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Biochemical methane potential of fruits and vegetable solid waste feedstocks

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Abstract

The biochemical methane potential of 54 fruits and vegetable wastes samples and eight standard biomass samples were determined in order to compare extents and rates of their conversion to methane. All the samples were obtained fresh, grown in nutrient enriched environment and belonged to mature age group. The ultimate methane yields (B_0) and kinetics of fruit wastes ranged from 0.18 to 0.732 l g^{-1} VS added and 0.016 to 0.122 d^{-1}, respectively, and that of vegetable wastes ranged from 0.19 to 0.4 l g^{-1} VS added and 0.053 to 0.125 d^{-1}, respectively. Temperature had no effect on the B_0 of mango peels; however, the conversion kinetics were higher at 35°C than at 28°C. All the samples of fruits and vegetable wastes tested gave monophasic curves of methane production. Substantial differences were observed in the methane yields and kinetics among the varieties in mango, banana and orange. Different fruit parts within the same variety showed different yields in orange, pomegranate, grape vine and sapota. The methane yields from the mango peels of some of the varieties, orange wastes, pomegranate rotten seeds and lemon pressings were significantly ($P < 0.05$) higher than the cellulose. Methane yields and kinetics of vegetable wastes in different varieties as well as within different plant parts of the same variety differed. Onion peels exhibited yields significantly ($P < 0.05$) similar to cellulose, while majority of the vegetable wastes exhibited yields greater than 0.3 l g^{-1} VS. These results provide a database on extent and rates of conversion of fruits and vegetable solid wastes that significantly contribute to organic fraction of municipal solid wastes (OF-MSW).

Keywords: Fruit wastes; Vegetable wastes; Methane yield; Methane production rate; Biochemical methane potential assay; OF-MSW

1. Introduction

Fruits and vegetable solid wastes (FVSW) represent a potential energy resource if they can be properly and biologically converted to methane. They are renewable and their net CO_2 contribution to the atmosphere is zero. Over 60×10^6 tons of fruits and vegetables are produced annually in India, of which only 1% is processed in the fruit and vegetable processing industries [1]. FVSW are transported to municipal dump sites and Mata—Alvarez et al. [2] have referred these wastes as organic fraction of municipal solid waste from a separated collection (SC-OF MSW). According to Gunaseelan [3], some of the earlier reports on anaerobic digestion (AD) of FVSW were carried out in 1–5 l batch digesters and continuously stirred tanks reactors (CSTR). The source of the FVSW were from commercial processing factories [4–9] which represent only 1% of the annual production in India. Methane yields of some of the FVSW were to be calculated from the data reported. Only

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limited data is available on the biochemical methane potential (BMP) and conversion kinetics of FVSW. The objective of this investigation was to determine the BMP of several fractions of FVSW and to provide a database to compare the extent and rates of conversion of various FVSW to methane.

2. Materials and methods

2.1. Feedstock

Fresh samples of FVSW were obtained from the vegetable market, domestic kitchen of the author and fruit juice shops, Coimbatore, India (Table 1). The samples belonged to 'mature' stage of growth and were grown in nutrient–enriched and irrigated environmental conditions. Standard biomass samples of sorghum and napiergrass were obtained from the Millet Breeding Station, Tamilnadu Agricultural University, Coimbatore. Microcrystalline cellulose powder marketed by Burbidges and Co., Bombay-13, India, was used as positive control. All the samples except cellulose were dried at 60°C, ground in a blender to pass through 2 mm mesh and stored at 4°C until used.

2.2. Seed inoculum

Inoculum was obtained from a 5 l mesophilic (35°C), CSTR, daily fed at a loading rate of 2 g volatile solids (VS) l^{-1} d^{-1} with a hydraulic retention time of 20 days. Mixture of vegetable wastes served as feed for the CSTR. Performance of the fermenter was stable with an average methane yield of 0.32 l g^{-1} VS added. The average total volatile fatty acids (VFA) and pH of the effluents were 180 mg l^{-1} as acetic acid and 7.8, respectively.

2.3. BMP assay

Methane production rate constants (k) and ultimate methane yields (B_0) were determined using the method of Owen et al. [10] with a few modifications. The composition of the basic nutrient medium was as outlined by Owen et al. 0.5 g total solids (TS) of each sample was added to a 135 ml serum bottle along with 75 ml of the nutrient and seed inoculum solution. An inoculum concentration of 20% (v/v) was used for each assay. All media preparations and transfers were performed in an atmosphere of nitrogen and carbon dioxide (70:30, (v/v)). Sealed bottles were inverted and incubated at 35 ± 1°C after the air in the head space is sucked out by using a vacuum pump. Samples were run in triplicates and controls included inoculum, cellulose and standard biomass (Sorghum and napier grass).

2.4. Analytical methods

TS , VS, VFA (steam distillation method) and pH were determined by standard methods [11]. Assay bottles were periodically analyzed for gas production and composition for 100 days. Gas production was determined with a glass syringe by the volume displacement technique [12]. The methane content of the biogas was determined using a Chemito model 8510 gas chromatograph with dual thermal–conductivity detectors. The stainless steel column was packed with Porapak Q. Injector, oven and detector temperatures were 100°C, 50°C and 200°C, respectively. The nitrogen carrier gas flow was 30 ml min^{-1}. The methane volumes were corrected by subtracting the mean methane volume of the inoculum control and were converted to standard temperature and pressure (STP, 0°C and 760 mm Hg). Methane yields were calculated by dividing the corrected methane volume by the weight of sample VS added to each bottle.

2.5. B_0 and k

The degradation of each sample was assumed to follow a first-order rate of decay. Thus, the production of methane was assumed to follow the equation

$$B = B_0\ (1 - e^{-kt}),$$

where B is the cumulative methane yield at time t. B_0 was assumed to equal the final B (after 100 days of fermentation). k was estimated by taking the reciprocal of the time from the start of the BMP assay until when B equaled $0.632B_0$ [13].

2.6. Statistical methods

Student's t-test was used to test the significance of differences between two sampling means [14].

Table 1
Fruits and vegetable solid wastes used in BMP assays

S. no.	Sample name	Varieties	Part used as feedstock	Sample source
1	*Mangifera indica L.* (Mango)	Neelum, killimukku, banganapalli, mulgoa, chenthuram, kudaduth and imampasand.[#]	Peels of fresh riped fruit	DK
2	*Musa paradisiaca L.* (Banana)	Robusta, rasthali, virupakshi, red banana, poovan, naadan, nendran and karpuravalli.[#]	Peels of fresh riped fruit	DK
3	*Citrus sinensis* Osbeck (Tight skinned sweet orange)	Mosambi	Peels of fresh riped fruit	DK
			Pressings (residue from the pressing of juice from cores)	FS
4	*Citrus reticulata* Blanco (Loose skinned mandarin)	Nagpur mandarin	Peels, seeds, whole rotten fruit	DK
			Pressings	FS
5	*Citrus limon* Burm. f (Lemon)	*	Pressings	FS
6	*Achras sapota L.* (Sapota)	Culcutta round	Peels, whole rotten fruit	DK
7	*Ananas sativus L.* (Pine apple)	Mauritius	Peels, leafy shoot	FS
8	*Punica granatum L.* (Pomegranate)	Bassein seedless	Peels, rotten pulpy seeds, whole rotten fruit,	DK
			Pressings	FS
9	*Vitis vinifera L.* (Grape vine)	Muscat (Panneer)	Pressings	FS
			Peduncle (stalk of grape bunch)	DK
10	*Lycopersicon esculentum* Mill (Tomato)	Var. Pyriforme (Pear tomato) Var. Commune (Common tomato)	Whole rotten fruit	VM
11	*Abelmoschus esculentus* (L) Moench (Ladies finger)	*	Fibrous stalk trimmed from the vegetable	DK
12	*Allium cepa L.* (Onion)	Bellary red	Exterior peels	DK
13	*Solanum tuberosum L.* (Potato)	Irish potato	Peels	DK
14	*Solanum melongena L.* var. esculentum (Brinjal)	Striped purple coloured brinjal	Stalk, whole fruit (Pest infested)	DK
15	*Coriandrum sativum L.* (Coriander plant)	*	Leaves, stems, roots, whole plant	VM
16	*Brassica oleracea L.* var. capitata L. (Cabbage)	Tight round headed cabbage	Leaves, stem	VM
17	*Brassica oleracea L.* var. botrytis L. (Cauliflower)	Tropical type	Leaves, stem	VM
18	*Brassica rapa L.* (Turnip)	White fleshed turnip	Leaves	VM
19	*Rhaphanus sativus L.*(Radish)	Pale pink, yellowish white	Leaves	VM
20	*Beta vulgaris L.* (Sugar beet)	Garden Beet	Leaves	VM
21	*Pisum sativum L.* (Garden pea)	*	Pods (seeds removed)	DK
22	*Daucus carota L.* (Carrot)	var. sativa	Leaves, petiole	VM
23	*Sorghum bicolor* (L) *Moench* (Sorghum)	Sweet Sorghum (CO 26)	Lamina, sheath, inflorescence with flowers, inflorescence with grains, roots.	MBS
24	*Pennisetum purpureum Schum* (Napiergrass)	CO 3	Lamina, sheath	MBS

[#] Varieties name mentioned in South Indian vernacular; [DK] domestic kitchen; [FS] juice fruit shop; [VM] vegetable market; [MBS] millets breeding station.

*not determined.

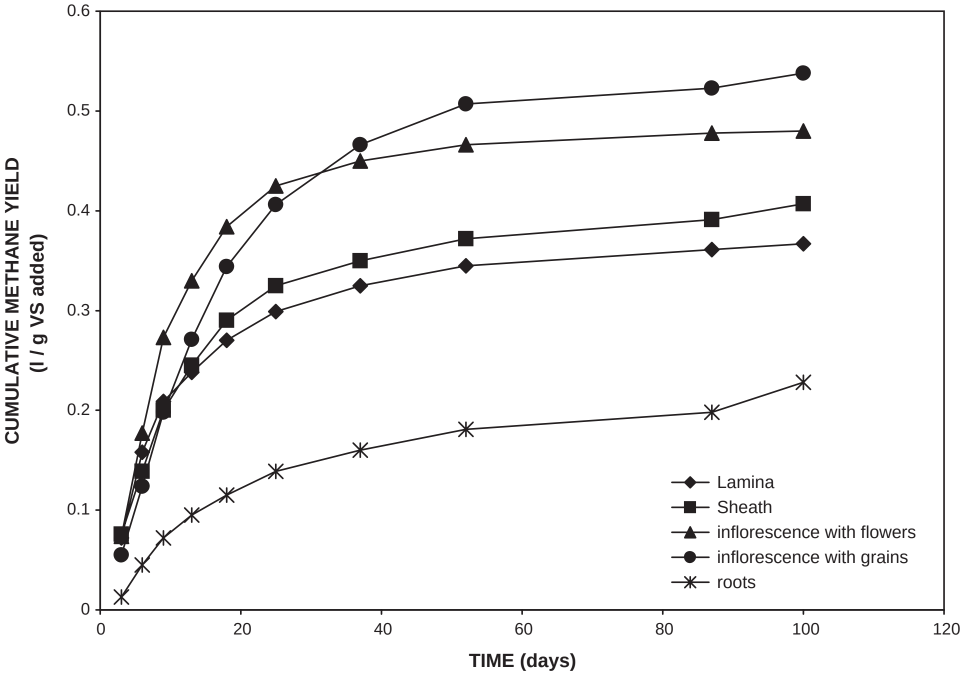

Fig. 1. BMP of different plant parts of sorghum.

3. Results and discussion

3.1. Standard biomass and cellulose

The corrected cumulative methane yield from sorghum (Sweet sorghum) (Fig. 1 and Table 2) showed that B_0 from leaf sheath (stem) was higher than lamina. Inflorescence with flowers and grains exhibited the highest yield. B_0 from roots were significantly ($P < 0.05$) lower than shoots. Literature data on methane yield from sorghum ranged from 0.28 to 0.42 l g^{-1}VS added from samples containing stems and leaves for a 60 day BMP assay at 35°C. Substantial differences in BMP yields were observed from sorghum varieties [15–17]. Typical BMP profile of napiergrass (Fig. 2 and Table 2) indicated significantly similar ($P < 0.05$) methane yield from Lamina and sheath. In earlier studies, the authors have achieved a BMP yield of 0.19–0.34 l g^{-1} VS added and rate of 0.05–0.16 d^{-1} from napiergrass [17]. Microcrystalline cellulose exhibited slightly higher yield than expected, 0.419 versus a theoretical 0.371 l g^{-1} VS added. Previous measurement of 0.39 l g^{-1}VS and 0.18 d^{-1} were reported from Avicel cellulose by Turick et al. [18] and 0.40 l g^{-1}VS from alpha-cellulose by Richards et al. [16]. All the samples of standard biomass tested gave monophasic curves of methane production and more than 90% of methane yield was achieved between 40 and 50 days of fermentation (Figs. 1 and 2).

3.2. Mango peels

Mango is the leading commercial fruit in India and no other cultivated tropical fruit possesses such an extensive range of varieties. The varieties names mentioned in this study are in South Indian vernacular [19]. A plot of the corrected cumulative methane yields of mango peels (Fig. 3) showed variability in methane yields and rates. Mulgoa exhibited the highest yield while there was no significant difference ($P < 0.05$) in the methane yields of Killimukku, Banganappali, Chenthuram and Kudaduth. The Neelum variety gave a lower yield of 0.37 l g^{-1} VS added. The estimates of B_0 and k for mango peels (Table 3) showed that there was no significant difference ($P < 0.05$) in B_0

Table 2
BMP of standard biomass samples and cellulose

Sample	Volatile solids (% of TS)	Ultimate methane yield ($l\ g^{-1}$VS added)	Methane production rate constant (d^{-1})
Sorghum bicolor (L) Moench (Sweet sorghum)			
Lamina	94.7	0.367 (0.028)^{a}	0.083 (0.004)^{a}
Sheath	91.7	0.407 (0.037)^{b,c}	0.069 (0.003)^{b}
Inflorescence with flowers	96.9	0.480 (0.028)^{d}	0.091 (0.001)^{c}
Inflorescence with grains	97.1	0.538 (0.045)^{d}	0.064 (0.027)^{a,b,c,d}
Roots	72.4	0.228 (0.043)^{e}	0.041 (0.004)^{d}
Pennisetum purpureum Schum (Napiergrass)			
Lamina	94.7	0.372 (0.015)^{a,b}	0.094 (0.009)^{a,c,e}
Sheath	90.6	0.342 (0.011)^{a}	0.107 (0.007)^{e}
Microcrystalline cellulose	99.4	0.419 (0.019)^{c}	0.039 (0.004)^{d}

Figures in parentheses are standard deviations; $^{a-e}$means in columns with different superscript letters differ ($P < 0.05$).

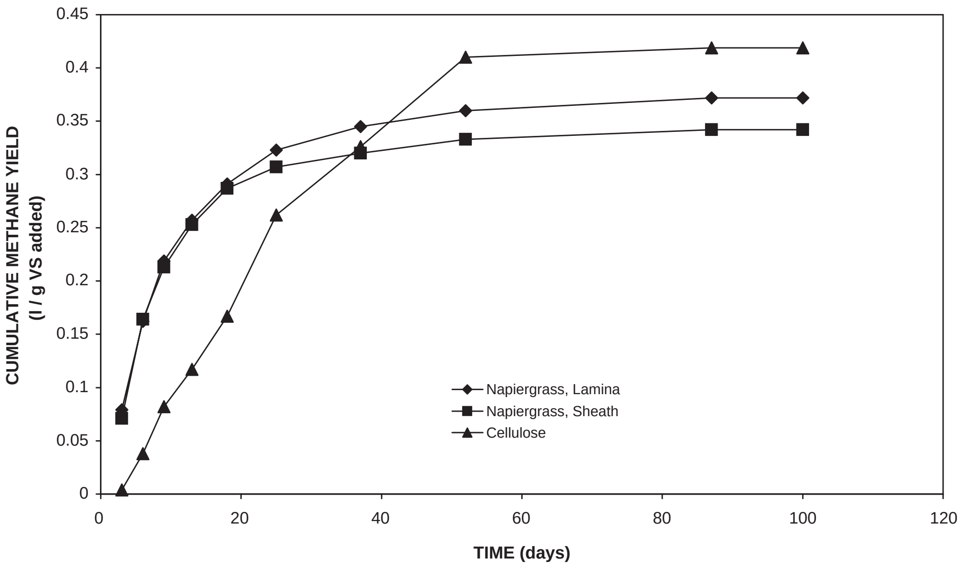

Fig. 2. BMP cumulative methane production of napiergrass and cellulose.

between 28°C and 35°C at a 100 day BMP assay. The methane production rate for mango peels ranged from 0.028 to 0.05 d^{-1}. The B_0 of Mulgoa, 0.523 $l\ g^{-1}$ VS added was higher than cellulose (Tables 2 and 3). All the samples of mango peels tested gave monophasic curves of methane production and more than 90% of methane yield was achieved between 40 and 50 days of fermentation (Fig. 3).

3.3. Banana peels

Banana, one of the most common fruits in India, is cultivated in 384×10^3 ha. The banana variety names are given in South Indian vernacular [20]. BMP profile of banana peels (Fig. 4) showed variability in methane yields. Robusta, Naadan and Virupakshi exhibited similar ($P < 0.05$) but lower yields than

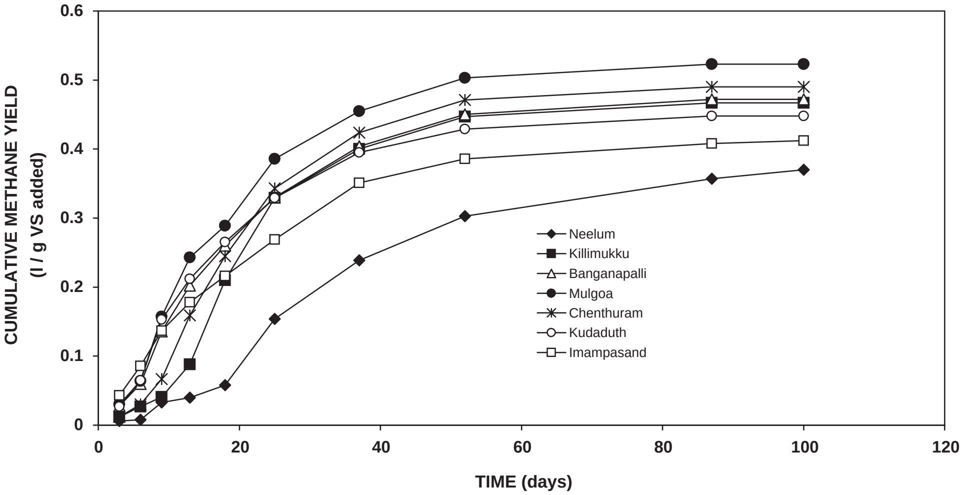

Fig. 3. BMP cumulative methane production of mango peel varieties.

Table 3
Effect of temperature and varieties on BMP of fresh mango peel samples

Sample	Volatile solids (% of TS)	Temperature (°C)	Ultimate methane yield ($l\ g^{-1}$VS added)	Methane production rate constant (d^{-1})
Mangifera indica peels				
Var. Neelum*	98.4	28	0.373 (0.012)^{a}	0.028 (0.001)^{a}
		35	0.370 (0.007)^{a}	0.028 (0.001)^{a}
Var. Killimukku*	97.4	28	0.449 (0.012)^{b,c}	0.036 (0.002)^{b}
		35	0.467 (0.016)^{b,c}	0.043 (0.001)^{c}
Var. Banganapalli*	94.4	28	0.440 (0.015)^{b,c}	0.041 (0.004)^{b,c}
		35	0.472 (0.018)^{b,c}	0.046 (0.003)^{c,d}
Var. Mulgoa*	88.9	28	0.514 (0.013)^{d,e}	0.038 (0.003)^{b}
		35	0.523 (0.018)^{d}	0.048 (0.002)^{d}
Var. Chenthuram*	97.9	28	0.469 (0.014)^{b,c}	0.036 (0.002)^{b}
		35	0.490 (0.008)^{c,e}	0.044 (0.001)^{c}
Var. Kudaduth*	98.3	28	0.448 (0.016)^{b}	0.042 (0.002)^{c}
		35	0.448 (0.014)^{b}	0.050 (0.002)^{d}
Var. Imampasand*	97.4	28	0.403 (0.014)^{f}	0.044 (0.002)^{c}
		35	0.412 (0.010)^{f}	0.041 (0.001)^{c}

$^{a-f}$means in columns with different superscripts differ ($P < 0.05$).
*Varieties mentioned in South Indian vernacular; figures in parentheses are standard deviations.

Poovan, Nendran, Rasthali and Red Banana. The estimates of B_0 and k for banana peels (Table 4) showed the lowest yield and rate for Karpuravalli. However, the methane production rates for banana peels were higher than most of the fruit wastes. Sharma et al. [21] have reported methane yield of 0.223–0.336 $l\ g^{-1}$ VS based on particle size from banana peels in 5 l batch digesters at 37°C with no mention of varieties. All the samples of banana peels tested gave monophasic curves of methane production and more than 90% of methane yield was achieved between 40 and 50 days of fermentation (Fig. 4).

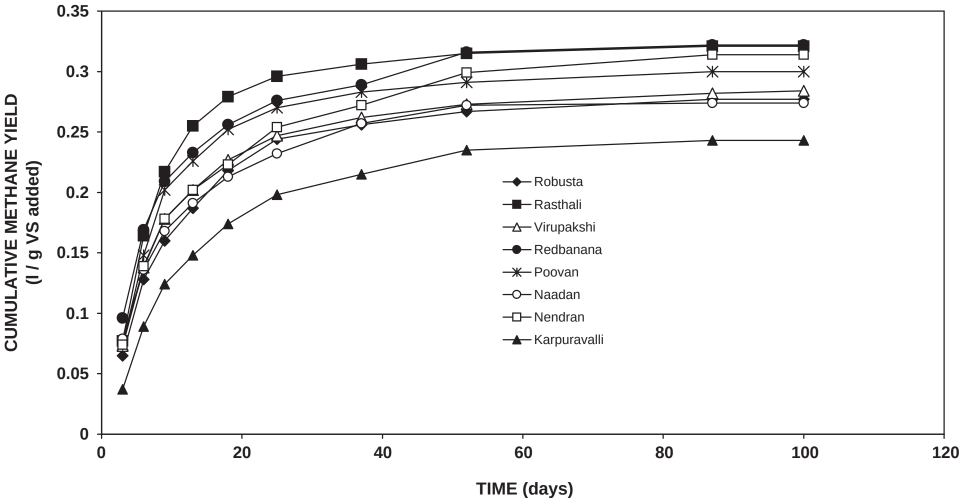

Fig. 4. BMP cumulative methane production of banana peel varieties.

Table 4
BMP of fresh banana peel samples

Sample	Volatile solids (% of TS)	Ultimate methane yield ($l\ g^{-1}$ VS added)	Methane production rate constant (d^{-1})
Musa paradisiaca peels			
Var. Robusta*	86.9	0.277 (0.007)[a]	0.089 (0.005)[a,e]
Var. Rasthali*	93.7	0.321 (0.013)[b]	0.122 (0.006)[b]
Var. Virupakshi*	89.4	0.284 (0.011)[a,d]	0.111 (0.014)[b,d,e]
Var. Red banana*	89.7	0.322 (0.018)[b]	0.117 (0.013)[b,d]
Var. Poovan*	91.4	0.300 (0.014)[a,b,d]	0.120 (0.008)[b,d]
Var. Naadan*	94.3	0.274 (0.009)[a]	0.102 (0.010)[a,d]
Var. Nendran*	91.7	0.314 (0.015)[b]	0.081 (0.012)[a,c]
Var. Karpuravalli*	92.3	0.243 (0.007)[c]	0.071 (0.004)[c]

[a–e]means in columns with different superscripts differ ($P < 0.05$).
*Varieties mentioned in South Indian vernacular; figures in parentheses are standard deviations.

3.4. Citrus wastes

Citrus is an important fruit crop in the South Asian Countries. Of this, the commercially loose skinned mandarin and tight skinned sweet orange are important. The production of citrus in India was 247×10^4 mt in 1989 [22]. The cumulative methane yields from citrus (Fig. 5) showed variability in methane yields and rates among the varieties and also among different fruit parts of a single variety. In the tight skinned orange, the yields from the pressings were higher than the peels ($P < 0.05$) whereas, in the loose skinned mandarin, peels and rotten fruit exhibited similar but higher ($P < 0.05$) yields than the pressings. B_0 and k for the citrus waste samples (Table 5) showed the highest yield and rate for the loose skinned seeds. Lemon pressings gave a yield of $0.473\ l\ g^{-1}$ VS. The yields and rates of all the samples of citrus wastes were significantly ($P < 0.05$) higher than cellulose (Tables 2 and 5). All the samples of citrus wastes tested gave monophasic curves of methane production and more than 90% of methane yield was achieved between 40 and 50 days of fermentation (Fig. 5).

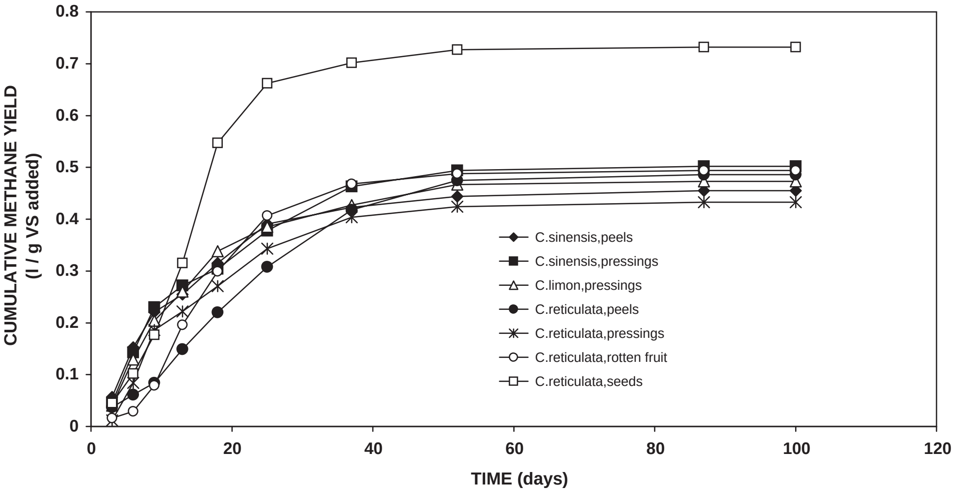

Fig. 5. BMP cumulative methane production of citrus species.

Table 5
BMP of fresh citrus wastes

Sample	Volatile solids (% of TS)	Ultimate methane yield ($l\ g^{-1}$ VS added)	Methane production rate constant (d^{-1})
Citrus sinensis			
(*Tight skinned sweet orange*)			
Peels	94.7	0.455 (0.018)^{a,c}	0.064 (0.004)^{a}
Pressings	92.3	0.502 (0.016)^{b}	0.052 (0.003)^{b}
Citrus reticulata			
(*Loose skinned mandarin*)			
Peels	97.3	0.486 (0.014)^{a,b}	0.040 (0.002)^{c}
Pressings	97.4	0.433 (0.011)^{c}	0.055 (0.002)^{b}
Whole rotten fruit	89.0	0.494 (0.017)^{b}	0.053 (0.002)^{b}
Seeds	94.7	0.732 (0.007)^{d}	0.062 (0.001)^{a}
Citrus limon			
(Lemon)			
Pressings	96.8	0.473 (0.011)^{b}	0.065 (0.001)^{a}

Figures in parentheses are standard deviations; $^{a-d}$means in columns with different superscripts differ ($P < 0.05$).

3.5. Miscellaneous fruit wastes

The estimates of B_0 and k for miscellaneous fruit waste samples [23] (Table 6) showed no significant difference ($P < 0.05$) in the methane yields of pine apple peels and leafy shoot. In pomegranate, different parts exhibited significantly ($P < 0.05$) different yields and rates. The peels gave a yield of $0.312\ l\ g^{-1}$ VS, while the yield from rotten seeds was significantly similar ($P < 0.05$) to the pressing. The methane yield from the entire rotten fruit was significantly similar ($P < 0.05$) to the average of the yields of two components. In grape wastes, the pressings showed a significantly ($P < 0.05$) higher methane yield and rate than the peduncle. In sapota waste, the methane yield and rate from the peels were

Table 6
BMP of fresh miscellaneous fruit waste samples

Sample	Volatile solids (% of TS)	Ultimate methane yield ($l\ g^{-1}$ VS added)	Methane production rate constant (d^{-1})
Achras sapota (Sapota)			
Peels	95.7	0.244 (0.007)[a]	0.085 (0.007)[a]
Whole rotten fruit	95.9	0.327 (0.010)[b]	0.055 (0.002)[b]
Ananas sativus L. (Pine apple)			
Peels	93.2	0.357 (0.007)[c]	0.088 (0.003)[a]
Leafy shoot	94.6	0.355 (0.011)[c]	0.062 (0.005)[b]
Punica granatum (Pomegranate)			
Peels	97.2	0.312 (0.019)[b,e]	0.034 (0.002)[c]
Rotten pulpy seeds	86.8	0.430 (0.018)[d]	0.062 (0.004)[b]
Whole rotten fruit	87.0	0.342 (0.021)[b,c]	0.044 (0.004)[d]
Pressings	97.1	0.420 (0.013)[d]	0.056 (0.001)[b]
Vitis vinifera L. (Grape vine)			
Pressings	93.2	0.283 (0.017)[e]	0.091 (0.007)[a]
Peduncle (Stalk of grape bunch)	88.9	0.180 (0.013)[f]	0.016 (0.003)[e]

Figures in parentheses are standard deviations; [a–f]means in columns with different superscripts differ ($P < 0.05$).

significantly ($P < 0.05$) lower than that of the rotten fruit.

3.6. Vegetable wastes

Methane yield from 23 samples of vegetable wastes [23] (Table 7) ranged from 0.19 to 0.4 $l\ g^{-1}$ VS added and methane production rate from 0.05 to 0.125 d^{-1}. Most of the vegetable wastes showed a methane production rate greater than 0.08 d^{-1}. Rotten tomato, onion peels, pest infested brinjal, lady's finger stalk, coriander plant wastes, cabbage leaves, cauliflower stalk, turnip leaves, radish shoots and green pea pods exhibited methane yields greater than 0.3 $l\ g^{-1}$ VS added. Methane yields from these wastes varied among various varieties and different plant parts of the same variety. In coriander plant wastes, methane yield for leaves was higher than that of structural roots. In a bioassay study [24], the reported methane yield from some vegetable crop residues ranged from 0.08 to 0.53 $l\ g^{-1}$ VS added, but no kinetics were reported.

4. Conclusions

The FVSW mentioned in this study are commonly used in South Indian homes and they form the bulk of wastes originated from domestic kitchen. They are dumped into municipal dust-pins and significantly contribute to the OF-MSW. The BMP of FVSW reported in this study provide an extensive database on the extent and rates of their conversion to methane. This study has demonstrated that substantial differences were observed in the methane yields and kinetics among the varieties of FVSW. Methane yields and kinetics of different plant parts of the same variety differed. Temperature had no effect on the B_0 of mango peels; however, conversion kinetics were higher at 35°C than at 28°C. All the samples of FVSW tested gave monophasic curves of methane production and more than 90% of the methane yield was achieved between 40 and 50 days of fermentation. Among the FVSW tested in this study, most of the varieties of mango peels, citrus wastes, pomegranate rotten seeds and pressings exhibited methane yields significantly ($P < 0.05$) higher than the cellulose. Most of the FVSW showed methane yields greater than 0.3 $l\ g^{-1}$ VS added and thus represent an excellent choice for commercial methane production. Work is underway to determine whether a relationship can be found between chemical composition and ultimate methane yields from FVSW.

Table 7
BMP of fresh vegetable waste samples

Sample	Volatile solids (% of TS)	Ultimate methane yield ($l\ g^{-1}$ VS added)	Methane production rate constant (d^{-1})
Lycopersicon esculentum (Tomato)			
Whole rotten tomato			
var. pyriforme	92.5	0.211 (0.012)^{a,i}	0.070 (0.009)^{a}
var. commune	98.1	0.384 (0.012)^{b}	0.094 (0.007)^{b,c}
Abelmoschus esculentus (Lady's finger)			
Fruit Stalk	91.9	0.350 (0.017)^{c,g}	0.074 (0.007)^{a,d}
Allium cepa (Onion)			
Exterior peels	88.2	0.400 (0.014)^{d}	0.091 (0.006)^{b,c}
Solanum tuberosum (Potato)			
Peels	90.9	0.267 (0.017)^{e,j}	0.090 (0.007)^{b}
Solanum melongena var. esculentum (Brinjal)			
Stalk	94.1	0.374 (0.016)^{b,c,d}	0.108 (0.013)^{c,e}
Whole fruit (pest infested)	91.1	0.396 (0.014)^{b,d}	0.087 (0.006)^{b,d}
Coriandrum sativum (Coriander plant)			
Leaves	80.0	0.325 (0.017)^{f,g}	0.083 (0.013)^{a,b}
Stems	85.7	0.309 (0.013)^{f,h}	0.075 (0.006)^{a,d}
Roots	83.3	0.283 (0.015)^{e,h}	0.086 (0.019)^{b,d}
Whole plant	84.9	0.322 (0.010)^{f,g}	0.075 (0.010)^{a,d}
Brassica oleracea var. capitata (Cabbage)			
Leaves	91.2	0.309 (0.013)^{f}	0.125 (0.008)^{e}
Stem	91.8	0.291 (0.012)^{e,h}	0.101 (0.009)^{b,c}
Brassica oleracea var.botrytis (Cauliflower)			
Leaves	82.0	0.190 (0.009)^{a}	0.059 (0.007)^{f}
Stem	87.1	0.331 (0.013)^{f,g}	0.093 (0.007)^{c}
Brassica rapa (Turnip)			
Leaves	84.4	0.314 (0.010)^{f,h}	0.098 (0.005)^{b,c}
Raphanus sativus (Radish)			
Shoots			
var. Pale pink	84.9	0.304 (0.012)^{f,h}	0.106 (0.010)^{c,e}
var. Yellowish white	81.7	0.293 (0.009)^{e,h}	0.070 (0.009)^{a}
Beta vulgaris (Garden beet)			
Leaves	81.4	0.231 (0.008)^{i,j}	0.053 (0.004)^{f}
Pisum sativum (Garden pea)			
Pods (seeds removed)	91.8	0.390 (0.013)^{b,d}	0.072 (0.004)^{a}
Daucus carota (Carrot)			
Leaves	93.1	0.241 (0.008)^{j}	0.082 (0.006)^{a,b}
Petiole	91.3	0.309 (0.010)^{f,h}	0.090 (0.006)^{b,c}

Figures in parentheses are standard deviations; $^{a-j}$means in columns with different superscripts differ ($P < 0.05$).

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