Assessment of sustainable non-plantation biomass resources potential for energy in India

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Abstract

In India, fuelwood, crop residues and animal manure are the dominant biomass fuels, which are mostly used in the rural areas, at very low efficiencies. Industrial and municipal (urban) residues such as wastewater, municipal solid wastes (MSW), and crop residues such as rice husk and bagasse can also be used for energy generation. In this paper, the potential of energy from crop residues, animal manure, MSW, industrial wastewater and biomass fuels that can be conserved for other applications through efficiency improvement is discussed. The total potential of energy from these sources in 1997 is estimated to be equivalent to 5.14 EJ, which amounts to a little more than a-third of the total fossil fuel use in India. The energy potential in 2010 is estimated to be about 8.26 EJ.

Keywords: Animal manure; Biomass; Fuelwood conservation and substitution; Sustainable energy

1. Introduction

In India, biomass fuels dominate the rural energy consumption patterns, accounting for over 80% of total energy consumed [1]. Fuelwood, crop residues (including plantation crops) and livestock dung are the biomass fuels used in rural areas. Fuelwood is the preferred and most dominant biomass source accounting for 54% of biofuels used in India [1]. Scarcity and increasing prices of fuelwood have been altering the biofuel consumption pattern. Due to scarcity of fuelwood, people are shifting to dung and various crop residues. The use of biofuels in domestic devices is associated with drudgery and adverse health impacts on women [2]. In most rural houses, the fuel use efficiency in domestic devices, particularly cook stoves, is low, in the range of 10–14% [1]. Thus, improving the conversion efficiency would be a significant step towards improving the quality of

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life and environment. Efforts are already under way to promote efficient devices and alternate energy sources for improving the quality of life and conserving biomass resources.

The urban energy demand in India is largely met by modern sources of energy such as electricity, LPG and kerosene. The urban population accounts for nearly one-fourth (25.7%) of the total population and is growing at a faster rate than the rural population in India. The population in the urban areas is likely to double by 2010, while the quantity of Municipal Solid Wastes (MSW) generated is expected to triple [3]. Thus, the disposal of solid and liquid streams is one of the major emerging environmental problems of urban India and requires large investments. As significant part of these materials is organic in nature, they could be effectively harnessed as feedstock for producing gaseous fuel and electricity. With growing industrialization, the industrial residue generation has also been growing; these could also be harnessed for energy generation.

The biofuel usage has changed over the years, particularly in urban areas. Even though there has been a shift from biomass fuels to fossil fuels and electricity in the urban region, the annual biofuel consumption in domestic sector at the national level is still high and has increased continuously from 206 million tonne (Mt) during 1953–54 to 383 Mt in 1996–97. Fuelwood meets more than half of the energy requirements for cooking and domestic water heating in the rural households while, it accounts for about one-third of the energy requirement in urban households [4]. Dung cake accounts for about 4% and 21% of the urban and rural energy requirements, respectively. Use of crop residues is restricted only to the rural areas as they are not available in the urban centres. Even though the share of biomass fuels in the national energy use is declining, the magnitude of fuelwood, crop residues and even cattle dung is projected to increase [5].

2. Sustainable national biomass resource potential

It is important to estimate total crop residue, cattle dung, MSW and industrial wastewater generated annually, their current usage levels and potential surplus available for energy use. Hence, the focus of this paper is to assess the energy potential of biomass resources in the form of residues and wastes, i.e. biomass from non-plantation sources in India with the following specific objectives: (i) to estimate total crop residue, cattle dung, MSW and industrial wastewater production, (ii) to estimate the fraction of crop residue, cattle dung and MSW, industrial wastewater available as energy source, and (iii) to assess the fuelwood conservation and substitution potential through shift to improved stove and kerosene/LPG, respectively.

The methodologies used to estimate the energy potential of the biomass sources are presented elsewhere [6].

2.1. Agricultural crop residues

For assessing the crop residues for energy potential it is imperative to understand the area under agricultural crops, cropping patterns and utilization of crop residues.

2.1.1. Area under agricultural crops and cropping pattern

In India, out of the total geographic area of 328 million hectare (Mha), the net cropped area accounts for about 43% and it appears that the net cropped area has stabilized around 140 Mha since 1970 [7]. However, the gross cropped area has increased from 152.8 Mha in 1960 to about 168.6 Mha in 1996–97 and is likely to reach 178.2 Mha by 2010. In India there are two main cropping seasons, namely Kharif (based on south-west monsoon) and Rabi (north-east monsoon). Gross cropped area includes land areas subjected to multiple cropping (normally double cropping) in irrigated land. Net irrigated area has increased substantially from 24 Mha during 1960–61 to 55 Mha by 1996–97. Rice and wheat are the dominant crops, together accounting for 41% of cropped area, while pulses, oil seeds and other commercial crops account for 13.8%, 15.9% and 10.2%, respectively. Cereals dominate the agricultural crops as shown in Table 1 [8,9] and account for 60% of cropped area, followed by pulses, cotton and sugarcane.

Out of 140 Mha of net-cropped area, more than 50% is estimated to become irrigated by 2010. It has been observed that the adoption of irrigation practices results in expansion of crops such as rice, wheat, cotton and sugarcane. It is estimated that expansion of irrigation by 2010 may result in increase of area under the above said crops by 6% (>10 Mha) at the cost of coarse cereals and millets. These changes would also influence production of crop residues in the future.

2.1.2. *Agricultural crop residue production*

The residue production varies from crop to crop. The data on the residue to product ratio (RPR) are given in Table 1. The straw to grain ratio of the cereals varies from 2.5 for maize to 1.6 for wheat. Straw, a low-density residue, is the dominant residue. Rice husk, a by-product of rice milling, accounts for 20% of paddy. Unlike the cereals, crops such as red gram, cotton, rapeseed, mustard, mulberry and plantation crops produce woody (ligneous) residues. Residue production for mulberry, coconut and sugarcane were estimated based on field studies [1,9].

The total crop residue production in India during 1996–97 is estimated to be 626 Mt of air dry weight (Table 1). The dominant residues are those of rice, wheat, sugarcane and cotton accounting for 66% of the total residue production. Sugarcane and cotton residue production is 110 and 50 Mt, respectively.

2.1.3. *Current use of crop residues*

The use of crop residues varies from region to region and depends on their calorific values, lignin content, density, palatability and nutritive value. Residues of most of the cereals and pulses have fodder value. However, woody nature of residues of a few crops restricts their use to fuel purpose only. The dominant end uses of crop residues in India are as fodder for cattle, fuel for cooking and thatch material for housing.

India has a large cattle population of 294 million. Even though India has 67 Mha of grazing land, grass productivity is low due to land degradation, leading to near total dependence of cattle on crop residues of cereals and pulses. The estimated total residues utilized as fodder was 301 Mt in 1996–97 and is projected to be 385 Mt for 2010, accounting for about 47% of total residues generation as shown in Table 2 [8,9]. Use of some crop residues as fodder is the priority in rural areas and only ligneous residues are likely to be available for use as an energy source.

In India, dung use as fuel is wholly restricted to the domestic sector, while crop residues are used as fuel in both domestic and industrial sectors. Ligneous and hardy crop residues namely, rice (husk), maize (cobs) and stalks of redgram, cotton, mulberry, coconut fronds and shells are mainly used for fuel purpose. About 44 Mt of sugarcane bagasse is used as fuel in sugar mills, and in small-scale crude rural sugar producing units. The total residue use as a fuel in India during 1996–97, as indicated in Table 2, is estimated to be 216 Mt and the projected value for 2010 is 278 Mt [9,10]. Reported estimates of different types of biomass used as fuel is given in Table 3 [1,5,11].

In addition to use of crop residues as fuel and fodder, the residue of some crops are used for thatching, composting, mulching, etc. Rice and wheat straw, and coconut fronds are used to a small extent for thatching in the rural areas. Non-woody leguminous crop residues are normally put into the composting pit after the harvest of the main produce. The leafy residue of sugarcane is burnt in the field. The total crop residue used for other purposes amounted to 109 Mt in 1996–97 and is projected to rise to 172 Mt by 2010 (Table 2).

2.1.4. *Availability of crop residues for energy generation*

Crop residues, which are used as fodder, will not be available as feedstock for energy. The total potential of non-fodder crop residues available for energy is estimated to be 325 and 450 Mt for 1996–97 and 2010, respectively (Table 4). Only the woody (ligneous) crop residues, rice husk and bagasse are considered for energy.

2.2. *Animal manure*

India has the world's largest bovine population and recorded 294 million during 1996–97

Table 1
Area under different crops and their respective residue production in India

Crop	Economic produce	1996–97			2010			Residue to final economic produce ratio	Type of residue	Moisture %	
		Gross cropped area (Mha)	Total economic production (Mt)	Total residue production Mt (air dry)	Gross cropped area (Mha)	Total economic production (Mt)	Total residue production Mt (air dry)			At harvest	At use
Rice	Food grain	43.3	81.3	146.5	46.1	118.8	213.9	1.8	Straw + husk	30	10
Wheat	Food grain	25.9	69.3	110.6	28.5	98.5	157.6	1.6	Straw	30	10
Jowar	Food grain	11.6	11.0	22.3	5.3	6.1	12.2	2.0	Stalk	30	10
Bajra	Food grain	10.0	7.9	15.8	8.6	6.8	13.6	2.0	Stalk + cobs	30	10
Maize	Food grain	6.2	10.6	26.3	6.6	13.0	32.5	2.5	Straw	30	10
Other cereals	Food grain	4.3	4.7	9.4	1.3	1.4	2.8	2.0	Stalk	30	10
Red gram	Food grain	3.6	2.7	13.5	3.6	2.7	11.2	5.0	Waste	20	10
Gram	Food grain	7.1	5.7	9.3	7.7	7.0	13.5	1.6	Waste	20	10
Other pulses	Food grain	12.5	5.8	17.1	12.5	5.9	17.1	2.9	Shell + waste	20	10
Ground nut	Oil seed	7.9	9.0	20.7	9.3	12.2	28.1	2.3	Waste	30	10
Rape seed & mustard	Oil seed	6.9	6.9	13.8	10.7	12.0	24.1	2.0	Waste	20	10
Other oil seeds	Oil seed	12.1	9.1	18.2	18.0	13.5	27.1	2.0	Waste	20	10
Cotton	Fiber	9.1	14.3	50.0	10.1	15.9	55.7	3.5	Seeds + waste	20	10
Jute	Fiber	0.9	9.8	15.7	0.6	6.5	10.5	1.6	Waste	30	10
Sugar cane	Sugar	4.2	277.2	110.8	5.5	463.5	185.4	0.4	Bagasse + leaves	30	30
Coconut + arecanut	Oil + confectionery	2.0	—	20.0	2.8	—	28.2	$10\,t\,ha^{-1}\,yr^{-1}$	Fonts	20	10
Mulberry	Silk fiber	0.3	—	3.0	0.3	—	3.3	$10\,t\,ha^{-1}\,yr^{-1}$	Sticks	20	10
Coffee + tea	Beverage	0.7	0.8	3.42	0.8	1.0	3.9	4.0	Twigs + branch	30	10
Total		168.6		626.5	178.2		840.6				

Source: [8,9].
Note: (1) Horticultural crops occupying in smaller area is not accounted. (2) For the year 2010, the area and productivity are projected based on the data from 1951 to 1995.
(3) Sugar cane biomass accounted for leaves and bagasse.

Table 2
Quantity of agricultural residues used as fodder, fuel and for other purposes in India (Mt)

Crop	1996–97			2010		
	Fodder	Fuel	Others[a]	Fodder	Fuel	Other[a]
Rice	119.9	16.3	10.4	173.0	23.8	17.2
Wheat	101.8	0	8.8	136.2	0.0	21.4
Jowar	22.3	0	0	12.3	0.0	0.0
Bajra	15.8	0	0	12.3	0.0	1.4
Maize	21.1	5.3	0	26.4	6.2	0.0
Other cereals	9.4	0	0	2.8	0.0	0.0
Red gram	0	13.5	0	0.0	8.8	2.4
Gram	0	7.3	2.0	0.0	13.5	0.0
Other pulses	0	8.6	8.5	0.6	8.3	8.2
Ground nut	0	4.1	16.6	0.0	3.7	24.4
Rape seed and mustard	0	13.8	0	0.0	24.1	0.0
Other oil seeds	0	18.2	0	0.0	27.1	0.0
Cotton	0	50.0	0	0.0	55.7	0.0
Jute	0	15.7	0	0.0	5.9	0.0
Sugarcane[b]	11.1	44.3	55.4	21.9	76.0	87.5
Coconut + arecanut	0	16.0	4.0	0.0	22.6	5.6
Mulberry	0	3.0	0	0.0	3.3	0.0
Coffee + tea	0	0	3.4	0.0	0.0	3.9
Total	301.4	216.1	109.2	385.4	278.7	172.0

Source: [8,9].
[a]Others include biomass used for composting, left in the field for thatching, etc.
[b]Sugarcane biomass includes for both leaves and bagasse on dry weight basis.

Table 3
Biomass use as fuel in India (Mt)

Reference	Fuelwood			Crop residues			Dung		
	1990	1995	2010	1990	1995	2010	1990	1995	2010
FAO [11]	172	197	241	—	—	—	—	—	—
Sarma et al. [5][a]	—	214	381	—	67	132	—	64	98
Ravindranath and Hall [1]	298	—	—	156	—	—	114	—	—

[a]Only combustible crop residues and dung used as dung cake are accounted.

(including cows, bullocks, buffaloes and calves), with cattle to human population ratio of 0.3. Cattle accounts for more than two-thirds of the bovine population, while buffalo account for 28.6% [1,12,13]. The population of goat and sheep is 169 million. Estimated populations of cattle and buffalo for 2010 are 224 and 97 million, respectively. Interestingly, the piggery and poultry industry has grown substantially in the last two decades in an organized way and hence manure from these would have a great potential for energy in the future.

Dung production depends on the cattle population and dung yield per animal. All the dung produced by cattle is difficult to collect and use. In India, the cattle are allowed to graze in open fields and hence, dung produced during grazing and working periods cannot be collected. Bullocks are largely used as draft animals for agricultural operations including rural transport and the dung cannot be collected. Hence, the dung collection would be mostly from droppings at the cattle sheds. Improved cows and buffalo are reared for milk production and generally stall-fed; thus, the dung collection efficiency is higher. Dung yield varies with breeds, animal, age, region and season.

Table 4
Amount of non-fodder crop residues potentially available for energy use

Crop	1996–97		2010	
	Mt	PJ	Mt	PJ
Rice	26.7	347	41	532
Wheat	8.8	115	21.4	278
Bajra	0	0	1.4	18
Maize	5.3	69	6.2	80
Red gram	13.5	176	11.2	145
Gram	9.3	121	13.5	176
Other pulses	17.1	222	16.5	215
Ground nut	20.7	284	28.1	384
Rape seed and mustard	13.8	189	24.1	330
Other oil seeds	18.2	249	27.1	371
Cotton	50	750	55.7	835
Jute	15.7	235	5.9	88
Sugarcane	99.7	1562	163.5	2581
Coconut + arecanut	20	300	28.2	423
Mulberry	3	45	3.3	50
Coffee + tea	3.4	51	3.9	59
Total	325.3	4715	450.7	6565

Based on mean annual average dung yield (fresh weight) of 4.5 kg day^{-1} for cattle and 10.2 kg day^{-1} for buffalo, total dung production is estimated to be 659 Mt annually, with cattle dung accounting for 344 Mt and buffalo dung accounting for 315 Mt as shown in Table 5 [12]. The corresponding dung produced from cattle and buffalo for 2010 is estimated to be 368 and 362 Mt, respectively with a total dung production of 730 Mt. The data on availability of animal manure from pig and poultry sectors are not available and not considered in this study. The dung collection efficiency of sheep and goat is assumed to be zero.

2.2.1. *Current dung usage and availability of dung for energy generation*

The data on the present usage of dung and potential availability for various purposes are given in Table 6. About 185 Mt, 40% of the dung collected is used as fuel in cookstoves. The quantity of dung used annually in the existing 2.7 million family type biogas plants—assuming 5 animals per plant is estimated to be 22 Mt. Cattle dung use for biogas has large potential for the future, as only 22% of the total potential for biogas plants is being utilized [14]. Thus, the quantity of dung unused amounts to 251 Mt. If the potential of 12 million family biogas plants, is built by 2010 at the rate of one million annually, 98.5 Mt of dung produced could be used for biogas production. Rest of the dung is likely to be used as manure for crop production.

Table 5
Livestock population, dung production and its availability in India

Year	1996–97			2010		
Animals	Cattle	Buffalo	Total	Cattle	Buffalo	Total
Population (million)[a]	209	84	294	224	97	321
Dung production (kg head^{-1} day^{-1})	4.5	10.2		4.5	10.2	
Total dung produced (Mt yr^{-1})	344	315	659	368	362	730
Dung recoverable percentage (%)	60	80		60	80	
Total dung recoverable (Mt yr^{-1})[b]	206	252	458	221	289	510

Source: [1,12,13].
[a]Population data projected for 2010 using past trends.
[b]Air dry weight.

Table 6
Energy equivalents of available dung as cooking fuel and for power generation

Energy equivalents of available dung	1997	2010
Estimated dung production (Mt)	659	730
Total dung recoverable (Mt)	458	510
Dung directly utilized as fuel (Mt)	185	—
Total dung unutilized and available for energy (Mt)	251	—
Family size biogas plants (Million)	2.7	12.0
Dung utilized in the biogas plants (Mt) (2.7 and 12 million plants, respectively)	22	98.5
Biogas produced (Mm^3) (with 2.7 and 12 million biogas plants, respectively)	780	3448
Energy equivalents of biogas produced (PJ) (from 22 and 98 Mt of dung, respectively)	17.9	80.5
Biogas potential (Mm^3) (if all collectable dung used for biogas, i.e. 458 Mt in 1997 and 510 Mt in 2010)	16030	17850
Energy potential of biogas produced (PJ)	336	374

The potential for family biogas plants in India is 12–17 million, but only 3.65 million plants had been built by 2003. Thus a large potential for family biogas is yet to be utilized. With the existing technology, the potential for biogas production annually is 8750 million m^3 (from 251 Mt of dung). This biogas could be used directly as cooking fuel (183 PJ) or for generation of 11.67 GWh of electricity annually.

2.3. *Fuelwood saving through efficiency improvement and fuel switching*

Fuelwood is the dominant fuel consumed in rural India. Dependency on fuelwood has consequences, firstly on environment due to non-sustainable extraction from forests, village commons and farms and secondly, on health and quality of life of women. Many projections indicate that rural communities would continue to depend on biofuels in the future while, in urban areas use of biofuels is likely to be insignificant as urban households have access to LPG, kerosene and electricity [1,5]. The scarcity of fuelwood, associated with its high price, necessitates conservation through use of efficient stoves and switch over to other fuels. Hence, in this section, the fuelwood conservation potential through shifting to efficient stoves is estimated by considering only rural households. The feasibility of different biomass conservation options is also discussed in this section. Energy required, efficiency of the fuel-device combinations and fuelwood conservation potential is given in Table 7 [9,15,16].

2.3.1. *Fuelwood conservation potential of improved stoves*

The traditional cookstoves using fuelwood have low thermal efficiencies of about 14% [1,17]. Efficient stove designs with over 30% of thermal efficiency are available and are being intensively implemented in India (Table 7). Field studies have shown that use of efficient stoves results in only about 20% saving of fuelwood compared with traditional stoves due to variation in cooking practices, inadequate user education, lack of repair and improper construction of improved stoves [15]. Nearly 50% of the improved stoves built are non-functional due to physical damage or poor maintenance. The total number of rural households projected to be covered under LPG (13.4 million), kerosene (20.1 million), family biogas (8.2 million) and community biogas (0.031 million) is 42 million by 2010. Thus, all the remaining 89.2 million households could be potentially covered under the improved stove programme. Based on the projected rates of dissemination, the fuel conservation potential of improved cookstoves is estimated to be 25.7 Mt annually by 2010 (Table 8).

2.3.2. *Fuelwood conservation potential in industrial sector*

The industrial biomass use in India include: rice husk use in small restaurants, brick firing and rice

Table 7
Energy required, efficiency of device and fuelwood conservation potential

Device	Consumption ($kg\,HH^{-1}\,yr^{-1}$)	Thermal efficiency of device (%)	Fuelwood conservation potential ($kg\,HH^{-1}\,yr^{-1}$)
Traditional cookstove	1800	14	
Efficient cookstove	1440	33	360
Kerosene stove	159	60	1800
LPG	120	60	1800

Source: [18].
Note: HH—household.

Table 8
Conservation potential by shifting from fuelwood to improved stoves

Technology	By year 2010			Method of estimation
	No of units (Million)	Operational units (%)	Fuelwood conservation (Mt)	
Improved stoves	89.2	80	25.7	89.2 million stoves $\times 1.8\,t\,HH^{-1}\,yr^{-1} \times$ 80% of stoves operational $\times$20% reduction in fuelwood use

Source: [15].
Note: Rural households—114 million in 1990 and 134 million by 2010.

parboiling; sugarcane bagasse use as fuel in sugar mills and jaggery (crude sugar) manufacturing units; and fuelwood for brick industry in rural areas and in urban establishments.

Fuelwood use in industrial sector is largely for brick industries and in urban establishments. Based on the current utilization pattern of biomass in energy sector, the overall efficiency of utilization is in the range of 10–15%, while utilization efficiencies in excess of 25% can easily be achieved. Thus, the savings could be up to 50% [1] compared to the prevailing situation. The total fuelwood use in the industrial sector is estimated to be 16 Mt. The fuelwood conservation potential by shifting to improved brick kilns is estimated to be 8 Mt (120 PJ) (Table 9).

2.3.3. *Fuelwood substitution potential of kerosene*

A national level study estimated that during 1991, 7.1% (8 million) of rural and 23.6% of urban households were dependent on kerosene for cooking [9,18]. Though, the first cost of biomass-fired stove is low, its use in urban areas is restricted due to high cost of biomass fuels compared to conventional fuels and poor supply or distribution network. With increase in rural incomes, about 15% of households (20.1 million) are projected to shift to kerosene for cooking from biofuels. Thus, the fuelwood conservation potential of shifting to kerosene is 36 Mt annually by 2010 (Table 10).

2.3.4. *Fuelwood substitution potential of LPG*

LPG is an ideal fuel for cooking. Currently, it is restricted to urban areas (27% of households). In the absence of LPG supply and servicing network and its shortages, it is unlikely that rural households will have access to LPG in the near future [9,18]. Further, high initial cost of cylinder and stove is beyond the reach of majority of rural households. However, about 10% of rural households on the fringes of urban centres may shift to LPG by the end of the decade. The annual

Table 9
Biomass conservation potential in industrial sector of India

Biomass	Quantity used (Mt)	Potential for improvement (%)	Potential for conservation (Mt)	
			Mt	PJ
Fuelwood[a]	16	50	8	120

Source: [1].

[a]Fuelwood use includes 6 Mt for brick industry in rural areas and 10 Mt in urban fuelwood use in establishments.

Table 10
Substitution potential of shifting from fuelwood to LPG and kerosene

Fuel	No of households likely to shift by 2010 (million)	Fuelwood conserved (Mt)	Method of estimation
LPG	13.4	24	13.4 million HH $\times$ 1.8 t fuelwood $HH^{-1}\ yr^{-1}$
Kerosene	20.1	36	20.1 million HH $\times$ 1.8 t fuelwood $HH^{-1}\ yr^{-1}$

Note: Rural households—114 million in 1990 and 134 million by 2010.

fuelwood conservation potential would be 24 Mt by shifting from conventional wood stoves to LPG by 2010 (Table 10).

The total fuelwood substitution potential of kerosene and LPG, assuming moderate growth rate is 60 Mt annually by 2010.

2.4. Municipal solid wastes

Generation of municipal wastes is not significant in rural areas. In this paper, we have considered the energy potential of solid waste generated by urban population only.

Municipal solid waste is normally collected, transported and dumped in the outskirts of towns and cities. Though sorting out for the recyclable materials by the rag pickers is common, other ways of handling, like composting, incineration, etc., also take place to some extent. The total quantity of solid wastes generated in larger towns and cities has been estimated at 20.7 Mt annually for an urban population of 217 million in 1991. This is expected to increase to 40 Mt by 2001 and reach 56 Mt by 2010 [19] as the urban population is increasing at a decadal growth rate of above 40%. The quantity of wastes generated per family in a week has also increased substantially from 7 kg during 1980s to 20–30 kg at present. The data from Table 11 reveals that MSW production per capita increases with the size of the urban centre and is highest for cities with a population greater than 5 million. In India, based on 1991 census data, the estimated quantity of MSW generated in 10 major cities is more than 10 Mt annually. The disposal of such huge quantities has become a major problem. Thus, the utilization of MSW for energy would mean a solution of this problem.

The MSW consists of glass, metal, paper, rubber, and other combustible organic matter. The organic matter component is of relevance to energy, particularly biomethanation. Paper plus other combustible matters together account for nearly 50% of MSW in urban areas [20].

2.4.1. Energy from landfill gas (LFG)

According to the Central Pollution Control Board (CPCB), the area under landfills in India has increased from 120 ha in 1947 to 20,200 ha in 1997. Unlike developed countries, in developing countries like India, the landfill system is not very prominent and well managed. Hence, it is not practicable to collect the methane, which escapes

Table 11
Quantity of MSW generated (collected) annually in India

Population range (Million)	MSW per capita ($kg\,capita^{-1}\,day^{-1}$)	Towns	MSW per town wet wt (kt) [22]	At national level wet wt (Mt)
0.1–0.5	0.21	272	33 ± 2	9.0
0.5–1.0	0.25	32	63 ± 11	2.0
1.0–2.0	0.27	15	120 ± 24	1.8
2.0–5.0	0.35	5	417 ± 128	2.1
>5	0.50	5	1729 ± 499	8.6
Total		329		23.5

Table 12
Energy potential from landfill gas of MSW

MSW generated ($Mt\,yr^{-1}$)	Quantity land filled @ 0.85% of total MSW ($Mt\,yr^{-1}$)	DOC content in MSW @ fraction 0.17 ($Mt\,yr^{-1}$)	Dissimilated DOC fraction (Mt) @ 0.77	Fraction of CH_4 ($Mt\,yr^{-1}$)	Energy value $PJ\,yr^{-1}$
23.5 Mt (1997)	20.0	3.40	2.61	1.73	86
56 Mt (2010)	50.4 @90%	8.56	6.59	4.38	219

DOC—degradable organic carbon.

into the atmosphere from waste dumps, either for flare or use as a source of energy. Systems need to be developed to collect methane and generate energy.

The total MSW generated in 1997 was 23.5 Mt. Based on the MSW collected in 5 large cities, the average MSW landfilled is about 85%. The estimated energy potential of landfill gas in the year 1997 is about 86 PJ (Table 12). It has been assumed that 90% of the MSW generated will be landfilled in 2010. The estimated energy potential of LFG in the year 2010 is 219 PJ.

Development of a landfill system for energy recovery would be a good option in warm climatic conditions of India. A system can be developed for successful collection and transportation of the MSW and efficient energy generation. An economic feasibility study has been done by IGIDR for Mumbai city [21]. For a total population of 10 million producing 1.82 Mt of MSW per year, the net methane that can be produced is equivalent to about 8.5 GJ. In the proposed landfill system, the disposal cost of solid waste varies from 222 to 566 $Rs\,t^{-1}$. In the conventional waste management system the disposal cost is estimated to be 4054 $Rs\,t^{-1}$.

2.5. *Industrial wastewater*

In addition to MSW, large quantity of wastewater is generated in certain industrial plants like breweries, sugar mills, distilleries, food-processing industries, tanneries, and paper and pulp industries. Out of this, food products and agro-based industries together account for 65–70% of the total industrial wastewater in terms of organic load [22]. Table 13 gives the estimate of wastewater generated in India by industries.

Conventional digesters such as anaerobic continuous stirred tank reactors (CSTR) have been used in India for many decades in sewage treatment plants for stabilization of the activated sludge and sewage solids. In recent times, the emphasis has shifted to high-rate biomethanation systems such as Upflow Anaerobic Sludge Blanket (UASB), fixed films, etc.

Table 13
Energy potential from wastewater in India

Industries	Wastewater produced (Mm^3)	COD of waste water ($kg\,m^{-3}$)	Energy value of CH_4 (TJ)[a]	
			1997	2010[b]
Distillery	6000	118.00	2973.60	105,138.00
Steel plants	1,040,000	0.60	936.00	92,664.00
Paper and allied products	7200	0.72	7.73	765.55
Sugar industry	230	2.30	0.79	78.56
Cotton	1550	0.60	1.40	138.11
Fertilizers	52	2.00	0.16	15.44
Refinery	15	0.30	0.01	0.67
Dairy	206	1.35	0.42	41.38
Pharmaceuticals	56	0.39	0.03	3.24
Coffee	1.3	2.80	0.01	0.55
Edible oil	1425	4.50	9.62	952.26
Total	1056,730		3,929.76	199,797.75

Source: [25,26].
Notes: The IPCC default value of 20% is considered as the fraction of wastewater treated in anaerobic systems. For distillery, 56% is considered based on literature.
[a]Methane producing capacity of 0.15 kg CH_4/kg COD for wastewater was considered.
[b]During 2010, the fraction of wastewater treated in anaerobic systems is assumed as 90% and wastewater production to increase proportionately to the population increase by 2010.

The world's first full-scale UASB demonstration plant for municipal wastewater was built in Kanpur, Uttar Pradesh in 1989 under an Indo-Dutch project and has been in operation since then. The plant is designed to treat 5 Ml day^{-1} domestic wastewater and the reported biogas yield is 0.1–0.15 $m^3\,kg^{-1}$ COD removed with a methane content of 75–80% [23].

2.5.1. *Characteristics of industrial water*

A total of 11 major industries have been considered for estimation of energy potential from industrial wastewater in India (Table 13). A total of 1.057 Tm^3 of wastewater is produced from these industries during 1997. The COD values of the wastewater generated were collected from published reports and books. The fraction of wastewater that was treated anaerobically for the different industries has been considered as 20% [24], except for distilleries, where 57% of the wastewater is treated in India (Table 13). An energy equivalent of 3.9 PJ can be produced by the industrial wastewater generated. For estimating the energy potential by 2010, it is assumed that 90% of the wastewater will be anaerobically treated and wastewater production will increase in proportion to the population increase. Accordingly, the energy potential will be 200 PJ (Table 13).

3. Concluding remarks

The energy value of agri-residues and other wastes, which include cattle dung, landfill gas (MSW) and industrial wastewater, is given in Table 14. The total energy potential in 1997 is estimated to be about 5.14 EJ, amounting to a little over a-third (at 39%) of the total energy value of fossil fuels used during 1996–97 (13.23 EJ). The estimated total biomass energy potential in 2010 is 8.76 EJ. Fossil fuel substitution potential of biofuels is complex to determine, as it depends on: (i) the type of energy replaced (heat or electricity or mechanical energy), (ii) efficiency of fossil fuel system substituted, (iii) efficiency of bioenergy system and the conversion process, (iv) quantity of commercially available residue, and (v) technologies, costs and policies.

Table 14
Energy potential of agri-residues and other wastes in India

Source	PJ	
	1997	2010
Crop residue	4715	6565
Dung	336	374
Landfill gas	86	219
Industrial wastewater	4	200
Biomass conservation	—	506
Biomass substitution	—	900
Total	5141	8764

The biofuels can be burnt as a source of heat energy, converted to gaseous fuels for heating or cooking and ultimately converted to electricity. For example, cattle dung can be dried and burnt directly as solid biofuel in a cook stove for heating or cooking or it can be converted to biogas through anaerobic digestion and used as gaseous fuel as a source of heat for cooking and finally, biogas can be converted to electricity. The fossil fuel substitution potential is likely to be different for different conversion process or end uses. Further, some of the crop residues as well as other non-plantation biomass may not be available for modern bioenergy or the quantity of non-plantation biomass that can be collected or utilized commercially is not known. It is important to note that technical potential estimated in this study has to be viewed with caution due to data limitations.

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