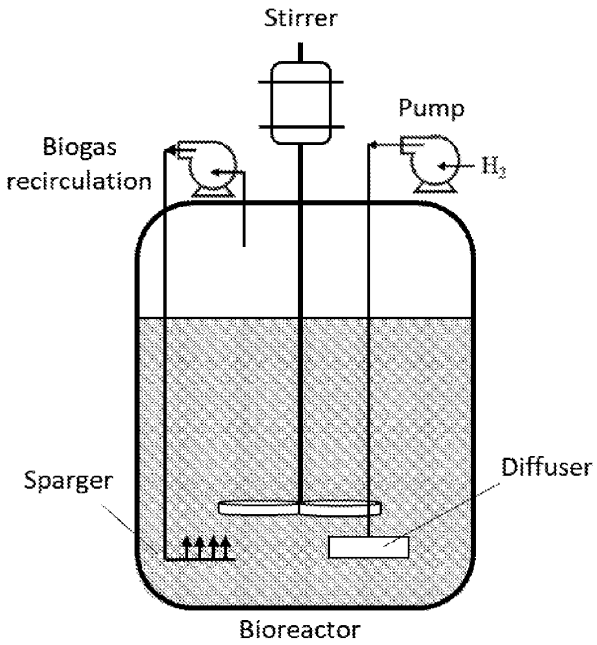

Stirrer
Pump
Biogas
recirculation
H_2
Sparger
Diffuser
Bioreactor

FIG. 1

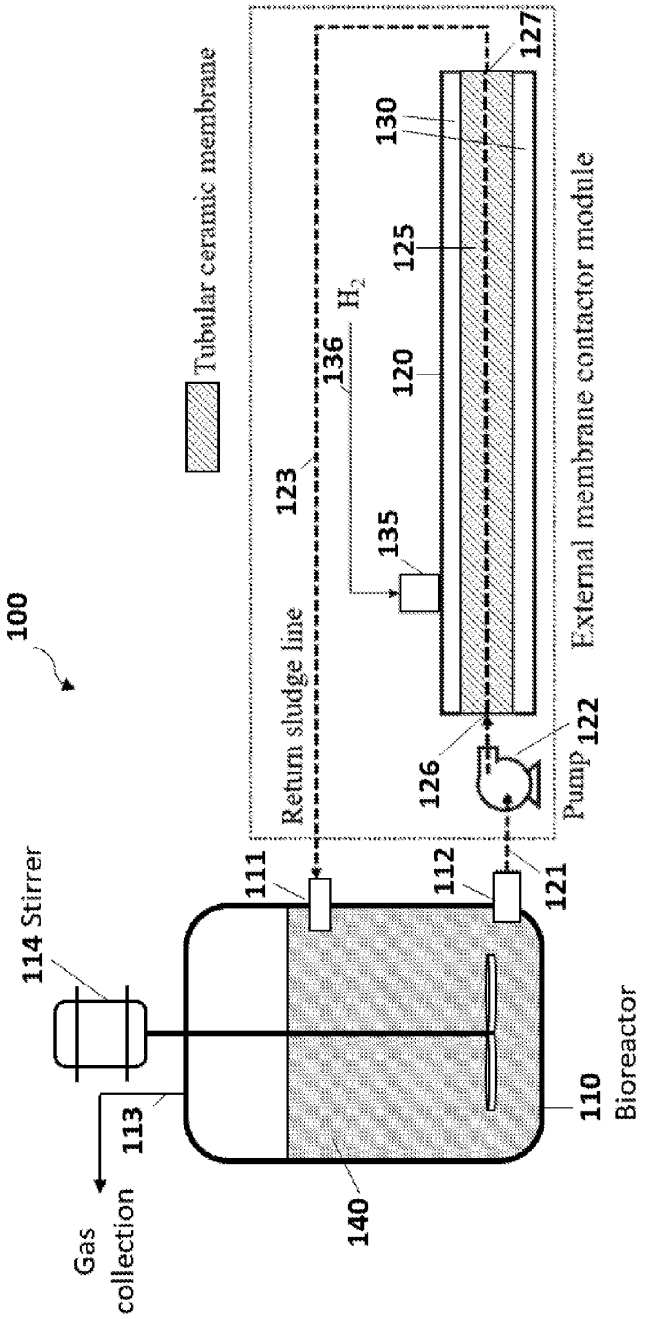

100
Tubular ceramic membrane
Return sludge line
External membrane contactor module
H_2
136
123
135
120
125
130
127
126
Pump
122
121
111
112
114 Stirrer
113
Gas collection
140
110
Bioreactor

FIG. 2

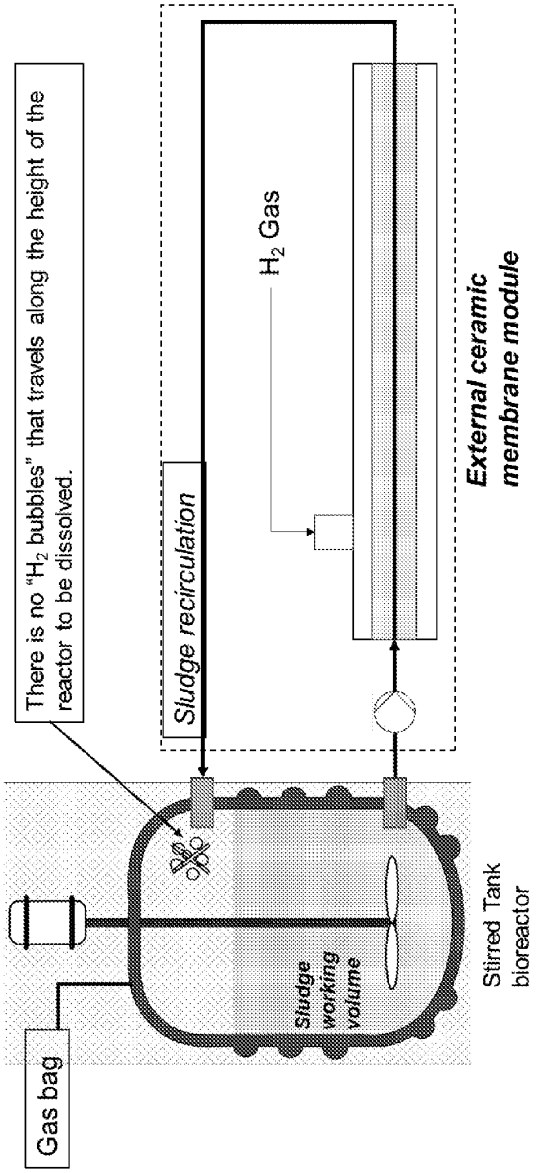

There is no "H2 bubbles" that travels along the height of the reactor to be dissolved.
Sludge recirculation
H2 Gas
External ceramic membrane module
Sludge working volume
Stirred Tank bioreactor
Gas bag

FIG. 3

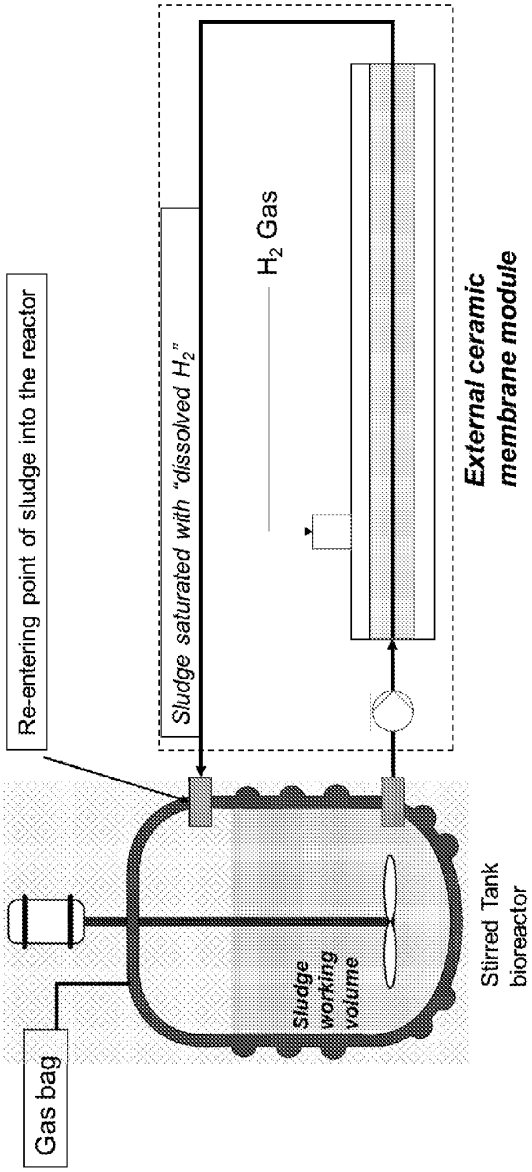

Re-entering point of sludge into the reactor
Sludge saturated with "dissolved H_2"
H_2 Gas
External ceramic membrane module
Stirred Tank bioreactor
Sludge working volume
Gas bag

FIG. 4

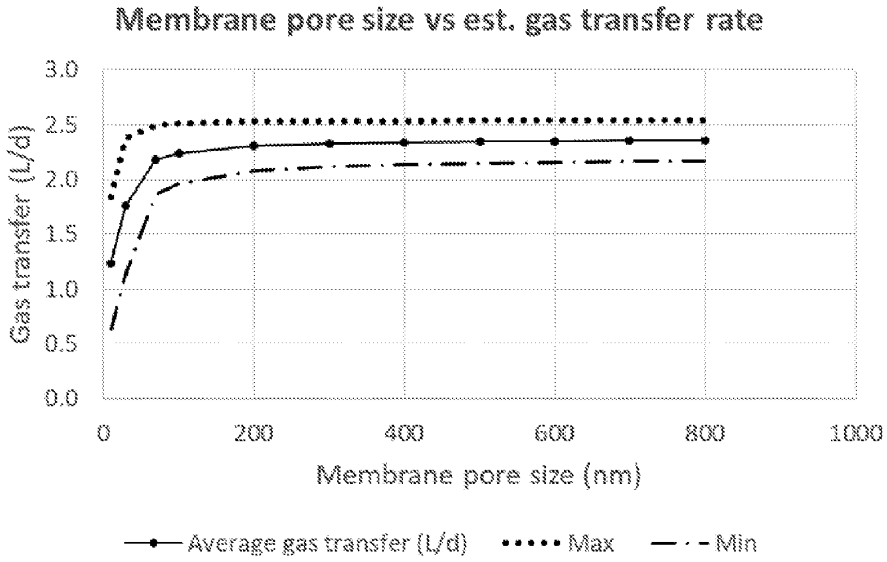

Membrane pore size vs est. gas transfer rate
Gas transfer (L/d)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
200
400
600
800
1000
Membrane pore size (nm)
Average gas transfer (L/d)
Max
Min

FIG. 5

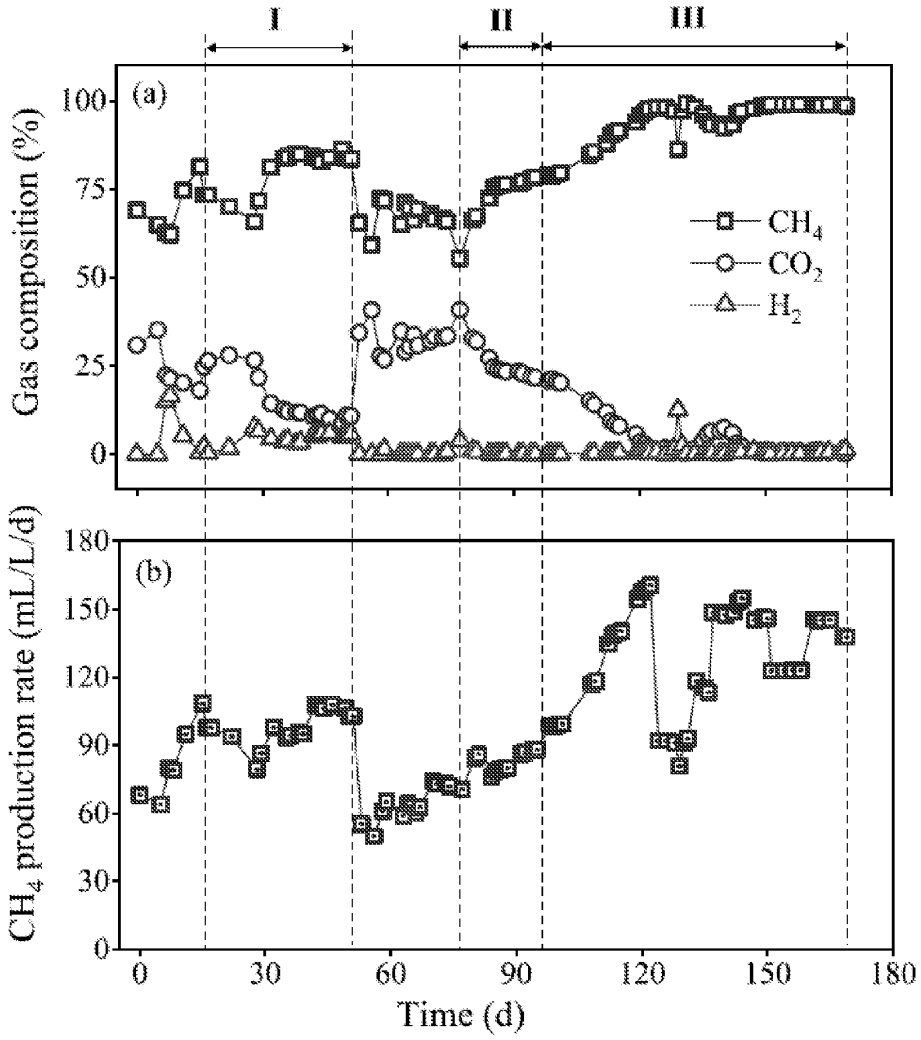

I
II
III
(a)
Gas composition (%)
100
75
50
25
0
CH4
CO2
H2
(b)
CH4 production rate (mL/L/d)
180
150
120
90
60
30
0
0
30
60
90
120
150
180
Time (d)

FIG. 6

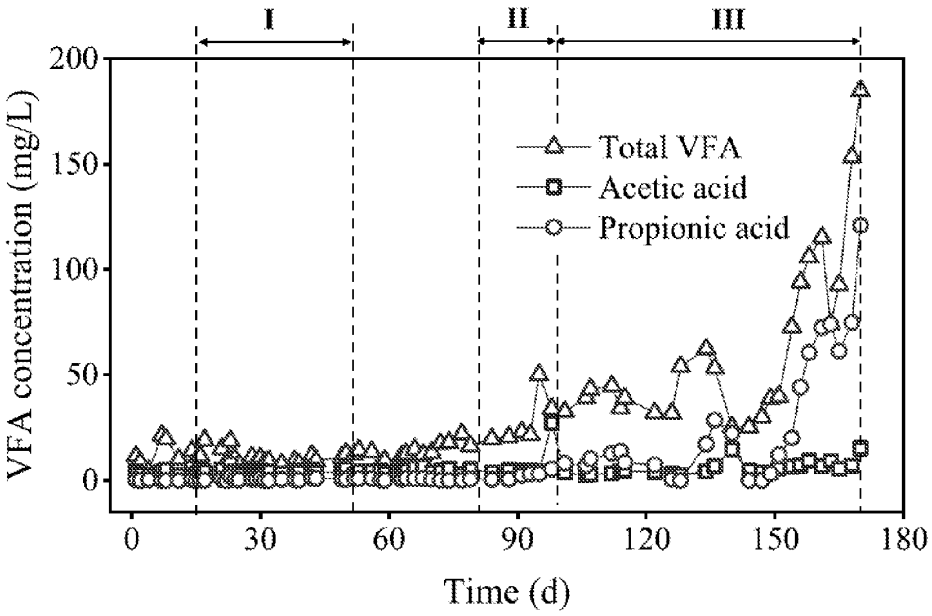

I
II
III
200
150
100
50
0
VFA concentration (mg/L)
Total VFA
Acetic acid
Propionic acid
0
30
60
90
120
150
180
Time (d)

FIG. 7

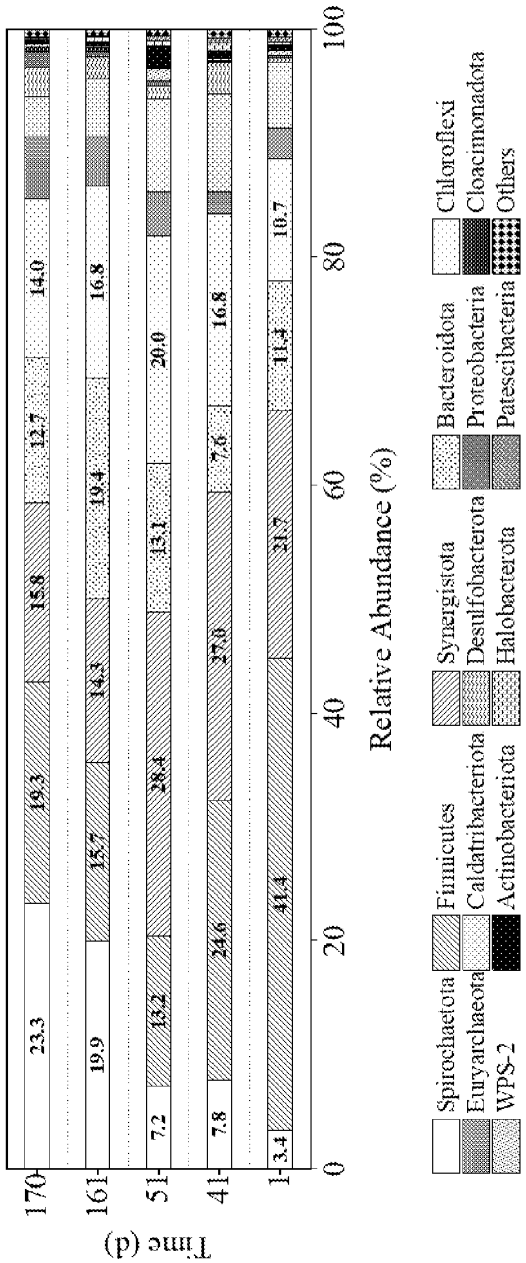

Time (d)
170
161
51
41
1
0
20
40
60
80
100
Relative Abundance (%)
23.3
19.3
15.8
12.7
14.0
19.9
15.7
14.3
19.4
16.8
7.2
13.2
28.4
13.1
20.0
7.8
24.6
27.0
7.6
16.8
3.4
41.4
21.7
11.4
16.7
Spirochaetota
Euryarchaeota
WPS-2
Firmicutes
Caldatribacteriota
Actinobacteriota
Synergistota
Desulfobacterota
Halobacterota
Bacteroidota
Proteobacteria
Patescibacteria
Chloroflexi
Cloacimonadota
Others

FIG. 8

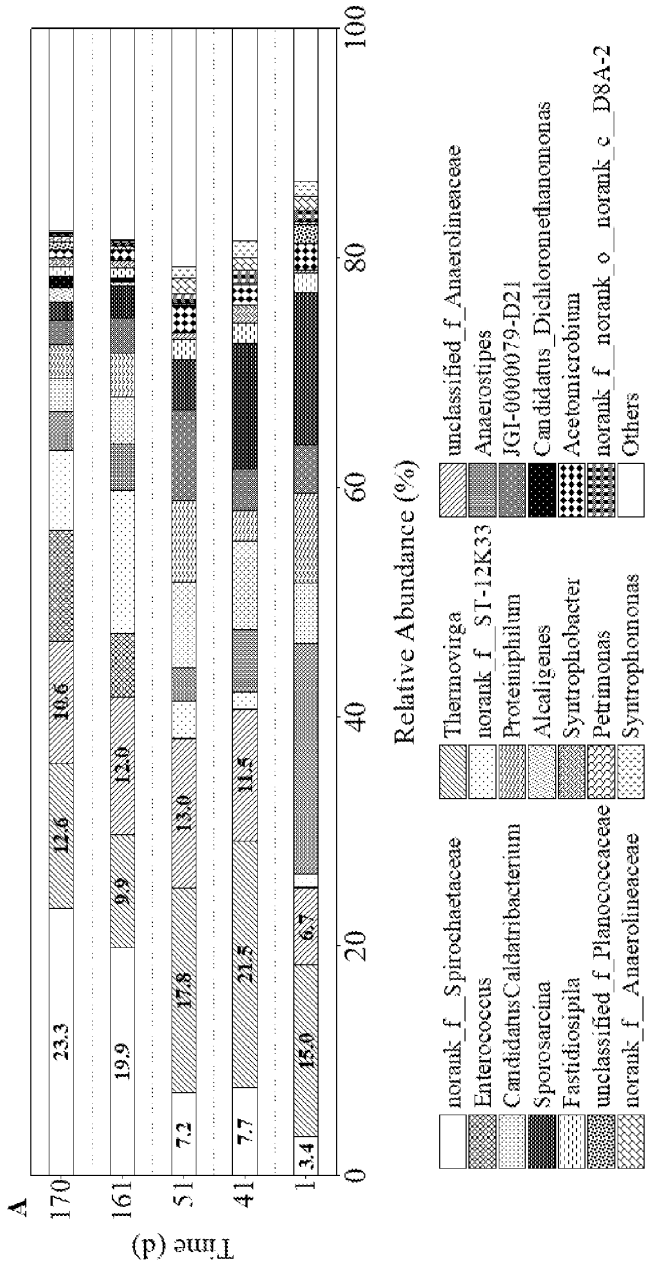

A
Time (d)
170
161
51
41
1
0
20
40
60
80
100
Relative Abundance (%)
23.3
12.6
10.6
19.9
9.9
12.9
7.2
17.8
13.0
7.7
21.5
11.5
3.4
15.0
6.7
norank_f__Spirochaetaceae
Enterococcus
CandidatusCaldatribacterium
Sporosarcina
Fastidiosipila
unclassified_f_Planococcaceae
norank_f__Anaerolineaceae
Thermovirga
norank_f__ST-12K33
Proteiniphilum
Alcaligenes
Syntrophobacter
Petrimonas
Syntrophomonas
unclassified_f_Anaerolineaceae
Anaerostipes
JGI-0000079-D21
Candidatus_Dichloromethanomonas
Acetomicrobium
norank_f__norank_o__norank_c__D8A-2
Others

FIG. 9A

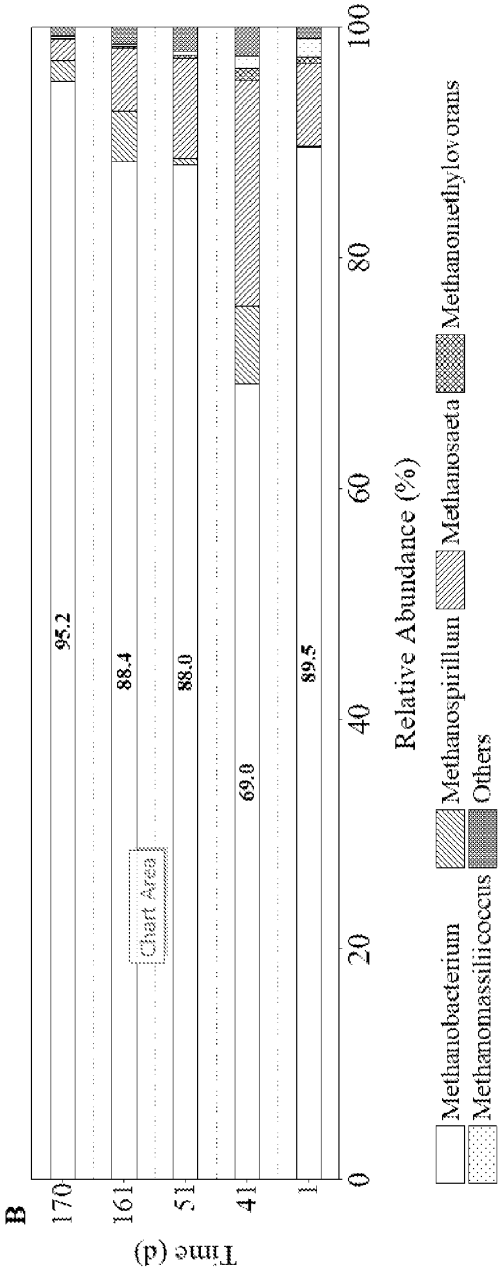

B
Time (d)
170
161
51
41
1
95.2
88.4
88.0
69.8
89.5
Chart Area
0
20
40
60
80
100
Relative Abundance (%)
Methanobacterium
Methanospirillum
Methanosaeta
Methanomethylovorans
Methanomassiliicoccus
Others

FIG. 9B

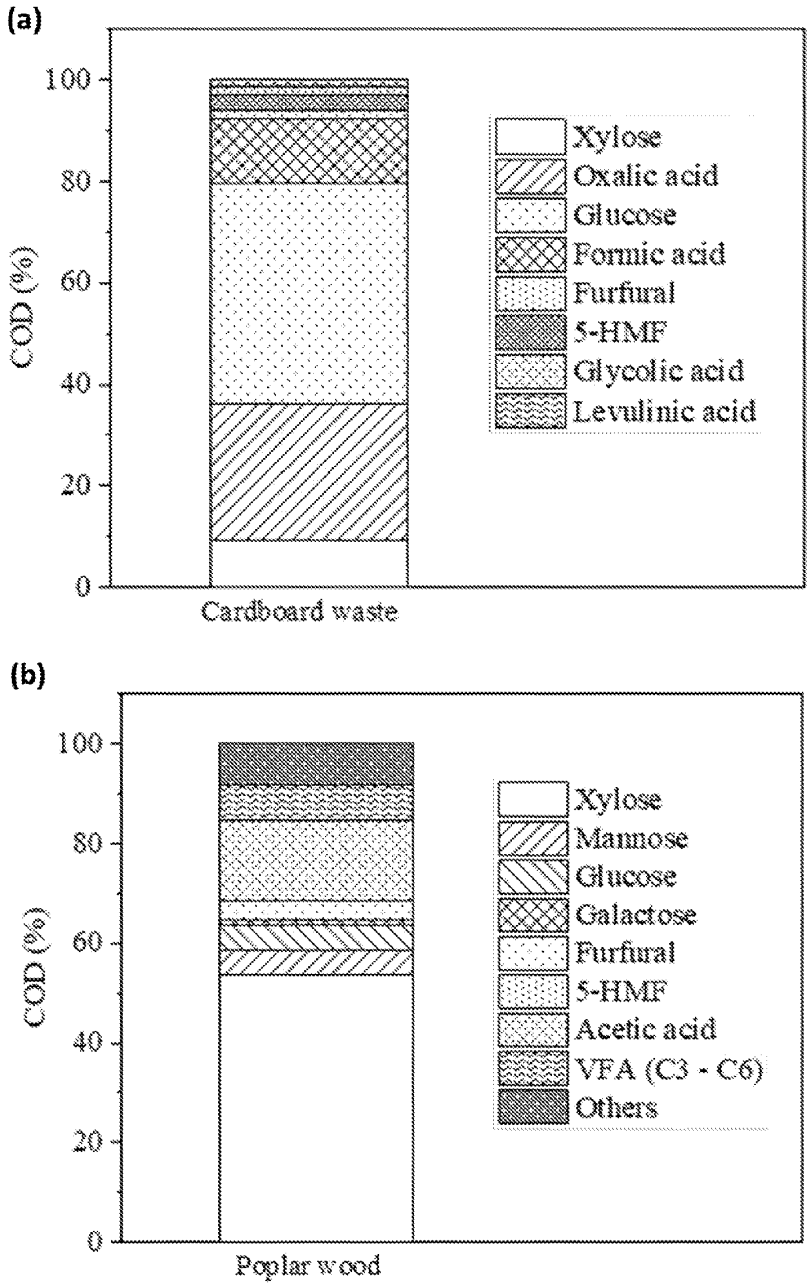

(a)
COD (%)
100
80
60
40
20
0
Cardboard waste
Xylose
Oxalic acid
Glucose
Formic acid
Furfural
5-HMF
Glycolic acid
Levulinic acid
(b)
COD (%)
100
80
60
40
20
0
Poplar wood
Xylose
Mannose
Glucose
Galactose
Furfural
5-HMF
Acetic acid
VFA (C3 - C6)
Others

FIG. 10

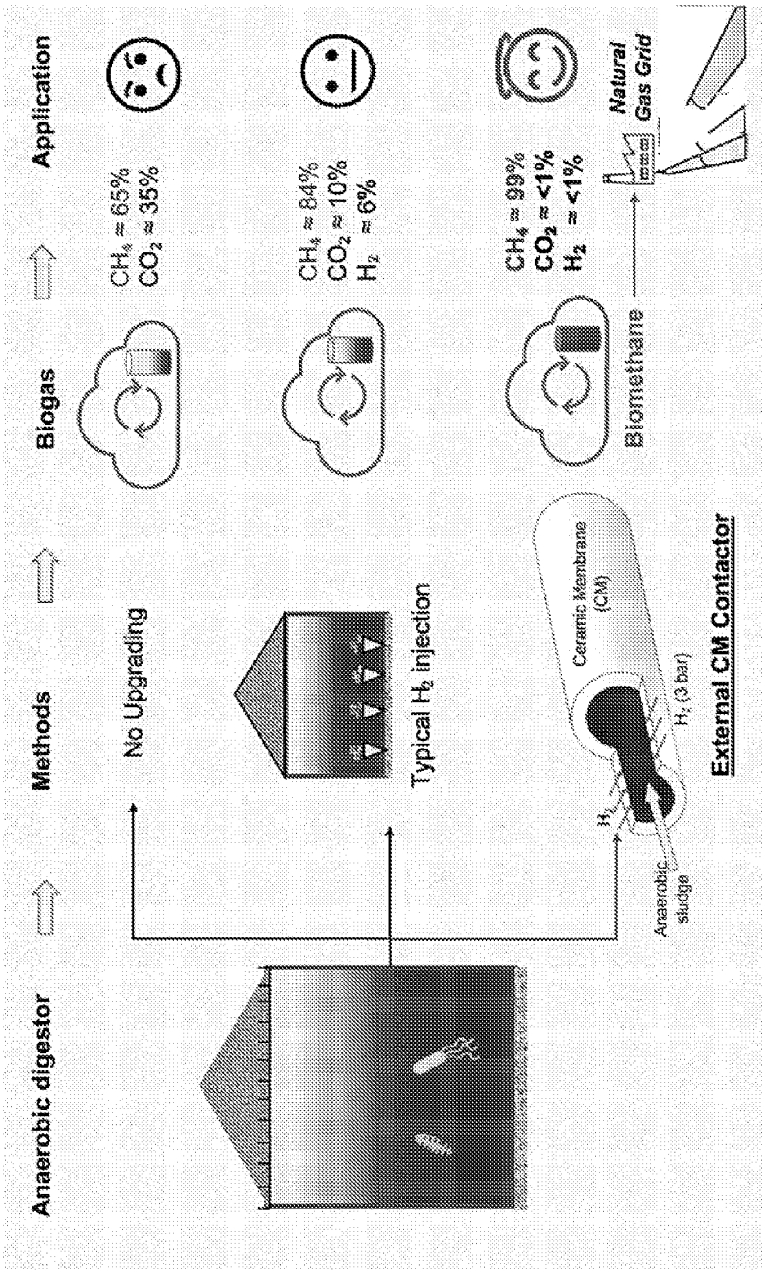

Anaerobic digestor
Methods
Biogas
Application
No Upgrading
$CH_4 \approx 65\%$
$CO_2 \approx 35\%$
Typical H_2 injection
$CH_4 \approx 84\%$
$CO_2 \approx 10\%$
$H_2 \approx 6\%$
External CM Contactor
Ceramic Membrane (CM)
H_2 (3 bar)
H_2
Anaerobic sludge
$CH_4 \approx 99\%$
$CO_2 \approx <1\%$
$H_2 \approx <1\%$
Biomethane
Natural Gas Grid

FIG. 11