Supplementary Information

for

Carbon-based Materials in Anaerobic Digestion for Methane Production: Unraveling the Multi-faceted Mechanisms and Shaping Future Perspectives

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Methanogen Genus / Group	Primary Metabolic Pathway	Typical generation time/incubation period	Typical Optimal pH Range	Typical Optimal Temperature Range	Representative Maximum Methane Yield Reported (Context)
Methanosarcina	Aceticlastic methanogenesis (cleavage of acetate to CH_4 and CO_2); some utilize methanol/methylamines	~12.6-36.5 h	~7.0	35-37°C	368 mL CH_4/g acetic acid (1); 8.1 mL CH_4 (15.5 mg±0.5 mg methanol) (2)
Methanothrix (Methanosaeta)	Obligate aceticlastic methanogenesis (exclusive use of acetate)	>10 d (low acetate concentration, syntrophic growth)	7.0-7.5	37°C	373 mL CH_4/g acetic acid (3)
Methanoculleus	Hydrogenotrophic methanogenesis (H_2/CO_2 as main substrates); some use formate/secondary alcohols	~1-2 d (inferred from acetate-assimilating activity)	6.7-8.0	37°C	37.6-41.6 mmol CH_4 $gVSS^{-1}$ d^{-1} (4)
Methanobacterium	Hydrogenotrophic methanogenesis (H_2/CO_2 utilization)	~5.4-24 h	7.0-7.5	37°C	9.21 mL $CH_4 \cdot L^{-1} \cdot h^{-1}$ (5)
Methanomassiliicoccus	Methylotrophic methanogenesis (methyl compounds + H_2)	~24-30 h	7.0-7.5	37°C	192 CH_4 nmol min^{-1} mg^{-1} protein (6)
Methanospirillum	Hydrogenotrophic methanogenesis (H_2/CO_2, formate); some use 2-propanol	~23-35 h	7.0-7.5	35-45°C	1.1-1.8 μmol CH_4 · h^{-1} mg-1 protein (7)
Methanobrevibacter	Hydrogenotrophic methanogenesis (H_2/CO_2, formate)	~24-48 h	7.0-8.0	36-42°C	71 mL CH_4 (554 mg VFAs) (8)

Table S1. Core Metabolic Characteristics and Fermentation Parameters of Methanogen Gener

Table S2. Comparison Table of Methane Yields in Anaerobic Co-Digestion (AcoD) Systems with Different Carbon Sources

Category	Carbon Source Combination	Methane Yield (with units and key conditions specified)
Previous Research	Food Waste (FW) + Algae (AL) (9)	334 mL CH_4/g COD $_{(Input)}$ (optimal ratio AL:FW = 2:8)
	Durian Shell (DS) + Pig Manure (PM) (10)	224.8 mL/g VS (optimal ratio DS:PM = 1:1)
	Food Waste (FW) + Waste Activated Sludge (WAS) (11)	293.6 mL/g VS (bio-co-pretreatment group, OLR = 11.25 g VS/(L·d))
	Poultry Dung (PD) + Alkali-Pretreated Compressed Wheat Straw (BWS $_{(add)}$, 2% KOH) (12)	254.25 NL CH_4/kg VS (thermophilic condition, 53℃)
	Raw Sludge (S) + Food Waste Leachate (F) + Microalgae Biomass (A) (13)	176 mL CH_4/g VS (optimal ratio 1S:1F:1A)
	Buckwheat Hull (BH) + Slaughterhouse Waste (SW) (14)	485 NL $kgVS^{-1}$ (optimal combination)
	Lipids + Food Waste (FW) (15)	Thermophilic: 288 mL CH_4/g COD; Mesophilic: 275 mL CH_4/g COD (Lipids/TS ≤ 50%)
	Corn Straw (CS) + Straw Depolymerization Wastewater (SDW) (16)	214.81 mL/g-VS (optimal substrate concentration 36.2 g/L, thermophilic 55±1℃)
	Organic Fraction of Municipal Solid Waste (OFMSW) + Steam-Exploded Giant Reed (GR) (17)	235.9 mL/g VS (optimal ratio OFMSW:GR = 75:25, mesophilic 37℃)
Research on the Addition of Carbon-Based Materials	Aloe Peel (AP) + Dairy Manure (DM) (18)	339.64 mL/g VS (0.36 wt.% aloe peel-derived carbon quantum dots AP-CQDs, mesophilic 36±1℃)
	Dairy Manure (DM) (19)	454.1 mL/g VS (UBC composite accelerant, containing activated carbon, mesophilic 36±1℃)
	Acorn Slag Waste (ASW) + Dairy Manure (DM) (20)	385.8 mL/g VS (2.16 g/L aloe peel-derived biochar AP-BC, optimal ratio ASW:DM = 1:3, mesophilic 36±1℃)
	Cow Manure (CM) + Aloe Peel Waste (APW) (21)	226.84 NmL/g VS (MEC 0.6V + 0.15 wt.% coconut shell-derived biochar CBC, mesophilic 36±1℃)

	Organic Fraction of Municipal Solid Waste (OFMSW) + Waste Activated Sludge (WAS) (22)	0.193 NL/g VS (granular activated carbon 5 g/L); 0.201 NL/g VS (graphite 5 g/L); 0.211 NL/g VS (graphene oxide 0.1 g/L); 0.206 NL/g VS (carbon nanotubes 0.1 g/L) (mesophilic 35℃, HRT=21 d)
	Cow Manure (CM) + Aloe Peel Waste (APW) (23)	350.21 mL/g VS (0.20 wt.% N, P co-doped biochar, mesophilic 37±1℃)
	Cow Manure (CM) + Vegetable Residue (VR) (24)	526 mL/g VS (biochar 0.20 g/L, cumulative biogas yield, mesophilic 36±1℃)
	Cow Manure (CM) + Food Waste (Rice + Bread) (25)	78.3 mL/g VS (granular activated carbon/nano zero-valent iron 15 g/L, co-digestion, thermophilic 55℃, COD removal rate 78.29%)
Research on the Addition of Carbon-Based Materials	Cow Manure (CM) + Aloe Peel Waste (APW) (26)	348.9 mL/g VS (5 mT magnetic field + 0.36 wt.% aloe peel-derived carbon dots CQDs, mesophilic 36±1℃)
	Cow Manure (CM) + Food Waste (FW) + Rice Straw (RS) (27)	469.72 mL/g VS (coconut husk biochar 15 g/L, optimal ratio CM30:FW50:RS20, mesophilic 35-40℃)
	Cow Manure (CM) + Corn Straw (CS) (28)	309 mL/g VS (granular activated carbon 15.38 g/L, optimal OLR=3.0 g VS/(L·d), C/N=25, mesophilic, VS removal rate 62.41%)
	Hulless Barley Straw + Pig Manure (29)	362.89 mL/g VS (activated carbon, mesophilic, 40.47% higher than control)
	Cow Manure (CM) + Aloe Peel Waste (APW) (30)	396.09 mL/g VS (2.625 g/L Fe/Ni-N-C, bimetal-modified nitrogen-doped coconut shell biomass carbon, mesophilic 37℃)

Table S3. Summary of Dominant Microbial Community Succession in Anaerobic Digestion Systems with Different Carbon-based Materials (CBMs)

The Type Of CBMs	Dominant Bacterial Community	Dominant Archaeal Community
Biochar (31)	*Geobacter sp.* (Detected in all sets); *Clostridium sp.*, *Bacillus sp.*, *Bacteroides sp.*, *Anaerobaculum sp.* (Present)	*Methanosarcina sp.* (215% increase); *Methanothermobacter sp.*, *Methanobrevibacter sp.* (Enriched)
Woody Biochar (32)	Lactobacillales (23.95%); Clostridiales (Predominant in later stage)	*Methanosarcina* (Dominant); *Methanoculleus* (Increased to 47.43% on day 2 vs control's 0.41%)
Carbon-Nanotube Hollow-Fiber (33)	*Pelobacter* (10.0% vs control's trace); *Geobacter* (6.9% vs control's 2.8%); *Aminiphilus* (10.0% vs control's 2.3%)	*Methanosaeta* (15.7% vs control's 4.4%)
Graphene (34)	*Pseudomonas* (11.73% vs control's 0%); *Clostridium* (Enriched)	*Methanosaeta* (47.1% vs control's 41.6%)
Biochar (35)	*Syntrophomonas* (19-21% increase); *Clostridium* sensu stricto (8-249% increase); *Petrimonas* (Enriched)	*Methanothrix* (45.73-52.42% vs control's 45.73%); *Methanobacterium* (15.27% on day 3 vs control's 14.83%)
Carbon Quantum Dots (18)	*Proteiniclasticum* (39.70% vs 37.56%, +2.14%); *Sporosarcina* (5.41% vs 0.76%, +4.65%); *Petrimonas* (10.40% vs 6.27%, +4.13%)	*Methanosarcina* (54.20% vs 31.63%, +22.57%); *Methanobacterium* (30.01% vs 24.38%, +5.63%)
Carbon Cloth (36)	*Sporanaerobacter* (34% vs 2%, +32%); *Enterococcus* (10% vs <1%, +>9%)	*Methanosarcina* (68% vs control's dominant *Methanosaeta*)
$NiFe_2O_4$-MXene@Carbon Felt (37)	*Trichococcus* (23% vs <1%, +>22%); *Longilinea* (9% vs 4%, +5%); *Clostridium* sensu stricto 7 (7% vs 2%, +5%)	*Methanosaeta* (34% vs 3%, +31%)
Granular Activated Carbon (38)	*Acetoanaerobium* (34% vs 25%, +9%); *Proteiniborus* (5% vs 1%, +4%)	*Methanobacterium* (23% vs 16%, +7%); *Methanolinea* (11% vs 5%, +6%)

Graphene (39)	*Geobacter* (9.9% vs 8.4%, +1.5%); *Pseudomonas* (6.85% vs 1.91%, +4.94%)	*Methanobacterium* (34.87% vs 24.02%, +10.85%); *Methanospirillum* (7.76% vs 2.15%, +5.61%)
Reduced Graphene Oxide (40)	*Defluviitoga* (7-67%); *Syntrophomonas* (Enriched); *Clostridium* (Enriched); *Coprothermobacte*r (Enriched)	*Methanothrix* (89-97%, higher than control); *Methanoculleus* (56% vs 49%, +7%)
N,P-Co-Doped Biochar (23)	*Proteiniclasticum* (39.70% vs 37.56%, +2.14%); *Sporosarcina* (5.41% vs 0.76%, +4.65%); *Petrimonas* (10.40% vs 6.27%, +4.13%)	*Methanosarcina* (54.20% vs 31.63%, +22.57%); *Methanobacterium* (30.01% vs 24.38%, +5.63%)
Carbon Quantum Dots (26)	*Acinetobacter* (44.90% vs control's 0%, +44.90%); *Clostridium* (13.71% vs 7.42%, +6.29%); *Petrimonas* (7.12% vs 5.35%, +1.77%)	*Methanosarcina* (Enriched); *Methanobacterium* (31.10% vs 4.38%, +26.72%); *Methanomassiliicoccus* (23.17% vs 5.47%, +17.70%)
Granular Activated Carbon (41)	*Smithella* (3.2% vs 2.6%, +0.6%; 14.4-82.9% increase in Phases I-III); *Mesotoga* (5.1% vs 3.3%, +53.3%)	*Methanothrix* (31.7% vs 34.2%, no increase); *Methanobacterium* (11.6-15.6%, stable vs control's 12.0-16.1%)

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