Sinanaerobacter chloroacetimidivorans gen. nov., sp. nov., an obligate anaerobic bacterium isolated from anaerobic sludge

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Abstract An obligate anaerobic bacterial strain (BAD-6T) capable of degrading acetochlor and butachlor was isolated from an anaerobic acetochlor-degrading reactor. Cells were Gram-stain positive, straight to gently curved rods with flagella. The major fermentation products in peptone-yeast broth were acetate and butyrate. The optimum temperature and pH for growth was 30 °C and 7.2–7.5, respectively. The major cellular fatty acids (> 10%) were C14:0 FAME, C16:0 FAME and cyc-9,10-C19:0 DMA. Genome sequencing revealed a genome size of 4.80 Mb, a G + C content of 43.6 mol% and 4741 protein-coding genes. The most closely related described species on the basis of 16S rRNA gene sequences was Anaerovorax odorimutans NorPutT in the order Clostridiales of the class Clostridia with sequence similarity of 94.9%. The nucleotide identity (ANI) value and digital DNA–DNA hybridization (dDDH) between the genomes of strain BAD-6T and Ana. odorimutans NorPutT were 70.9% and 15.9%, respectively. Based on the distinct differences in phylogenetic and phenotypic characteristics between strain BAD-6T and related species, Sinanaerobacter chloroacetimidivorans gen. nov., sp. nov. is proposed to accommodate the strain. Strain BAD-6T is the type strain (= CCTCC AB 2021092 T = KCTC 25290 T).

Keywords 16S rRNA gene sequence · Activated sludge · Sinanaerobacter chloroacetimidivorans gen. nov. · Sp. nov. · Taxonomy

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Introduction

Chloroacetamide herbicides, such as alachlor, acetochlor, pretichlor, propisochlor, butachlor and propiochlor, are an important class of herbicides and widely application in agriculture. However, their large-scale application has led to a continuous increase in the amount of residues in the environment, which has caused a serious threat to the ecological environment and human health (Lerro et al. 2015; Luo et al. 2004; Seghers et al. 2003). Chloroacetamide herbicides are highly toxic to aquatic organisms, and their
residues in the soil damage subsequent crop rotations, especially in sandy soils with low organic matter content (Kim et al. 2013; Li et al. 2013; Zhang et al. 2011b). Thus, study the microbial degradation of chloroacetamide herbicides is of importance. At present, many aerobic chloroacetamide herbicide-degrading bacterial strains have been isolated and the aerobic catabolism have been elucidated (Chen et al. 2014; Chu et al. 2016; Wang et al. 2015; Zhang et al. 2011a). However, there was little study on the anaerobic degradation of chloroacetamide herbicides.

In our previous study, an anaerobic sludge capable of efficiently degrading acetochlor was obtained through pressure acclimation using sediment collected from an abandoned herbicide manufacturing plant (Liu et al. 2020). A bacterial strain BAD-6 T was isolated from the acclimated activated sludge. The strain is obligately anaerobic and could efficiently degrade acetochlor and butachlor. Based on the analysis of 16S rRNA gene sequence, the strain was order Clostridiales of phylum Firmicutes, a polyphasic taxonomic. In this study, polyphasic taxonomic approach was carried out to determine the taxonomic position of strain BAD-6 T.

**Materials and methods**

**Bacterial isolation**

Strain BAD-6 T was isolated from a continuous flow anaerobic reactor treating wastewater containing acetochlor. The initial sludge sample collected from an abandoned herbicide manufacturing plant in Kunshan City, Jiangsu Province, China. The geographic coordinates are E120°56′38″ and N31°22′05″. The medium for isolation was composed of the following (PYT): peptone (0.5 g), yeast extract (1.0 g), tryptone (0.5 g), acid hydrolysed casein (1.0 g), soluble starch (1.0 g), glucose (1.0 g), K₂HPO₄ (0.6 g), MgSO₄ (0.2 g), sodium pyruvate (0.6 g), L-cysteine hydrochloride (0.20 g), resazurin (1.0 mg), trace element solution (1.0 ml), and vitamin solution (1.0 ml) in 1.0 L distilled water. The pH value was adjusted to 7.2 using 50 mM NaH₂PO₄/Na₂HPO₄. The solutions of trace elements solution and vitamins solution are formulated as described by Widdel et al. (1983). For solid medium, 18 g L⁻¹ agar was added. The medium was boiled and put into a serum bottle full with nitrogen (purity, 99.999%) as the headspace to ensure anaerobic conditions. Then the serum bottle was sealed with rubber stopper. After autoclaving, the medium was supplemented with a sterile vitamin solution. The anaerobic sludge taken from the reactor was diluted, and 100 µL of each dilution was spread onto the PYT agar plate in an anaerobic chamber (COY-7000220A, COY Laboratory Products Inc, Michigan, USA). Unless indicated otherwise, all the strains were anaerobically cultured on PYT at 37 °C. The strain was preserved at − 80 °C in PYT broth supplemented with 20% (v/v) glycerol.

**PCR assay**

PCR amplification of the 16S rRNA gene was performed with the universal primers 27F and 1492R (Frank et al. 2008). The PCR product was purified by the PCR gel extraction kit (Omega Bio-Tek) and inserted into pMD19-T vector (TaKaRa Biotechnology). The inserted fragment was sequenced using an automated sequencer (model 3730, Applied Biosystems). The 16S rRNA gene sequences were compared with known sequences in GenBank of the NCBI (www.ncbi.nlm.nih.gov/BLAST/) and in EzBioCloud’s identify service (www.ezbiocloud.net/identify). Sequence alignment was performed using the CLUSTAL_W program. Phylogenetic trees were reconstructed by the neighbor-joining (NJ) (Saitou and Nei 1987), maximum-likelihood (ML) (Felsenstein 1981) and minimum-evolution (ME) (Fitch 1971) algorithms, using the MEGA software (version 7.0) with Kimura’s two-parameter calculation model (Kimura 1980). The topologies of the phylogenetic trees were assessed by bootstrap analysis of 1000 replications (Felsenstein 1985).

**Chemotaxonomic characterization**

For genomic sequencing, the total DNA of strain BAD-6 T was extracted according to the method described by Sambrook et al. (1989). The draft genome of strain BAD-6 T was sequenced by Illumina Hiseq 4000 platform at Shanghai Biozeron Biotechnology Co., Ltd (Beijing, PR China). Paired end libraries with average insert length of 350 bp were constructed; then, 100 × libraries were obtained from clean paired end read data. Raw sequencing data assembly was performed using SOAPdenovo version
2.04 (Luo et al. 2012). The assembled genomes were annotated with the Rapid Annotation with Subsystem Technology (RAST) server (Aziz et al. 2008). The genomic sequences of Anaerovorax odorimutans NorPutT, Aminipila butyrica FH042T and Eubacterium brachy ATCC 35585T were obtained from the NCBI database. Comparative genomic analysis was carried out by the compare-function-based tool of the Seed Viewer (Overbeek et al. 2014). To further clarify the taxonomic relationship between strain BAD-6T and its closest relatives Ana. odorimutans NorPutT (Matthies et al. 2000), Ami. butyrica FH042T (Ueki et al. 2018) and E. brachy ATCC 35585T (Holdemqn et al. 1980), average nucleotide identity (ANI) values and digital DNA–DNA hybridization (dDDH) between BAD-6T and the three type strains were calculated using the OrthoANIu algorithm (https://www.ezbiocloud.net/tools/ani) (Yoon et al. 2017) and genome-to-genome distance calculator (http://ggdc.dsmz.de/ggdc.php/) (Chun et al. 2018), respectively. The DNA G + C content was determined from the genome sequence.

Morphological, physiological, and biochemical characterization

For morphological characterization, BAD-6T was observed using transmission electron microscopy (H-7650; Hitachi) at exponential cells. Motility of cells was tested using the hanging-drop method (Bernardet et al. 2002). Endospore formation was determined as previously described by Logan et al. (2009) Growth of the strain under aerobic conditions was examined as described previously (Ueki et al. 2009). The Gram-stain was performed using the method described by Beveridge et al. (2007). To analyze the biochemical and physiological characteristics, strain BAD-6T was cultivated in PYT broth at 37 °C. Growth at different temperatures (10, 15, 25, 28, 30, 37, 42, 45 and 50 °C), different NaCl concentrations (0, 0.5, 1.0, 2.0, 3.0, 4.0 and 5.0%, w/v) and different pH values (pH 4.0–10.0 at intervals of 0.5 pH units) were assessed. Growth was monitored by measuring the OD_{600}. For determination of salt tolerance, the PYT broth was adjusted to different NaCl concentrations. For estimating the pH range, the PYT broth was adjusted prior to sterilization using citrate/Na_{2}HPO_{4} buffer (pH 4.0–5.0), Na_{2}HPO_{4}/NaH_{2}PO_{4} buffer (pH 6.0–8.0) and glycine/NaOH buffer (pH 9.0–10.0).

Mineral salt medium (MSM) (Liu et al. 2020) was used to determine the abilities of strain BAD-6T to degrade acetochlor and butachlor. The strain BAD-6T was inoculated into MSM supplemented with acetochlor or butachlor (50 μM). Then the serum bottle was shaken on a rotary shaker at 37 °C and 150 rpm/min. Each treatment was performed in triplicate, and the control group without strain BAD-6T was set under the same conditions. After incubation for 14 days, the culture was sampled to determine the concentrations of acetochlor and butachlor by HPLC as described by Liu et al. (2020).

The main organic acids products of peptone-yeast extract (PY) medium fermentation were detected using HPLC as described by Zhang et al. (2018). Other enzymatic activities and utilization of various carbon sources were investigated using commercial kits (API 20NE, API ZYM and API 50CH) and Biolog GENIII MocroPlate according to the manufacturers’ protocols. Determination of the respiratory quinone system was performed as described previously (Collins et al., 1977). For analysis of fatty acids, cells of strain BAD-6T were cultured in PYT broth at 37 °C in the exponential phase. Cellular fatty acids were saponified, methylated and extracted as described previously, which was performed by using the Sherlock MIS (MIDI) system.

Results and discussion

Phylogenetic characterisation

An almost-complete 16S rRNA gene sequence of strain BAD-6T (1527 bp) was acquired. Comparative analysis of 16S rRNA gene sequences assigned strain BAD-6T to the class Clostridia in the phylum Firmicutes. Strain BAD-6T was closely related to Ana. odorimutans NorPutT (similarity 94.9%), Ami. butyrica FH042T (94.4%) and E. brachy ATCC 35585T (90.5%). The 16S rRNA gene sequences similarities between BAD-6T and Ana. odorimutans NorPutT (94.9%), Ami. butyrica FH042T (94.4%) and E. brachy ATCC 35585T (90.5%) were below the threshold value for defining bacterial genera (95.0%) recommended by Yarza et al. (2014). In the phylogenetic tree based on the NJ algorithm, strain BAD-6T formed a separate branch (Fig. 1), and the overall membership was also supported by the ML and ME
trees (Fig S1 and S2). These results indicated that strain BAD-6T might represent a novel genus.

Genomic characterisation

The draft genome of strain BAD-6T consisted of 69 contigs and the N50 length was 0.20 Mb. Comparative genomic analyses between strain BAD-6T and Ana. odorimutans NorPutT, Ami. butyrica FH042T, E. brachy ATCC 35585T were conducted (Table 1 and Fig. S3). The size of the genome and the number of protein-coding genes of strain BAD-6T were 4.80 Mb and 4741, respectively. The size of the genome and the number of protein-coding genes from strain BAD-6T were much higher than those of Ana. odorimutans NorPutT (3.26 Mb and 3062, respectively), Ami. butyrica FH042T (3.33 Mb and 3199, respectively) and E. brachy ATCC 35585T (1.54 Mb and 1464, respectively). In addition, the numbers of RNAs of strain BAD-6T (54) were much larger than those of Ana. odorimutans NorPutT (45) and E. brachy ATCC 35585T (37), and were lower than those of Ami. butyrica FH042T (83).

In the characteristics of subsystems (subsystem coverage and sub-system category distribution), the genomes between strainBAD-6T and Ana. odorimutans NorPutT, Ami. butyrica FH042T, E. brachy ATCC 35585T were significant different. Most of the annotated genes of strain BAD-6T were responsible for the cofactors, vitamins, prosthetic groups, pigments (136), protein metabolism (142), amino acids and derivatives (295) and carbohydrates (309) (Table 1 and Fig. S3). The number of genes presumed to be involved in cofactors, vitamins, prosthetic groups, pigments; amino acids and derivatives and carbohydrates were higher than those of Ana. odorimutans NorPutT, Ami. butyrica FH042T and E. brachy ATCC 35585T; while the number of genes presumed to be involved in membrane transport, protein metabolism and RNA metabolism were similar with Ana. odorimutans NorPutT and Ami. FH042T, and were much larger than those of E. brachy ATCC 35585T.

The ANI values obtained between the genomes of strain BAD-6T and Ana. odorimutans NorPutT, Ami. butyrica FH042T, E. brachy ATCC 35585T were 70.9%, 68.1%, and 66.8%, respectively (Table S1). The dDDH between strain BAD-6T and the three related type strains were 15.9%, 17.3%, and 19.3%, respectively (Table S1). All these data were below the 80% (ANI) and 20% (dDDH) thresholds (Rodriguez and Konstantinidis 2014; Zhang and Huang 1990).
which were recommended for describing a novel bacterial genus.

**Phenotypic and physiological characteristics**

Colonies of strain BAD-6\textsuperscript{T} were faint yellow with a smooth surface on PYT agar after incubation for 2 days. Cells were Gram-stain-positive and straight or slightly curved rods, and 0.3–0.5 \( \mu \text{m} \) in diameter and 1.8–2.5 \( \mu \text{m} \) in length. Cells were motile with one or two peritrichous flagella (Fig. S4). The strain could not grow aerobically and could not produce spores. The temperature range for growth was 16–42 \(^\circ\text{C}\) with the highest growth rate at 30 \(^\circ\text{C}\). The strain grew at pH 6.3–8.0 with optimum being pH 7.2–7.5. The strain has the highest growth rate without adding NaCl in PYT broth. Strain BAD-6\textsuperscript{T} could degrade 98.2\% of

### Table 1

Comparison of genomic characteristics between BAD-6\textsuperscript{T} and the strains with higher genomic similarity

| Characteristic                                      | 1                      | 2                      | 3                      | 4                      |
|----------------------------------------------------|------------------------|------------------------|------------------------|------------------------|
| Number of contigs                                   | 69                     | 57                     | 1                      | 27                     |
| N50 value (Mb)                                      | 0.20                   | 0.10                   | 0                      | 0.14                   |
| Genome size (Mb)                                    | 4.80                   | 3.26                   | 3.33                   | 1.54                   |
| Protein- coding genes                               | 4741                   | 3062                   | 3199                   | 1464                   |
| RNAs                                               | 54                     | 45                     | 83                     | 37                     |
| Accession numbers                                   | JAGSND0000000000       | GCA_000426305          | GCA_010669305          | GCA_000488855          |
| Cofactors, vitamins, prosthetic groups, pigments    | 136                    | 100                    | 63                     | 64                     |
| Cell wall and capsule                               | 39                     | 28                     | 33                     | 10                     |
| Virulence, disease and defense                      | 53                     | 60                     | 49                     | 30                     |
| Potassium metabolism                                | 6                      | 2                      | 5                      | 1                      |
| Miscellaneous                                      | 17                     | 5                      | 5                      | 0                      |
| Phages, prophages, transposable elements, plasmids  | 3                      | 2                      | 10                     | 3                      |
| Membrane transport                                  | 54                     | 44                     | 30                     | 45                     |
| Iron acquisition and metabolism                     | 5                      | 8                      | 7                      | 0                      |
| RNA metabolism                                      | 50                     | 48                     | 37                     | 24                     |
| Nucleosides and nucleotides                         | 96                     | 91                     | 51                     | 29                     |
| Protein metabolism                                  | 142                    | 149                    | 169                    | 87                     |
| Cell division and cell cycle                        | 3                      | 3                      | 3                      | 3                      |
| Motility and chemotaxis                             | 28                     | 7                      | 0                      | 0                      |
| Regulation and cell signaling                       | 2                      | 12                     | 10                     | 2                      |
| Secondary metabolism                                | 4                      | 4                      | 4                      | 0                      |
| DNA metabolism                                      | 59                     | 67                     | 60                     | 51                     |
| Fatty acids, lipids, and isoprenoids                | 49                     | 21                     | 31                     | 22                     |
| Nitrogen metabolism                                 | 9                      | 5                      | 6                      | 0                      |
| Dormancy and sporulation                            | 2                      | 14                     | 6                      | 1                      |
| Respiration                                         | 38                     | 39                     | 13                     | 19                     |
| Stress response                                     | 31                     | 18                     | 29                     | 11                     |
| Metabolism of aromatic compounds                    | 7                      | 1                      | 2                      | 0                      |
| Amino acids and derivatives                         | 295                    | 190                    | 250                    | 55                     |
| Sulfur metabolism                                   | 6                      | 4                      | 4                      | 2                      |
| Phosphorus metabolism                               | 13                     | 7                      | 26                     | 3                      |
| Carbohydrates                                       | 309                    | 83                     | 111                    | 34                     |

Strain: 1, BAD-6\textsuperscript{T}; 2, *Anaerovorax odorimutans* NorPut\textsuperscript{T}; 3, *Aminipila butyrica* FH042\textsuperscript{T}; 4, *Eubacterium brachy* ATCC 35585\textsuperscript{T}
acetochlor and 67.4% of butachlor after inoculation for 14 days.

Chemotaxonomic characterisation

The strain produced acetate and butyrate after incubation for 3 days in PY medium. Strain BAD-6T could utilize carbohydrates and organic acids (D-cellobios, gentiobiose, D-turanose, D-melibiose, α-D-glucose, D-mannose, D-fructose, D-galacturonic acid, L-galactonic acid lactone, D-glucuronic acid, glucuronamide, tetrazolium violet, D-galactose, 3-methyl glucose, D-fucose, L-fucose, L-rhamnose, D-glucose-6-phosphate, D-fructose-6-phosphate, and sodium butyrate). Strain BAD-6T could only use serine for growth. Catalase, oxidase, nitrate-reducing activities, and indole production were not detected. Strain BAD-6T could hydrolyse esculin but not urea or gelatin. The strain were positive for activities of alkaline phosphatase, acid phosphatase, and naphthol-AS-BI-phosphohydrolase. In addition, esterase (C4) and leucine arylamidase were weakly positive. No substances could be used by BAD-6T as detected in the API 50CH system.

The major fatty acids (> 10%) of strain BAD-6T were C14:0 FAME (15.12%), C16:0 FAME (16.69%) and cyc-9,10-C19:0 DMA (10.13%). In addition, small amounts (> 5.0%) of iso-C15:0 FAME (5.18%), cis-7-C16:1 FAME (6.87%), and C16:0 DMA (8.09%) were also detected in strain BAD-6T (Table S2). However, respiratory quinone was not detected in strain BAD-6T.

Taxonomic conclusion

Some characteristics of the strain BAD-6T were compared with its neighboring genus (Table 2). Strain BAD-6T can utilize carbohydrates and D-serine, and has flagella, while the Ana. odorimutans NorPutT can not use any carbohydrates or amino acids and has 3–5 flagella. In addition, the G + C content of strain BAD-6T (43.6%) was much more than that of Ana. odorimutans NorPutT (31.5%). There were also some differences between strain BAD-6T and Ami. butyrica FH042T, e.g. Ami. butyrica FH042T could not use any carbohydrates. Ami. butyrica FH042T and BAD-6T could use different types of amino acids. The major fatty acids of strain BAD-6T are C14:0 FAME, C16:0 FAME and cyc-9,10-C19:0 DMA; while Ami. butyrica FH042T are C14:0, C16:0 DMA, C17:2/C17:1 9cw, and C18:1 9c DMA. The strain BAD-6T and E. brachy ATCC 35585T are also different in morphology, physiology and biochemistry, such as cell size, cell morphology, and carbohydrate utilization. It is worth noting that the similarities of 16S rRNA genes between the strain BAD-6T and other type strains are less than 95% and the phylogenetic trees of BAD-6T forms a separate branch with type strains based on the NJ, ML and ME algorithm.

In summary, phylogenetic analysis shows that strain BAD-6T belongs to a novel genus. Due to cell morphology, growth temperature, carbon source assimilation, DNA G + C content and fatty acid profile, the BAD-6 strain can be clearly distinguished from other strains (Table 2). In addition, the ANI and dDDH values between the strain BAD-6 and Ana. odorimutans NorPutT, Ami. butyrica FH042T, E. brachy ATCC 35585T were significantly lower than the recommended cut-off values for the species boundary. Thus, based on the data, we propose the novel genus Sinanaerobacter gen. nov. in the order Clostridiales to accommodate strain BAD-6T as Sinanaerobacter chloroacetimidivorans.

Description of Sinanaerobacter gen. nov.

Sinanaerobacter (M.L. fem. n. Sina China; Gr. pref. an- not; Gr. masc. n. aer air; N.L. masc. n. bacter a rod; N.L. masc. n. Sinanaerobacter an anaerobic rod from China).

Obligately anaerobic, motile rods. Gram-stain-positive. Utilize carbohydrates and D-serine. Oxidase and catalase activities are negative. Compounds even-numbered fatty acids or fatty acid methyl esters are major components of cellular fatty acids. Does not have any respiratory quinones. The genus belongs to the order Clostridium.

The type species is Sinanaerobacter chloroacetimidivorans.

Description of Sinanaerobacter chloroacetimidivorans gen., nov. sp. nov.

Sinanaerobacter chloroacetimidivorans (chlo.ra.ce.mi.dio'rans. N.L. neut. n. chloracetimidum chloracetimid; L. pres. part. Vorans eating; N.L. part. adj. chloracetimidivorans eating chloracetimide).
Cells are straight to gently curved rods with flagella, 0.3–0.5 μm in diameter and 1.8–2.5 μm in length, and motile with peritrichous flagella. Spore formation is not observed. Colonies on PYT agar are faint yellow with a smooth surface. B-vitamins are not required for growth. Grows at 16–42°C (optimum 30°C), pH 6.3–8.0 (optimum pH 7.2–7.5) and 0–5% w/v NaCl (optimum 0% w/v) were observed. Fermentation can produce acetate and butyrate in PY medium. Carbohydrates and organic acids (D-cellobios, gentiobiose, D-turanose, D-melibiose, α-D-glucose, D-mannose, D-fructose, D-galacturonic acid, L-galactonic acid lactone, D-glucuronic acid, glucuronamide, tetrazolium violet, D-galactose, 3-methyl glucose, D-fucose, L-fucose, L-rhamnose, D-serine, D-glucose-6-phosphate, D-fructose-6-phosphate, and sodium butyrate.) improve the strain growth. Only D-serine can be utilized. Does not utilize other amino acids (L-alanine, L-arginine, L-aspartic acid, L-glutamic acid, L-histidine, L-pyroglutamic acid, L-serine and D-aspartic acid). Oxidase, catalase and nitrate-reducing activities are negative. Esculin is hydrolysed, but urea and gelatin are not hydrolysed. Indole and arginine dihydrolase are not produced. The strain is positive for activities of alkaline phosphatase, acid phosphatase, and naphthol-AS-BI-phosphohydrolase. In addition, esterase (C4) and leucine arylamidase are weakly positive. The genomic DNA G+C content is 43.6 mol%. C14:0 FAME, C16:0 FAME, cyc-9,10-C19:0 DMA are detected as major components by the cellular fatty acid analysis. Does not have any respiratory quinones.

The GenBank/EMBL/DDBJ accession numbers for the 16S rRNA gene sequences and the whole genome of strain BAD-6T are MW727621 and JAGSND0000000000, respectively. The type strain BAD-6T (= CCTCC AB 2021 092T = KCTC 25290T) was isolated from the anaerobic acetochlor-degrading sludge in Kunshan City, Jiangsu Province, China.

### Table 2 Major physiological characteristics of strain BAD-6T and its phylogenetic neighbours. All strains are Gram-stain positive and no spore

| Characteristics          | 1                  | 2                  | 3                  | 4                  |
|--------------------------|--------------------|--------------------|--------------------|--------------------|
| Isolation source         | Anaerobic sludge  | Anoxic brackish    | Methanogenic reactor of cattle waste | Human Periodontitis |
| Cell shape               | Straight to gently curved rods | Slightly curved rods | Straight to gently curved rods | Coccioid/rods |
| Cell size (μm)           | 0.3–0.5 × 1.8–2.5 | 0.7–0.8 × 1.9–2.7  | 0.7–1.0 × 3.0–40   | 0.4–0.8 × 1.0–3.0  |
| Motility                 | +                  | +                  | +                  | -                  |
| Temperature range (optimum (°C)) | 16–42 (30)        | 12–50 (30)         | 10–35 (30)         | 37 (optimum)       |
| pH growth range (optimum) | 6.3–8.0 (7.2–7.5) | 5.1–8.0 (7.2–7.6)  | 5.3–8.2 (6.1–6.8)  | NR |
| Carbohydrates            | +                  | -                  | -                  | NR |
| Amino acids              | D-serine           | -                  | L-Arginine, L-Lysine, L-Serine | NR |
| PY Fermentation acid production | Acetate, butyrate | Acetate, butyrate | Acetate, butyrate | Isovalerate, isobutyrate, acetate, formate, succinate |
| Major CFAs               | C14:0 FAME, C16:0 FAME, cyc-9,10-C19:0 DMA | NR | C14:0, C16:0 DMA, C17:2/C17:1 9cw, C18:1 9c DMA | NR |
| Genomic DNA G + C content (mol%) | 43.6 | 31.5 | 44.7 | 37.9 |

Strain: 1, BAD-6T; 2, Anaerovorax odorimutans NorPutT; 3, Aminipila butyrica FH042T; 4, Eubacterium brachy ATCC 33089T. +, Positive, negative, NR, not determined
Author contributions Conceptualization, funding acquisition, and supervision: Jian He and Na Li; Laboratory work, data analysis and writing-original draft: Yixuan Bao; Writing-review and editing: Junwei Liu, Xuan Zhang, Peng Lei, Jiguo Qiu. All authors read and approved the final manuscript.

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Data availability The GenBank/EMBL/DDBJ accession numbers for the 16S rRNA gene sequences and the whole genome of strain BAD-6T are MW727621 and JAGSND000000000, respectively.

Declarations

Conflict of interest The research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. All the authors declare that they have no conflict of interest.

Consent to participate All authors agree to have participated in the research proposed to be published and agree to be published in the journal.

Consent for publication All authors agree to have participated in the research proposed to be published and agree to be published in the journal.

Ethical approval The authors have declared that no ethical issues exist.

Human and animal participants This article does not contain any studies with human participants or animals performed by any of the author.

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