission (KVIC and hence the term KVIC design) with some design improvements for large scale dissemination.[1] Gaseous fuels burn clean, are generally smoke-less and soot-less allowing easy, rapid and clean cooking with very little smoke related health hazards. This gave AD and biogas plants the symbol of technology for sustainable development (including rural sanitation) between 1960 and1970. It is only in the early seventies that the biogas plants became attractive to replace fossil fuel dependence as well as to overcome the threat to environmental sustainability after the two oil crises. India then started a country-wide program—the National Program on Biogas Development (NPBD) to rapidly disseminate biogas plants in rural India with mixed levels of acceptance and success.[76,85] As a result of the widespread and long run campaign for disseminating cow dung biogas plants, anaerobic digestion and biogas plants are now synonymous with these "Gobar-gas plants" although many other feed stocks and biogas plant designs are possible and are in use. With regards to use of biogas, although originally planned as a cooking fuel, a much larger set of options for use exists today. Over the last 20 years a lot of research has been undertaken, primarily to understand the underlying microbiological processes as well as to identify ways to control the underlying processes. Nevertheless, it is important to note that such a long tradition of cow-dung biogas plants has strongly influenced newer designs, applications and even thought processes.

3.3 *Biogas plant designs for animal waste feedstock*

Animal wastes such as cattle and buffalo dung function as "ready mix" materials wherein by the addition of water and it is converted to a simple to handle slurry. This slurry undergoes, without any further processing, a rapid anaerobic digestion without too much external interference in a warm country like India. Much of the research was therefore guided by objectives so as to achieve a desirable level of digestion as quickly as possible while maximizing the gas production, the nutrient recovery as well as minimizing capital costs involved in setting up the biogas plants around 1970.[86,87] Only much later in the 1980–90, we first find the social and environmental objectives attached to biogas plant designs and ancillary technologies.[8,84] Biogas plants have the potential to ferment animal and some crop wastes and simultaneously avoid local pollution to water and soil.[88] In various countries today, the methane emitted from animal wastes add to their national C-footprint and therefore efforts are underway to firstly collect the biogas emitted and secondly substitute fossil fuels using biogas thus collected.

The cattle rearing and ownership pattern in India is different from many other countries. Cattle are generally held in a dispersed manner with a few cattle head per family. Anaerobic digestors built in India therefore are small and need to cater to family's energy needs (usually cooking)—called family sized biogas plants. Further, because potential users of biogas plants were in villages that were poorly connected to the grid and therefore without reliable source of grid electricity for domestic illumination, biogas plants were designed with a marginally extra capacity to provide 2–3 h of lighting using a mantle lamp.[76] The use of biogas plants in typical rural Indian homes remove the 2–4 h fuel wood collection chore for girl-children thus empowering these young women who cook on biogas (as discussed later).[17] Reduction in drudgery of gathering fuel wood,[8,84] reduced drudgery filled working hours in the kitchen, lowered exposure to wood smoke, provided options to use the free time to earn local livelihoods as well as from the newer options to generate value added products (VAP).[10] VAPs from biogas plant residues and outputs provide elements to increase the social component of sustainability and more importantly enhances the triple bottom-line of environmental, social and economic sustainability in rural and peri-urban India—these were also included into the research objectives for biogas plants for rural areas. Having built elements of sustainability into the biogas plant designs, to a certain extent, a large scale dissemination of such biogas plants were envisaged to lead to the current goal of sustainable energy for all[17]—the current declaration of UN for the year 2012.

In a typical biogas plant, animal dung and water is mixed in a ratio of (1:1). This mixture is let into the digester and allowed to ferment under anaerobic conditions for periods ranging from 35 to 55 d depending upon the local temperatures.[84] Bacteria start multiplying in this fermentation tank (the biogas plant) in the absence of oxygen to convert about 25–35% dry matter in the animal dung slurry to biogas (60% methane and 40% carbon dioxide) yielding between 35–45 L biogas per kg of wet dung fed (at about 18% TS). This plant is operated in a continuous manner by feeding the dung slurry daily and removing the digested slurry to flow out at a similar rate of input. The digested slurry with about 6–7% solids (25–35% TS degradation) comes out daily as output which is dried, stored in a moist form similar to compost and used later on as manure. Under normal circumstances it is difficult to separate the water that is mixed initially with dung because slurry of a strength higher than 6% TS settles very slowly.[11,89] The biogas yielding process is mildly exothermic but the heat produced is inadequate to sustain the digester temperatures in winters. Conventional digesters lose heat and in order to keep the fermentation going it is necessary to maintain an average temperature in the range of 18–35°C. In cold climates solar heaters have been designed to preheat the daily charge of water and dung in order to sustain gas yields at even at low ambient temperatures while maintaining the same retention time and digester volume (from 35 to 50 l/kg dung; *CST solar heated biogas plant*).[62,63]

The most commonly used biogas plant design/models for cattle dung based biogas plant in India are the floating drum KVIC and the fixed dome Janata models (and its variants). Today the KVIC model is commonly constructed for a slightly larger size of 6 and 8 m^3/d gas production capacity at a HRT of 30, 40 or 55 days depending on the local temperature regimes. The reactor is fed a cow-dung slurry in water 'semi-continuously' (daily) through an inlet pipe. This daily input of dung slurry displaces an equal volume of slurry from within the reactor through an outlet pipe. When the reactor is designed to have a greater height: diameter ratio, a central partition wall is included to prevent short circuiting and the fresh input leaving the digester in a partially fermented state. Cattle dung, generally having a solid content of 18%, is diluted to 9% (dung:water = 1:1) before feeding and the daily gas yield is around 0.35–0.5 m^3/ m^3 of the digester volume. There were around 80,000 KVIC models built in India by the early 1980 with cow dung as the feed however, with the introduction of the cheaper 'Janata' and the 'Deenabandhu' models, fewer KVIC type floating drum models were constructed from the 90s.[76] The Janata and the Deenabandhu models are based on the Chinese fixed dome design and adapted to cattle dung slurry. A typical cow dung fed biogas plant of the Janata/Deenabandhu models are 20–40% cheaper than the floating drum or KVIC model (between 1990–2005). These plants are designed for a 45–60 d retention time and can be constructed in various sizes ranging from 2–30 m^3/d gas production capacities; the most common sizes are 2, 3, 4 and 6 m^3 gas/d. Up to 1986, a total to 642,900 digesters had been built in India. Janata model biogas plant produces 0.33 m^3

biogas/m^3/day. Today a majority of the biogas plants built is the variant of the Janata model called the Deenabandhu model.[70,76]

Over 4 million family sized biogas plants have been built in India out of a possible 12–17 million cattle dung based biogas plants. These plants use animal dung as sole feedstock.[24] India has a bovine population of over 300 million (cows 224 million and buffaloes 94 million in 2010). The total dung production for cattle and buffalo is estimated to be 659 Mt annual based on an average dung yield of 4.5 kg/d of cattle and 10.2 kg/d of buffalo and from this the total dung recoverable would be 510 Mt for 2010. If this entire bovine dung can be recovered then 17,850 Mm^3/yr of biogas can be generated in India equivalent to providing 25 million house biogas on a daily basis.[90] However, the ownership of animals in typical Indian villages is generally skewed and many families own insufficient number of cattle heads. Thus, as each family sized plant needs between 40–50 kg animal wastes daily, as indicated earlier, only 12–17 million households have the required number of cattle to run a biogas plant effectively round the year. Those households that cannot collect 50 kg dung per day cannot run the biogas plant effectively to cook their food only using biogas. This therefore limits the envisaged unbridled spread of biogas plant technology into rural areas—biogas plants capable of using alternative feed stocks such as straws, agro-residues, weeds, etc. need to be evolved if widespread cooking using biogas is envisaged.[21]

The disadvantages of cattle dung based biogas plants, therefore include difficulty in ensuring the collection of the required quantity of dung on a daily basis. Moreover, families who do not own sufficient number of heads of cattle to meet a minimum daily dung availability cannot run such biogas plants effectively. Assuming a stall-fed animal produces a daily dung output of 15 kg, and then one family would require 3 stall-fed cattle to run a biogas plant. This in reality has been a difficulty since not all families in a village can afford them. Most of the cattle owners, for a long time now, send their cattle to graze and therefore dung is available only when these animals are bedded for the night, and only the dung produced during this period becomes accessible for being fed to biogas plants. Under such situations, running community based biogas plants was tried and found more viable if all the dung resources of the village could be pooled in and used for providing common energy services.[8] However, there have been few successful operational models that have succeeded at a village scale and remained viable.[8,23] These studies suggested that alternative feedstocks like biomass, food waste etc. were to be introduced to overcome such shortfalls.[24] Poultry and piggery wastes have been found to be alternatives for dung based biogas plants. Poultry manure has 20–25% total solids of which 15–16% is volatile solids and calorific value of 3200 kJ/kg of wet manure. Poultry manure generated is 60–100 g/bird/day and has a biogas production potential of 0.01 m^3/day/bird. From this the total biogas generation from all the poultry farms in India has been estimated to be 438,227 m^3/d.[90] Similarly swine manure production is 2 kg/animal/day with a total solid content of 17% and biogas yield of 0.08 m^3/animal/d.[91] Chicken manure and swine manure have a high nitrogen content of (12.5 and 15%) and therefore these feedstocks need to be co-digested with cow dung or other N-deficient biomass feedstocks to overcome potential threat of ammonia toxicity.[92] Basic approach to biogas production from dung is to make a slurry (1:1; 9% TS) of the dung or a mixture of manure and dung and use it as a feedstock.

In the period between 80–90s a large number of plant failures that occurred due to poor construction and materials used[76,85] have led to the evolution of many forms of prefabricated biogas plants. The earliest among these is the bag type of digesters[63] and much later as a partial substitution of the vulnerable gas holder by fiber reinforced plastic (FRP)[76] and later even complete biogas plants made from HDPE and FRP.[73] Much of these new generation plants are generally variants of either the KVIC type digesters or the Deenabandhu type plants. They do not have newer processes employed and generally cannot accept typical agro-residues such as straws, husks or weeds as the primary feed stock. Nevertheless they address a weakness of the built in situ types of plants of the past. It must, therefore, be accepted that unless large scale dissemination programs are evolved and are based on multi feed biogas plants that are capable of using any mix of biomass feedstocks, much of the rural population will remain without access to this technology[17] (*discussed later in this volume*).

3.4 *Biomass decomposition and emergence of biomass based biogas Plants*

3.4.1 Decomposition pattern of biomass feedstock: The gas production from leafy biomass feedstocks is generally twice that of animal dung.[24,54,55,68] Most of the leafy biomass produce biogas in the range of 300–500 l/kg total solids, TS. Biomass feedstocks show a decomposition pattern different from that of cow dung and hence the biogas plant designs developed for dung fail to work with biomass.[24] These biomass feed stocks are mainly composed of pectin, hemicellulose, cellulose and lignin. Most of these feedstocks have 30–40% ligno-cellulosic matter that is recalcitrant under typical anaerobic conditions (of the biomethanation plant) and comes out undigested after digestion process in a typical biogas plant. The digestion pattern of biomass under anaerobic conditions is expected to follow a sequential pattern in which most of the pectic materials (the easiest to degrade) are converted into VFA within the first 3 days of fermentation followed by hemicellulose, cellulose and a part of lignin. Amongst herbaceous biomass feedstocks, two broad types may be found: the one that degrade very rapidly because of their low lignin content or the young stage at which these are harvested makes them easy to degrade, a lot of fruit and vegetable wastes fall in this category. The second and more predominant are the agro-residues which have a significant recalcitrant content and therefore slow down the decomposition—both under aerobic and anaerobic conditions. In the first category over 80% of the constituent degradation happens in the first 10 days for the soft type of biomass while it takes longer for agro-residues. A majority of biomass feedstocks contain significant levels of a rapidly fermentable fraction, which when subjected to anaerobic digestion, quickly gets converted to several fermentation and methanogenic intermediates, mainly volatile fatty acids (VFA), H_2 and CO_2. Rapid VFA fluxes of this nature stall methanogenesis and biogas fermentors become acidic. Another problem associated with biomass decomposition is that biomass particles generally have a lower density than the digester liquid or acquire it as soon as a few biogas bubbles adhere to them.[24,54,55] These bubbles make the biomass feedstock float in the digester liquid during their stay in the reactor leading to incomplete digestion. Most of the earlier technologies used for dung based biogas plant when used for biomass, the feedstock was powdered and rendered into a slurry by mixing with water and fed into the conventional model of an animal dung based biogas plant—typically a derivative of the KVIC floating drum design. To overcome the floating nature, a continuously stirred tank reactor has always been opted for the dispersal of the floating biomass layer. The pre-treatment by powdering or other particle size reduction does not address the problem of biomass floating in the digester because however small the particle size is achieved, it still adheres to biogas bubbles and begins to float in a static digester. When conventional dung based biogas digesters are fed a slurry made of powered biomass and water, the digesting mixture within always segregates into distinct liquid and solid phases (floating) unless these are physically stirred every few minutes. In the absence of continuous stirring, the floating layers tend to dry up leading to incomplete digestion or complete cessation of fermentation depending upon the dryness of the floating layer. This tendency has been addressed differently in the plug-flow digester and the solid state fermenters and is discussed later.[24,25,54,55]

3.4.2 Pretreatment methods: As indicated above, because the powdered biomass and liquid segregate into two layers several trials have been carried out to find pretreatments that can overcome this tendency of biomass feedstocks. Mechanical, chemical and biological pretreatment are the 3 main types of pretreatment applied to biomass to facilitate better and faster biogas production as well as simpler handling.[93] Mechanical treatment involves the use of a beater or pulverizer to reduce particle size, thereby increasing the surface area allowing for a better access to microbes, reduce the floating nature and allow frequent mixing of the digester contents to finally lead to a higher biogas yield.[94–97] The aim of chemical methods such as acid pretreatment or alkali hydrolysis is to remove lignin from the biomass which in turn produces higher methane yield and reduces the SRT. These chemical methods could either be used as complete and stand alone treatment step for complete hydrolysis to sugars or breaking certain links in the hemicellulose-lignin polymeric system so as to provide increased diffusivity to hydrolytic enzyme. Alkali pretreatment methods have accordingly been adopted by several researchers to achieve increased volatile acid and gas production in anaerobic digesters.[97] Two types of enzymatic hydrolysis and aerobic pre-treatments are commonly used in biological pretreatment steps. An external source of commercial enzyme or pure culture of lignin removing bacteria have often been used to remove or break certain lignin-hemicellulose bonds and the material treated thus is later used for biogas production.[98,99] Aerobic pretreatment is again introduced in feedstocks to partially remove lignin, improve the VFA production, suppress methanogens (during pretreatment) and increase biodegradability of the feedstocks.[100]

3.4.3 Solid-state Stratified Bed (SSB) fermentation process: Solid-state stratified bed reactor has emerged as an option to avoid the use of a large volume of water in biogas plants, e.g., making a slurry of the feedstock which has been considered as the primary cause of the floating problem.

Avoiding a large component of water in the digesters therefore avoids the tendency of biomass to float and obviates the elaborate pre-treatment and stirring needs of a slurry type digester. The SSB reactor loosely emulates a bioreactor landfill in the way it functions, however, unlike the landfill, this is a continuous process functioning about 150 times faster than landfills. It has a very small liquid component compared to the size of biomass bed that is fermenting[23,24] It accepts fresh or dried unprocessed biomass feedstocks that are dumped on to an existing and decomposing biomass bed within the reactor. The reactor configuration constitutes a digesting biomass bed (with very little water) fed from the top and digested material removed from the outlet below. The outlet is placed in a water seal and the entire bed is a solid mass. In effect a two stage acidogenic-methanogenic phase separated system design has been simplified into a single reactor configuration when methanogen rich biomass bed is allowed to form in the lower part of the reactor and operated in the following manner. When a small quantity of recycled digester liquid is sprinkled over the decomposing biomass bed, VFA rich pockets are dissipated. The dissipated VFAs leach downward and reach the lower part of the biomass bed, the layer intensively colonized by methanogens, these leaching VFAs are rapidly converted to biogas.[71] The daily feeding is simplified by having an opening at the top which can be opened to introduce fresh feedstock every day. Here, even though appreciable quantities of air is introduced into the reactor during the biomass feeding operation, it does not hamper the process since the methanogens colonize far below in the decomposing biomass bed. A small volume in the reactor, 5–10% constitutes the liquid phase which also doubles up as the liquid seal to trap the biogas produced within and channelize it to a separate gas storage system. This kind of a biogas plant gave an output of 0.4–0.5 m^3 biogas/m^3/day.[54,55,64,65] This technology is in an advanced stage of field testing and being readied for dissemination.

3.4.4 Plug flow digester: Pretreatment of biomass feedstocks firstly renders these feedstocks softer, removes the rapid VFA producing components that inhibit the methanogens through VFA flux, slow down the fermentation process so that rapid gas production and floating nature is arrested (or to some extent escaped). In this process of pretreatment by partial decomposition, between 30–40% of the useful total solids in the biomass feedstock is digested away in an aerobic manner, without production of biogas. In other words about 30–50% of the biogas potential is sacrificed to make the biomass feedstock amenable to anaerobic digestion in a conventional biogas plant.[101] It is, however, possible to combine a pre-treatment step into the design of the digester such that the VFA fluxes that occur initially, the products of this flux enter the digester and is converted to biogas instead of being lost in a typical open to air pre-treatment system. The biomass feedstock after the initial VFA flux is usually amenable to uninhibited solid state fermentation wherein the TS degradation rate (usually acid production rate) and the acid consumption rates match. At this stage, the solid decomposing biomass does not require a large liquid phase and can be carried out even when the biomass is afloat atop a liquid zone and has little access to the liquid zone or slurry type fermenter. This phenomenon is utilized to evolve and design the plug flow reactor for any mix of biomass feedstocks. VFA flux producing or slow to decompose biomass as well as green or dry or any mix of them can be subjected to this form of biogas production. The advantage of such a plant design is the absence of a need for a large liquid phase or the daily addition of water as is usually done for cattle dung based biogas plants. While the first stage removes about 30% of the digestible biomass the second decomposition that occurs even when biomass feedstock is still afloat converts another 30–50% of the total solids such that between 50–80% of total TS (total solids) conversion to biogas is possible with most biomass feedstocks. Towards the end of 30–40 days SRT, much of the VS (volatile solids) are decomposed but the feedstock is usually still afloat, albeit to a much lesser degree. This floating and digested mass towards the outlet is manually removed to facilitate continuous operation. Such an approach addresses a critical need for India, that a plant of this nature can accept any mix of feedstocks—multi-feed. It can also rapidly switch between green and dry feedstocks. This is important because it is not possible to obtain a single type of feedstock throughout the year in India and biogas plants need to have the capability of accepting any mix of biomass feedstocks without changes to design, process or switching in operational methods.[11,22–25,56]

3.4.5 Comparison of various biomass biogas plant technologies of India for use with USW or agro-residues: Batch and semi-continuous anaerobic digestion systems are two widely used techniques for bioenergy conversion of organic fraction of USW in developing countries like India. Batch digestion systems are the simplest ones to use owing to their ease of application, operation, moderate investment and associated maintenance costs. The analysis of the performance of various types of anaerobic digesters developed, pilot or field tested based on various parameters reported in literature in the context of India is presented in Table 2. In addition, problems faced in operating (including VFA fluxes) are explained based on the changing physical, chemical and fermentation properties determined by laboratory studies on these feed stocks. The fermentation strategy is explained in terms of the ability of the process or design to address difficulties/obstacles challenging anaerobic decomposition of biomass constituents (physical, chemical and biological) while positioning them for use in small towns/decentralized locations in metropolises of India. Problems in fermenting USW biomass are short-listed to be

a. floating nature of USW constituents,
b. large particle sizes impeding ideal loading or fermentation rates
c. VFA fluxes during initial decomposition stages inhibiting methanogenesis
d. difficulties in designing manual feeding/spent biomass removal to enable continuous operation (grid independent operation)
e. significant variations in USW constituents and their properties during the year and the vulnerability of the process to this fluctuations.

From literature a comparison on the 5 chosen and the most promising processes/design are being made as seen in Table 2.

3.4.6 KVIC derived design: There are many variants of the original KVIC design and processes that are adapted to use processed urban solid wastes (USW). Owing to the fact that a large part of the feedstock is highly decomposable, many of the cattle dung digester designs are adaptable to finely ground USW, a few soft agro-industrial wastes, etc. The decomposition pattern of various biomass feed stocks have been studied and fractions remaining non-decomposed have been monitored.[43,44] Very little floating matter is found in the digester when kitchen waste is blended with

Table 2: Basic features of five types of biogas plants capable of using biomass that have been developed for India.[43,44]

Parameter and units	TERI	BARC	PFR	SSB	KVIC
Size of the reactors (m^3)	Pilot	8–100	3–180	6	5–100
No of reactors operated (No)	1	10	15	5	>50
Period of longest uninterrupted operation (d)	300	1460	1825	1825	>1000
Biomass (k-kitchen, FW-food wastes, ss = source segregated)	K/FW	K/FW	ssUSW	ssUSW	K/FW
Pre-processing (if any, So-sorting, Sh-shredding)	So + Sh	So + Sh	N	N	So + Sh
Feed stock size reduction if any (blending/pulverizing)	Y	Y	N	N	Y
Particle size permissible in feed (mm)	<25	<15	<300	<300	<15
Daily Feed rate (kg fresh/m^3/d)	50	20	12	12	10–12
Daily Feed rate (kg dry/m^3/d)	2–4	2	2	2	1.0–1.5
Total SRT (d)	6.66	12–18	35	35–40	35
Source of original inoculum	CDS	CDS	CDS	CDS	CDS
Start-up time (days)	NA	60	30	30	NA
Aceticlastic rate mL gas/hr/g or mL reactor	NA	NA	14.96*	14.9*	0.5
H_2-oxidative Methanogenic activity (mL/g or ml/reactor)	NA	NA	5.8*	5.8*	0.5
Gas production rate (m^3/m^3/d)	2.5	0.5	0.4–0.6	0.4–0.6	0.5–0.8
Specific gas yield fresh (m^3/kg)	0.045	0.06	0.05–0.08	0.08–0.1	0.05
Specific gas yield dry (m^3/kg TS)	0.45	0.3–0.4	0.5	0.35	0.4–0.5
VS conversion/transformation (%)	NA	NA	75–80	70–80	70–90
Methane content (%)	70–75	62–67	65–70	65–70	50–65
Gas storage	NA	MS drum	balloon	MS drum	MS/Fl
Inlet	NA	C pipe	Masonry	Masonry	AC.pipe
Outlet	NA	C pipe	Masonry	Masonry	AC.pipe
Liquid recirculation if any	Y	Y	N	Y	N

[CDS-cow dug slurry, c-pipe-concrete pipe, AC-asbestos-cement pipe; MS-mild steel, BM-biomass: KVIC-Khadi and Village Industries Commission (Indian Floating drum type); TERI-The Energy and Resources Institute; BARC-Bhabha Atomic Research Centre; PFR-Plug Flow Reactor, SSB-Solid-state Stratified Bed].

water to form a paste and fed into the reactor. The concept of a slurry based biogas reactor is thus easily extended to this feed stock because the composition of the ingredients when collected close to dwellings or market yards resembles that of the older cattle dung and this feedstock can be fed as a slurry when fresh.[24,25,54,102] With such feed stock, a large VFA flux is typical where the acidogenic rate is about 8–10 times higher than methanogenesis at typical operating temperatures in the range of 20–30°C.[103] This allows overall loading rates (OLR) not exceeding 1–1.5 kg VS/m^3/d after which VFA accumulation is found to occur in the digesters and alternatives need to be found to operate beyond this VFA feed rate. As a result of this mismatch between acidogenesis, methanogenesis and buffering capacity of the feedstock, a large number of these plants have feed rates in this region. Most of the popular small plant designs are based on this principle. The gas produced has most often been used as a substitute to LPG in the kitchen[43,44] or more recently for street lighting which allows "island" type operation and does not need grid synchronization (Bangalore/Pune city).

3.4.7 TERI (TEAM) process: This design consists of separate acidogenic and methanogenic phases. Typically segregated urban waste is shredded, processed and fed into one of the six acidogenic digesters as a single batch. The acidogenic phase involves a batch operated system where digester liquid contents are recycled frequently during 6 d HRT. For small operation 6 such acidogenic digesters are employed. Liquid is recycled within the acidogenic digester for 6 d HRT to allow VFA accumulation and thus methanogenesis is suppressed. The spent feed from the acidogenic reactor is taken to a dewatering platform and further dried to compost. After the acidogenic phase the liquid containing VFA from the digester is pumped to a locally developed Upflow anaerobic sludge blanket reactor (UASB) module for conversion to biogas and resultant methane production. During this cycle of 6 d HRT, the content of one reactor is emptied into the UASB module. Gas yields reported range from 130–260 l/kg TS depending upon the decomposability of the feed stock tried.[66]

BARC process: This process (named Nisargarun process) uses a thermophilic, microaerophilic acidogenic stage of 2–6 d HRT and a simple CSTR type mesophilic methanogenic stage with a 10–12 d HRT.[100] The major feed stock tried in most of the locations using this process has been food and kitchen wastes arising from industrial type canteens and more recently segregated USW. The heat energy to maintain thermophilic acidogenic stage is derived from the use of solar water heaters that provide hot water to create slurry of the incoming food waste blended in a 5–10 HP blender. The use of a thermophilic micro-aerophilic acidogenic stage greatly reduces the SRT required for the acidogenic stage. After a 2–6 d HRT, the digested material is pumped to simple mesophilic CSTR based methanogenic stage. With food wastes the yields are reported to be in the range of 300–400 l/kg TS fed. The key factor is the use of a simple blender that converts the food waste to slurry form with water and the use of a thermophilic micro-aerophilic acidogenic stage that greatly hastens the digestion process. It is critical that tender biomass capable of being converted to a slurry is used. Pre-segregation of USW is thus essential for its satisfactory operation. Today there are large plants that can take between 1–2 t/d feed rate. The biogas produced is stored in a balloon and gas is used for street lighting.

As seen in the earlier section, the potential capability for high rates of conversion is limited by the fermentation properties of biomass feedstock which in turn limits the variety and capabilities of the causative micro-organisms that can function under the ensuing physico-chemical and fermentation environment. Therefore these two factors narrow down the potential to create processes with high conversion rates, as is possible with soluble feedstocks. This limit is further narrowed by how much intact and unprocessed biomass can be fed to the digester or held in the digester. For example, to build digesters for rural India where grid electricity is either unreliable or simply not available for powdering biomass, one strategy is to build digesters and processes that can function on unprocessed biomass feedstocks and they are fed intact into digesters. Under such a situation, the physical properties of feedstocks, such as the packing density, limits how much biomass can be held within a digester to about 300–400 kg wet biomass (50–65 kg dry solids/m^3). Assuming a 30–35 d SRT required, the feed rates then become limited to 1.7–2.2 kg TS/m^3/d. At this biomass feed rate, the maximum biogas production expected would be between 0.4–0.6 m^3 biogas/m^3 digester/d (m^3/m^3/d). The low feed rate that limits the level of outputs makes high digester efficiencies difficult to achieve. The biomass biogas plants, being more complex than animal waste biogas plant designs are therefore expected to be between 1.25–1.5 times higher in cost for the same extent of biogas produced (installation costs as Rs/m^3/d capacity). Making such processes sustainable merely on the basis of conversion efficiency, rates of conversion and cost of installation are therefore not possible and alternatives need to be found (as discussed in the following sections).

4 Sustainability and Addressing Sustainability Issues

Cooking in over 90% of rural, nearly half of peri-urban and a fifth of urban homes is generally done in smoky, soot-filled and often dark kitchens in simple cook stoves that burn fuel-wood incompletely and inefficiently causing a lot of smoke to be produced that spreads into nearby areas *[discussed in another paper—Energy Access, P. Balachandra in this volume]*.

4.1 *Biomass biogas plants and their role as a sustainable technology*

As indicated above cooking in a majority of rural (about 90%) and peri-urban houses and a fifth of urban homes is carried out under drudgery filled conditions marked by dense wood smoke, soot laden walls and dark kitchens. This occurs because woody fuel used is burnt incompletely and inefficiently leading to a lot of smoke.[83] Constant inhalation of this smoke brings about various health issues and while spending about 2–4 h/d for its collection is the cause of drudgery, especially to women. Low quality fuels such as dried animal dung, crop residues, twigs and branches, etc. are burnt and they tend to produce a lot more smoke while their over-extraction has been considered a threat to the local green cover. This constitutes the environmentally related sustainability threat that needs to be overcome in addition to threats to health and the larger dimension of sustainable development. Such a high dependence on fuel-wood as the main energy source for this activity, cooking has often been considered as a threat to the green cover emerging from a demand for wood and threatening a rapid loss of tree cover (>200 Mt/yr in India)[104] Fuel wood based cooking is the single largest need for energy in rural areas *(Ungra Studies)*[105] accounting for about 30–40% of primary energy use at a country level[104] and therefore at a national and regional level forms the single largest threat to the environmental segment of sustainability. During the 70's and the 80's the continued extraction of fuel wood at such rates were considered to threaten the sustainability of the tree cover over India and therefore science and technology alternatives that reduced this threat were urgently required. Biomass biogas plants overcomes the earlier mentioned limitations to the number of rural Indian households who can run biogas plants—unlike the limited supply of cattle dung, fermentable herbaceous biomass is in adequate availability to be used sustainably by each household in most parts of India. This, therefore, in technology terms, can offer a sustainable solution to meet cooking energy needs and also allows for sustainable development of the region while overcoming threats to green cover. One of the primary requirements is to establish that there are adequate biomass resources to ensure continued and sustainable use in rural India.

4.2 *Biomass availability and resource sustainability*

Biomass, defined as all land and water-based vegetation as well as organic wastes, fulfilled almost all of humankind's energy need prior to the industrial revolution. In the present day scenario, once again its utilization for generation of energy has gained importance because, firstly it is renewable and can be raised sustainably without net addition of CO_2 to atmosphere. Further, in an agriculturally dominant land use as in India, biomass is available over the entire spread of the country. In this context the main types of biomass include non-woody agro-residues, herbaceous plants or grasses/shrubs, terrestrial and aquatic weeds and to some extent animal wastes. India is rich in biomass resources and the overall biomass generation from agricultural sources is 399 Mtpa. The surplus biomass has been estimated to range widely from 125 Mtpa[106] (*only crop residues*) to about 500 Mtpa (*total surplus biomass*).[21] Various types of biomass available in India and their biogas production potential are shown in Table 3. Other types of leaf biomass such as parthenium, napier grass, sea weeds, etc also have a good biogas production potential but have not been estimated in detail.

4.3 *Sustainability issues addressed by anaerobic digestion and biogas plants*

As indicated in the previous section, alternative options to make biogas plants sustainable and economically attractive have been considered necessary. One strategy would therefore be to create value added by products from digested residue, surplus gas or digester liquid and value all other advantages appropriately for their triple bottom line sustainability indices including GHG emission avoidance.

4.3.1 N recovery and recycle: One of the earliest sustainability threats in agriculture has been the shortage of N in soils and therefore the resulting shortfall in crop productivity. In response, one of the earliest S&T approaches to handling this shortage has been to increase the efficiency of N recycling by adopting anaerobic fermentation of agro-residues to anaerobic compost.[3,5,6] Beginning from standardization of anaerobic-aerobic composting by the Bangalore method in order to maximize the retention of

Table 3: A few for the biomass types generated in India and their biological methane potential (BMP).

S.no	Name of the crop	Annual production, thousand MT	Type of residue	Total residue available	Fermenter	Biogas potential (m³/kg VS)	Reference
1	Rice	145,050	Husk	29,010	BMP	0.13	107
			Straw	2,17,575	Btach 5L	0.30	108
2	Wheat	78,000	Pod	23,400		–	–
			Straw	1,17,000	BMP	0.30	109
3	Maize	18,500	Cobs	5,500	–	–	–
			straw	37,000	Batch-CSTR	0.34	110
4	Sugarcane	276,250	Bagasse	91,162.50	Batch-CSTR	0.09	111,112
			Leaves	13,812.50	BMP	0.28	109
5	Cassava	6,060	Solid waste	3,636	BMP	0.26	113
			Strach for roots	10,908	Packed bed	0.60	114
6	Cotton	3,000	Boll shell	3,300	–	–	–
			Husk	3,300	BMP	0.09	115
			Stalk	34.9	Two phase	0.37	116
7	Millets	12,410	Stalk	14,892	BMP	0.30	110
8	Coffee	300.3	Husk	150.15	BMP	0.20	117
			Pruning Wastes	1.328	–	–	–
9	Banana	80,000	Residue	2,40,000	BMP	0.28	118
			peel		BMP	0.20	25
10	Coconut	13,125.20	Shell	2887.5	–	–	–
			Husk and Pith	6,956	–	–	–
11	Areca nut	330	Husk	0.857	BMP	0.20	58
12	Bajra	7,690	Cobs	2,537.70	–	–	–
			Stalks	2307	BMP		110
13	Barley	1200	Stalks	1,560	BMP	0.23	118
14	Coriander	250	Stalks	287.5	BMP	0.31	119
15	*Syndrella*	–	Leaf	–	BMP	0.48	54
16	*Parthenium*	–	Leaf	–	BMP	0.39	54
17	Paper mulberry	–	Leaf	–	BMP	0.51	54
18	*Acacia auriculiformis*	–	Leaf	–	BMP	0.20	68
19	Cabbage	6,148	Leaf	–	BMP	0.02	25
20	Orange	–	Peel	–	BMP	0.05	25
21	Bamboo	–	Leaf	–	BMP	0.10	25
22	Teak	–	Leaf	–	BMP	0.10	25
23	News print	–	Paper	–	BMP	0.10	25
24	*Jacaranda*	–	Leaf	–	BMP	0.2	65

N in the composting mass (about 85%) and capture of the remaining ammonia by a layer of soil spread over it, to latter times up to the 1960s (trying to achieve the same via biogas plants), the facilitation of near 100% N recycle from farm wastes back to the crop has been achieved. Thus a long standing sustainability threat of that period has been addressed and overcome by the first generation biogas plants although it may be said that the number of users who adopted did not lead to a measurable sustainability due to various reasons. These plants have the ability to recycle N produced daily in various domestic and farm wastes could now be recycled from year to year with very little losses. Obviously, towards the 70's with the advent of synthetic fertilizers, this interest was lost. Today, as we have begun to consider alternatives to fossil-fuel derived N, recycling farm and domestic level plant nutrients through biogas plants can provide an appreciable level and an excellent opportunity to manage N and other plant nutrient containing wastes produced on a daily basis and store it for a period until the next crop is sowed. Being an organic source of N, there is hope that the efficiencies of crop uptake will also be high.

4.3.2 Anaerobic fermentation of leaf and animal wastes: As shown earlier, much of the early research at various R&D institutions early last century and persisting up to the 60s and 70s has been to find a method to conserve all the N available in day to day wastes as well as agro-wastes and return it completely to soil. Today as the cattle system is fast losing importance, biomass biogas plants have the potential role of converting most rural biomass to energy and N-and plant nutrient rich organic manure (compost) with the least level of N-losses and thereby addressing N conservation and sustainability issues. Thus technology readiness exists and needs to be translated to practice.

4.3.3 Hygiene and rural sanitation: Animal wastes are produced daily in villages. The practice of storing them in the open and allow open air composting has been implicated to be one of the root causes of a large number of insects vectors and epidemics, especially flies and mosquitoes in rural India. The sanitation and hygiene drives that began in the middle of last century emphasized the daily removal of animal dung and the need for processing it away from access to flies and mosquitoes. Processing them anaerobically through biogas plants has been widely publicized to avoid the fly and mosquito menace and resultant epidemics. Early in the campaigns for biogas plants one of the virtues of biogas plants has been shown to be reduction in the number of insects—flies and mosquitoes in villages with biogas plants. In fact it has been constantly emphasized that the digested slurry does not attract flies.[1,120]

4.3.4 Gas and lighting: Between the 60s and 80s a major push for biogas plants were the ability of biogas plants to provide clean cooking gas, some farm power and assured lighting. This was considered the route to sustainable development (CST, ASTRA formation document, 1975). Large biogas plants have also been shown to enable farm mechanization and provide a fuel for pumpsets and making agriculture more reliable. Predominant among these is the emphasis on mantle lighting systems along with cooking.[1,5,9,82]

4.3.5 Cooking gas, energy security and protection of the green cover: During the period between 1970 to mid 1990s, biogas plants were considered as a renewable and locally controlled energy source that could catalyze 'sustainable development' and met various criteria of sustainability as articulated today. Many grid independent villages were created which were provided basic development catalyzing energy services such as domestic lighting, reliable drinking water supply powered by biogas, essential commercial options such as flour milling etc. These initially fitted the need of a 'vehicle' for "sustainable development" measured predominantly with the then societal understanding of rural development, conservation of environment (maintaining green cover—the crisis of that period), empowered local users—especially women and removed their drudgery as also freeing girl children from the burden of gathering fuel—wood and fetching water and enabling them education. These systems were partially sustainable in economic terms—recovered the O&M costs. Advocates of community biogas plant systems saw that the complete village level collection and processing of animal wastes provided cooking gas as well as energy security measured in terms of reliable illumination, safe water supply, flour milling, etc. and even combated the "tragedy of Commons".[8,9] The achievements were also measured by yardsticks such as to how much fuel wood was not burnt in the village and thereby sustained green cover.

4.3.6 Cooking gas, rural development: After the mid-80s till now, biogas plants have been promoted to provide clean cooking gas. Clean cooking gas without accompanying drudgery has been considered an important index of sustainable rural development where rural women who worked more than 14 h/d could now avoid about 5–6 h/d of drudgery because biogas based rural energy utilities such as cooking gas, domestic water supply and home illumination (all through biogas) clearly alleviated drudgery, allowed girl children to go to school all of which led to sustainable rural development.[17,19,20]

4.3.7 Energy security and livelihoods: Modern biomass based biogas plants such as the plug flow reactors, discussed earlier in this paper, not only meets the primary cooking energy needs but various technology development efforts have gone on to ensure that the three main by-products of the biomass based biogas plants could provide reliable, year-round livelihoods to biogas plant users—particularly women and local enterprises. Simultaneous accrual clean energy as well as women's empowerment objective makes the sustainability outcomes to be broad based and meeting the triple bottom line yardsticks for sustainability. The potential outputs from a biomass biogas plant are captured in the Figure 6 below.

Biomass based biogas plants have several additional uses and applications that can make the use of these biogas plants in rural India economically attractive, provide livelihoods, socially empowering and environmentally sustainable because a lot of value added outputs can be produced even from very limited resources and valuable plant nutrients needed for sustaining the ecosystems need not be 'exported'. In the absence of export of primary products of land and only value added products on the other hand including gaseous fuels addresses one of the key sustainability issues of loss in soil fertility through export of plant nutrients [*discussed in paper on soil sustainability—Parama and Munawery*].

While, the animal dung based biogas plants could address only nutrients carried in animal wastes, the modern biomass based biogas plants can address the larger nutrient management in plant biomass itself. These biogas plants like any other animal dung plants provide biogas and anaerobic compost. In addition, surplus gas can be used for pico-power power generation (SI mode), grain silo fumigation, CO_2 enrichment in nurseries etc. The digester liquid (after filtration) is a good source of pest repellent, feed for algal-fish pond etc. The digested biomass is a good feedstock for mushroom cultivation, vermicompost, inoculant carrier, seed preservation, methanogenic biofilm support etc (Figure 6). After recovering these value added products there is still adequate organic fraction left to be added to soils as humus and compost.

Not all cellulose and lignin is converted to biogas and around 40–50% of the initially fed biomass feedstock is recovered undigested. Considering the short life of organic carbon it is possible to make variety of value added products based on the end users choice, available resources skills and markets. By developing mass balances for each of these options, the sustainability threats, the possible way out and nutritional balance is now possible to show that local decisions can enhance the choice of technologies and use these biogas plants as a key-stone technology.[11]

4.3.8 Decentralized energy production and energy security with green fuels: Future focused development planning along current understanding of sustainability and sustainable development as well as a low-C development path suggests that it is possible for typical rural farmers to not only raise crops much in the same way that they are doing now (to meet food security) but also convert some of the surplus biomass to various gaseous fuels, especially biogas and provide significant levels of energy security to the village, region and country. This can create a low-C development path. Today a large part of biomass residues are neither

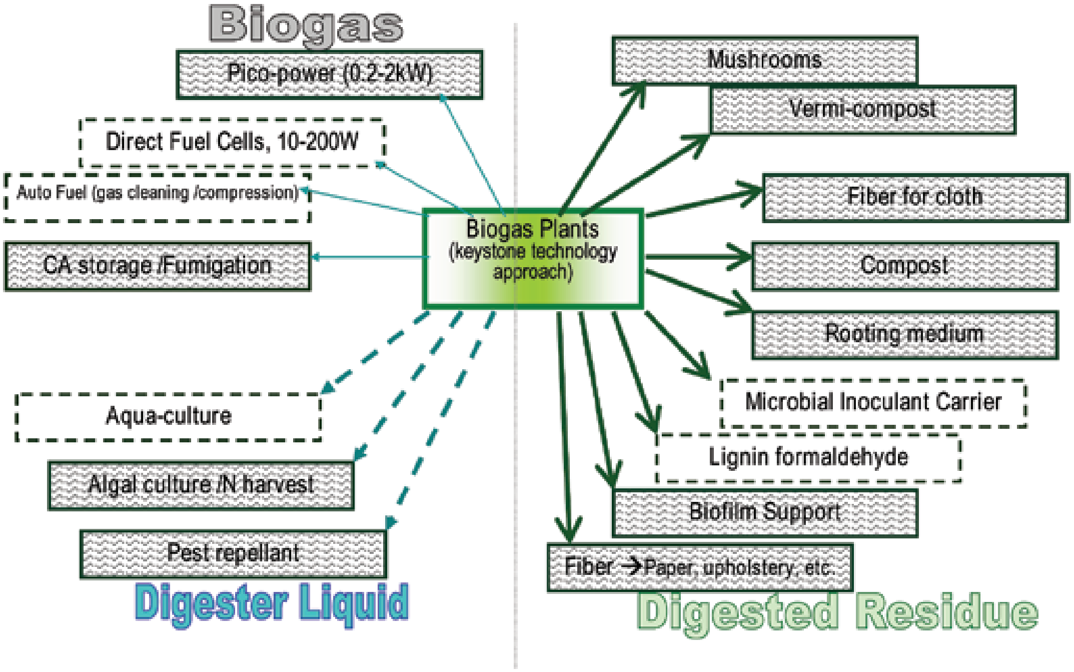

Figure 6: The sustainability of the biomass biogas plants have been greatly enhanced and made broad-based by making it possible for the potential user to generate over 15 possible routes to sustainable livelihoods and strengthening the local agriculture as well. The boxes shaded in grey are technologies developed at CST.[11]

collected or processed for value added products and often set fire as an easy route to recover plant nutrients from them as ash. Sugarcane trash (15 t/ha/yr), paddy straw (>4 t/ha/crop in North India), banana stems (75–100 wet tons/ha/yr), etc. are well known examples. A lot of weeds harvested from crop and wastelands are not even accounted for. These form valuable biomass resources that are amenable for conversion to a high value auto-fuel such as SNG. Decentralized production of biogas could be collected on to a gas grid and enable surplus gas from rural areas to be sent to peri-urban and urban areas after meeting the local energy needs. This approach can provide a clean development path that is also people friendly, rewards people producing clean fuel, and makes the triple bottom-line sustainability conceivable and consider it achievable (Figure 7).[17] If each family in a village can have a biogas plant which can be fed with 15 kg/day biomass, then 6 m^3/day of biogas can be produced by one family out of which 1 m^3/day can be used for their daily cooking needs and the rest 5 m^3/day can be sold to village methane co-operatives that functions similar to milk co-operatives. This means that 50 million rural families in India can produce 70–100 million tons of oil equivalent energy in a decentralized manner without pollution. Much of the required technologies are already available or have been field tested. Biogas and ancillary technologies then can also meet future sustainable auto fuels.

4.3.9 Gender dimensions of biogas for cooking and a means of hygiene in India: Cooking with fuel wood gathered from the village common land has always been a complicated situation in a village household in terms of health issues and time wasted. Cooking with fire wood results in smoke and over a period of time this leads to health issues. Anaerobic digesters (biogas plants) can provide a complete solution to this with smoke-less cooking and also the time spent by the village women in collecting fire wood for cooking can be invested in feeding and maintaining the biogas plant. By replacing a typical dung based biogas plant with biomass based biogas plant would not only provide hygienic cooking conditions but can also turn out to be a source of income for cash strapped women. For the success of a biomass based biogas plant it is important that there should be a convenient and assured biomass supply. Biomass based biogas plant (fed with any type of leaf biomass, oil seed cakes, weeds etc.) would not only provide biogas for cooking, sale and other uses but also compost and other products (Figure 6). A lot of by products of the biogas plants provide outputs that can be used within the village, empowering women who work on it and process these by-products. A biogas stove burns efficiently transferring about 55% of the heat in the burning gas to the cooking vessel. This also makes the cooking process very quick, around 30 minutes even in a rural home. This leaves sufficient time to women for other gainful pursuits.

4.4 *Future work: Need for new feedstocks and fermentation concepts*

The interspecies microbiological, physico-chemical and molecular exchanges are still poorly understood. Making better biomass biogas plants require that we understand and utilize the same to achieve better

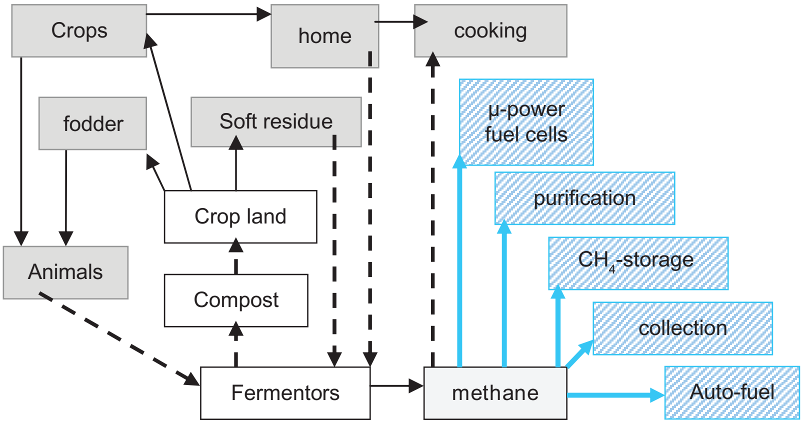

Figure 7: Existing and proposed flow of soft residues and methane.
Note: S&T interventions required to develop and sustain methane production are depicted in the blue boxes with bold blue arrow links. Many of these are at advanced stages of dissemination or field trials and provide livelihood uses in rural areas that are vital for sustainability and climate resilience. Boxes in light gray and links in dotted lines are emerging or existing situation and resource use centers.

process control and improvements in performance. Although a lot of metagenomic techniques have been used to identify taxa and organisms present, the roles, function and efficiencies need to be assessed and incorporated into processes. Knowing that one species succeeds another with digestion, the exact mechanisms which facilitate these microbiological successions need to be determined and managed to obtain stable processes. Quite often, the physico-chemical and environmental regimes required for various actors in the process have a very narrow overlap—and this needs to be widened by facilitating greater species and function redundancies in order to make the process a lot more rugged and functional in a wider range of physico-chemical and environmental determinants.

The number of stable continuous AD processes for biomass feedstock digestion is few and for a large scale harness of AD in order to provide sustainable energy for all a greater number of AD processes and corresponding digester designs need to be evolved. New fermentation concepts and AD processes with simple to install biogas plant designs for biomass are required. Pre-fabricated biogas plants that can be assembled by the user and started quickly are needed to speed up the spread of AD and biogas plants in India. In continuation of the keystone technology approach for biogas plant, along with new plant designs, a large number of end-use devices as well as by-products of the biogas plants are needed to make the biogas plants meet a larger number of aspiration and usefulness among end-users, and energy services and needs in villages. Creating a large livelihood base around biogas plants will strengthen the much needed economic and social components of sustainability. A few of such technologies could be a. lifeline electricity for entrepreneurship in villages, b. off-the-shelf micro AD composters for household level USW/garden wastes processing, c. technology chain for creating village level gas grid for SNG equivalent gas, d. a larger basket of by products for local and urban uses and e. creating local livelihoods.

The direct benefits of biogas plants to biogas plant users are not easily monetized today, and therefore biomass biogas plants and its large scale and rapid spread will remain unattractive unless remunerations reach users quickly. In today's market scenario, greater monetary benefits accrue from by products and emissions avoided. Therefore there is a need to create business and enterprise packages that bundle CO_2 emissions avoided, the livelihood products created and marketed, the financing of the biogas plants, daily sale of surplus methane, etc. The sharing of benefits needs to be bundled into small-scale enterprises whose profitability would require effective functioning and use of these biogas plants and large scale use would inherently increase sustainability in the region while providing sustainable energy for all.

5 Conclusion

Anaerobic digestion and biogas plant technology has been evolved and partially deployed to meet several sustainability crises for over a century in India—largely in rural and agricultural sectors. For nearly a century, anaerobic digestion and biogas technology focused conserving a labile set of plant nutrients in farm wastes and convert it into a storable, stable and low loss "anaerobic compost" most suited to farmsteads and subsistence farming. However, over the last three decades biogas plants have been deployed to provide renewable energy along with a sustainable development focus. The spread of this technology has reached about 40% of possible users and has had <50% functional plants (survival) 10 years after installation. Firstly, it is good for a technology to be in use so long in a system of rapid technological obsolescence and at the same time is not good that it has hardly made sufficient inroads to local and rural enterprises both for technology and energy services. To meet the energy needs of another 80–110 million rural households another sustainable energy technology with multiple benefits is required. The emergence of the technology of biomass based biogas plants along with potential for providing many livelihoods from its by-products, provides a promise to firstly meet the larger goal of "sustainable energy for all" because it uses widely available non-dung crop residues, agro-wastes and weeds as the sole feedstock without interfering with other biomass uses. This approach can firstly meet a very large rural population, address/answer several of the of the environmental, social and economic triple bottom-line sustainability criteria. However, this needs to be spread in a different way compared to the ones done earlier to be firstly successful and second to become popular and used in a wide-spread use to ensure overall sustainability is achieved. R&D needs to be carried out to improve the underlying process, make it rugged, widen the basket of marketable by products, provide for much larger set of possible livelihood technologies so that it becomes empowering to use them in a large scale. Finally, there is a need to consider new marketing strategies, such that using typical villages/village clusters as functional units, create healthy enterprises that keep large numbers of such plants operating and share the benefits with the users.

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H.N. Chanakya has a PhD in Microbiology from UAS Bangalore and has been working in the field of anaerobic digestion of rural residues, wastewater and solid wastes as well as drinking water purification for over 30 years at the Centre for Sustainable Technologies, Indian Institute of Science, Bangalore. He has developed over eight technologies in the field of sustainable energy and water. In the area of wastewater his research interests lie in evolving low energy and sustainable wastewater/grey water treatment coupled to energy and nutrient recovery including the use of mixotrophic algae. He also helps the Karnataka State in an advisory capacity for its mandatory and regulatory bodies in the area of wastes and wastewater management.

Sreesha Malayil has a bachelor's degree in Biotechnology from VTU, Karnataka and has been carrying out research on the anaerobic digestion of various fibrous biomass feed stock for multiple outputs such as fiber, compost, pest repellant and biogas for the last four years. She has designed and disseminated domestic scale biogas plants for household wastes. Her interests lie in providing metagenomic, molecular and biochemical understanding of the process of anaerobic fiber extraction in biomethanation plants and optimizing the overall process.