Gelria glutamica gen. nov., sp. nov., a thermophilic, obligately syntrophic, glutamate-degrading anaerobe

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A novel anaerobic, Gram-positive, thermophilic, spore-forming, obligately syntrophic, glutamate-degrading bacterium, strain TGOT, was isolated from a propionate-oxidizing methanogenic enrichment culture. The axenic culture was obtained by growing the bacterium on pyruvate. Cells were rod-shaped and non-motile. The optimal temperature for growth was 50–55 °C and growth occurred between 37 and 60 °C. The pH range for growth was 5–8 with optimum growth at pH 7. In pure culture, strain TGOT could grow on pyruvate, lactate, glycerol and several sugars. In co-culture with the hydrogenotrophic methanogen Methanobacterium thermautotrophicum strain Z-245, strain TGOT could grow on glutamate, proline and Casamino acids. Glutamate was converted to H2, C O2, propionate and traces of succinate. Strain TGOT was not able to utilize sulphate, sulphite, thiosulphate, nitrate or fumarate as electron acceptors. The G+C content was 33.8 mol%. Sequence analysis of the 16S rDNA revealed that strain TGOT belongs to the thermophilic, endospore-forming anaerobes, though no close relations were found. Its closest relations were Moorella glycerini (92%) and Moorella thermoacetica (90%). Strain TGOT had an unusually long 16S rDNA of more than 1700 bp. The additional base pairs were found as long loops in the V1, V7 and V9 regions of the 16S rDNA. However, the loops were not found in the 16S rRNA. The name Gelria glutamica gen. nov., sp. nov. is proposed for strain TGOT

Keywords: thermophilic bacteria, interspecies hydrogen transfer, obligate syntrophic glutamate oxidation, proline oxidation, propionate formation

INTRODUCTION

Because proteins are encountered in almost every ecosystem, the biodegradation of amino acids is a very important microbial process. The conversion of amino acids in methanogenic environments has been studied over the last 20 years, especially in temperate environments (Barker, 1981; Nagase & Matsuo, 1982; McInerney, 1989). However, in moderately thermophilic methanogenic environments, the degradation of amino acids has not been studied in detail. Only a few bacterial species have been described to degrade amino acids under thermophilic conditions (Cheng et al., 1992; Örlygsson, 1994; Tarlera et al., 1997; Plugge et al., 2000).

Glutamate conversion under methanogenic conditions can occur in different ways (Table 1). The formation of acetate and butyrate as the organic end-products has been described for many anaerobes that belong mainly to the genus Clostridium. This type of conversion of glutamate is hydrogen independent. Other examples of hydrogen-independent glutamate conversions are the homoacetogenic fermentation (Dehning et al., 1989) and the reductive formation of propionate (Nanninga et al., 1987). The formation of hydrogen is more likely to occur in methanogenic environments, where hydrogen-scavenging methanogens convert the hydrogen to methane with the concomitant reduction of CO₂. In the presence of methanogens, the free energy available from the overall reactions is higher (Table 1). Under
Table 1. Change of free energy for the conversion of glutamate to various products at 55 °C under anaerobic conditions

<table>
<thead>
<tr>
<th>Reaction</th>
<th>ΔG' (kJ) 10⁶ Pa H₂</th>
<th>1 Pa H₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glutamate + 2H₂O → acetate + HCO₃⁻ + ßH⁺ + NH₃ + ßbutyrate</td>
<td>-61.1</td>
<td>-61.1</td>
</tr>
<tr>
<td>Glutamate + 3H₂O → 2acetate + HCO₃⁻ + H⁺ + NH₃ + H₂</td>
<td>-41.6</td>
<td>-73.1</td>
</tr>
<tr>
<td>Glutamate + 2H₂O → 2acetate + 2HCO₃⁻ + ßH⁺ + NH₃</td>
<td>-64.0</td>
<td>-64.0</td>
</tr>
<tr>
<td>Glutamate + 2H₂O → 1acetate + ßpropionate + ßHCO₃⁺ + 2ßH⁺ + NH₄⁺</td>
<td>-69.0</td>
<td>-69.0</td>
</tr>
<tr>
<td>Glutamate + 4H₂O → propionate + 2HCO₃⁻ + NH₃ + 2H₂</td>
<td>-160.0</td>
<td>-79.0</td>
</tr>
</tbody>
</table>

standard conditions, these reactions yield small amounts of energy. In particular, the exclusive formation of propionate from glutamate is very difficult, since the free energy at 55 °C is only -160 kJ (mol glutamate)-¹ (Table 1). It is highly unlikely that a single organism can perform this reaction. However, in a methanogenic consortium, the hydrogen formed is consumed via interspecies hydrogen transfer and the energy that becomes available from this reaction increases to -790 kJ (mol glutamate)-¹.

Earlier research indicated the presence of a propionate-forming, obligately syntrophic bacterium in a thermophilic, syntrophic, glutamate-degrading, propionate-oxidizing enrichment (Stams et al., 1992). From this mixed culture, we isolated a bacterium that produced propionate as the major product from glutamate, in addition to traces of succinate. In this paper, we present detailed information about the organism and we propose to name the organism Gelria glutamica gen. nov., sp. nov.

METHODS

Strains and source of organisms. The glutamate-degrading strain TGO⁰ was isolated from a thermophilic, syntrophic, propionate-oxidizing enrichment culture as described by Stams et al. (1992). Strain TPO, a syntrophic, propionate-oxidizing bacterium, was isolated from the same enrichment culture. Morrella thermoacetae DSM 521¹ and Morrella glycercini DSM 1125⁴ were obtained from the DSMZ. Methanobacterium thermotrophicum Z-245 (= DSM 3720) has been used before; this methanogen was recently renamed Methanothermobacter thermautotrophicus Z-245 (Wasserfallen et al., 2000).

Media and cultivation. A bicarbonate-buffered medium with the following composition was used (l⁻¹): 0.4 g KH₂PO₄, 0.53 g Na₂HPO₄, 0.3 g NH₄Cl, 0.3 g NaCl, 0.1 g MgCl₂, 0.6H₂O, 0.11 g CaCl₂ 2H₂O, 1 ml alkaline trace element solution, 1 ml acid trace element solution, 1 ml vitamin solution, 0.5 mg resazurin, 4 g NaHCO₃, 0.25 g Na₂S, 7.9H₂O and 0.5 g yeast extract. The trace elements and vitamins were as described in Stams et al. (1993). All compounds were heat-sterilized except for the vitamins and the solution of Na₂S, 7.9H₂O, which were filter-sterilized. Incubations were done in serum bottles sealed with butyl rubber stoppers (Rubber bv) and a gas phase of 182 kPa N₂/CO₂ (80.20, v/v). For the cultivation of methanogens, a gas phase of 182 kPa H₂/CO₂ (80.20, v/v) was used and, after growth, the gas phase was changed to N₂/CO₂. Organic substrates were added from anaerobic sterile stock solutions, to final concentrations of 20 mM (unless otherwise stated). To obtain an axenic culture, soft agar (0.7–0.8 % agar noble; Difco) was added to the medium described above, supplemented with 20 mM pyruvate as the carbon source. Light microscopy confirmed purity.

For the reconstitution experiments with axenic cultures of strain TGO⁰ (5 %, v/v), strain TPO (2 %, v/v) and Methanobacterium thermotrophicum Z-245 (2 %, v/v) were inoculated in medium with 20 mM glutamate.

Temperature and pH. The temperature optimum was determined in bicarbonate-buffered medium containing 20 mM pyruvate at pH 7 and duplicate bottles were incubated at temperatures ranging from 30 to 75 °C. The pH optimum was tested in medium by adding 0.15 g KH₂PO₄ L⁻¹ instead of sodium bicarbonate. The pH value of the medium containing 20 mM pyruvate was adjusted with NaOH or HCl under the N₂ atmosphere. Duplicate bottles were incubated at 55 °C at pH values ranging from 4.5 to 9.5. For determinations of the temperature and pH optimum, OD₆₅₀ and acetate production were measured as indicators for growth.

Growth and substrate utilization. Utilization of substrates by strain TGO⁰ in pure culture and in co-culture with Methanobacterium thermotrophicum Z-245 was determined by monitoring growth and substrate depletion as well as product formation. All incubations were performed at 55 °C, pH 7. The effect of electron acceptors on the growth of strain TGO⁰ was tested in medium with 20 mM glutamate.

G + C content. Isolation and purification of genomic DNA was carried out according to Marmur (1961). The G + C content of the DNA was analysed using thermal denaturation as described by Owen et al. (1969).

16S rDNA sequence analysis. Total DNA was extracted from strain TGO⁰ as described previously (Zoetendal et al., 1998). PCR was performed with the bacterial primers 7f and 1510r (Lane, 1991) by using the Tag DNA polymerase kit (Life Technologies) to amplify the bacterial 16S rDNA. PCR products were purified with the Qiaquick PCR purification kit (Qiagen) according to the manufacturer’s instructions. Primers 538r, 1100r (Lane, 1991) and 968f (Nübel et al., 1996) labelled with Infrared Dye 41 (MWG-Biotech) were
used as sequencing primers. The sequences were analysed automatically on a LI-COR DNA sequencer 4000L and corrected manually. Phylogenetic analysis and tree construction were performed with the programs of the ARB software package (Strunk & Ludwig, 1991). FASTA homology searches with sequences of the EMBL and GenBank DNA databases were performed and the results were compared with those obtained with the ARB programs. Because strain TGO could add additional loops in several regions of the 16S rDNA, we did the database comparison with the complete sequence of 1725 bp and also with the sequence without the additional loops.

**RNA isolation, RT-PCR and dot-blot hybridizations.** RNA was extracted from strain TGO as described by Zoetenbal et al. (1998). Specific probes targeting the V1, V7 and V9 regions of the 16S rDNA of strain TGO were applied in order to investigate whether such additional loops were also present in the 16S rRNA. The sequences of these oligonucleotides were 5'-GCTCTGGGCGTATTAGA-3' (V1 region), 5'-GTTAACCCTTGGCTTTG-3' (V7 region) and 5'-CTCAATCCCGAAGTITAA-3' (V9 region). Primer 538r (Lane, 1991) was used as a positive control for Eubacteria. Dot-blot hybridizations were performed with strain TGO, Moorella thermoacetica, Moorella glycerini and Escherichia coli as described by Oude Elferink et al. (1997). All membranes were hybridized overnight at 40 °C. RT–PCR of the 16S rRNA genes of strain TGO, Moorella thermoacetica, Moorella glycerini and Escherichia coli was performed by means of bacterial primers 7f and 1510r using the Access RT–PCR system (Promega). Prior to the RT–PCR amplification, the samples were incubated with RNase-free DNase (Promega) to remove all traces of DNA. The integrity and size of the nucleic acids were determined visually after electrophoresis on a 1-2% agarose gel containing ethidium bromide in the presence of markers and compared with the 16S rDNA of strain TGO.

**Other methods.** Gases and organic acids were analysed by GC and HPLC as described by Pluge et al. (2000). Amino acids were analysed by HPLC as described by Kengen & Stams (1994). Occasionally, glutamate was determined enzymically with glutamate dehydrogenase as described by Bernt & Bergmeyer (1974). Ammonium was analysed by the indophenol-blue method (Hanson & Philipps, 1981). Inorganic compounds tested as electron acceptors were analysed by HPLC as described by Scholten & Stams (1995). Gram and flagella staining were done by standard procedures as described previously (Pluge et al., 2000).

**RESULTS AND DISCUSSION**

**Isolation of the glutamate-oxidizing strain TGO**

A thermophilic, syntrophic, propionate-oxidizing enrichment, as described by Stams et al. (1992), was also able to convert glutamate to acetate, NH$_4^+$, HCO$_3^-$ and CH$_4$. When the enrichment culture was growing on glutamate, a small, rod-shaped bacterium became predominant. It was not possible to obtain the bacterium in pure culture by adding an inhibitor of methanogenesis (bromoethanesulphonic acid, BES) to the enrichment culture. No degradation of glutamate was observed when BES was added. The bacterium could be purified by serial dilution in media containing agar (0.7–1.0%) with pyruvate as the organic substrate. The colonies that appeared in the agar and on the surface of the agar were 0.7–1.0 mm in diameter. The colonies were white and round at the surface and lens-shaped in the agar. A single colony picked from the agar grew in medium containing pyruvate and with 0.05% yeast extract. Repeated transfer from liquid medium to soft-agar medium resulted in an axenic culture of a strain designated TGO. This strain was characterized further.

**Morphology and cellular characterization**

The isolated strain TGO is a rod-shaped, spore-forming organism. The Gram stain was positive. Cells were 0.5 μm in diameter and 1–1.5 μm in length when grown on pyruvate (Fig. 1). If the bacterium was grown on glucose, the cells were 0.5 μm in diameter and 3–20 μm in length. Spores were located terminally and were 0.5 × 0.5 μm in size and developed in the late exponential phase. Motility was never observed, nor were flagella found.

**Physiological characterization**

Strain TGO was able to grow on glutamate only in the presence of the methanogenic archaeon Methanobacterium thermotrophicum Z-245. Glutamate (15 mM) was converted to propionate (12.9 mM), succinate (1.0 mM), NH$_4^+$ (14.9 mM) and CH$_4$ (8.9 mM). The carbon and electron recovery were respectively 93 and 98% (excluding the biomass formed). The doubling time of strain TGO in co-culture with Methanobacterium thermotrophicum Z-245 on glutamate was 0-23 day$^{-1}$. Several thermophilic bacteria are known to utilize glutamate with the concomitant production of H$_2$, but these organisms also grow in pure culture on glutamate. Caloramator proteocalculus, Caloramator coloannisii and Thermaferrovibrio acidaminovorans (Cheng et al., 1992; Tarlera & Stams, 1999; Pluge et al., 2000) are examples of such thermophilic glutamate-degrading organisms. In pure

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**Fig. 1.** Phase-contrast micrograph of strain TGO grown on pyruvate. The arrow indicates the start of spore formation. Bar, 5 μm.
culture, they form acetate, $\text{NH}_4^+$, $\text{CO}_2$, and $\text{H}_2$. *Thermanaerovibrio acidaminovorans* also forms propionate in pure culture. When *Thermanaerovibrio acidaminovorans* is grown in co-culture with a methanogen, the products formed from glutamate conversion shift in favour of propionate formation. However, considerable amounts of acetate are still formed. Examples of mesophilic glutamate-degrading organisms that show the same degradation products as *Thermanaerovibrio acidaminovorans* are *Acidaminobacter hydrogenoformans* and *Aminobacterium mobile* (Stams & Hansen, 1984; Baena et al., 2000). Like strain TGO$^T$, *Aminobacterium mobile* only grows on glutamate in the presence of a hydrogen scavenger.

Strain TGO$^T$ is the first example of an organism that is unable to form acetate from glutamate and forms mainly propionate. As a consequence, the organism has to grow in a syntrophic co-culture with a methanogen, since the free energy under standard conditions is only slightly negative (Table 1). It is unclear why strain TGO$^T$ does not form acetate from glutamate, even though acetate production could be detected after growth on several sugars, lactate and pyruvate. The formation of traces of succinate during glutamate utilization suggests that direct oxidation takes place via $\alpha$-ketoglutarate and succinyl-CoA. This pathway was also suggested to be used in propionate formation in *Thermanaerovibrio acidaminovorans* and *Acidaminobacter hydrogenoformans* (Cheng et al., 1992; Stams & Hansen, 1984).

Yeast extract (minimum 0·02%) was required for growth. Pyruvate was converted by strain TGO$^T$ to acetate, propionate, succinate (traces), $\text{H}_2$, and $\text{CO}_2$. Glycerol was utilized slowly by the pure culture but, in co-culture, glycerol was converted rapidly to acetate, traces of propionate and $\text{CH}_4$.

Other substrates that could be used by the pure culture of TGO$^T$ were lactate, arabinose, fructose, galactose, glucose, maltose, mannitol, rhamnose and sucrose. Sugars were converted mainly to acetate and propionate with the formation of traces of hydrogen and formate.

In co-culture with the methanogen *Methanobacterium thermoautotrophicum* Z-245, strain TGO$^T$ could also grow on Casamino acids, $\alpha$-ketoglutarate and proline. Proline (18·6 mM) was degraded to propionate (17·3 mM), $\text{NH}_4^+$ (18·2 mM) and $\text{H}_2$ (27·2 mM) and the amount of hydrogen formed was calculated from the amount of methane measured. Anaerobic proline oxidation has been reported for two other bacteria, *Desulfobacterium vacuolatum* (Rees et al., 1998), a versatile amino acid-utilizing sulphate reducer, and *Geovibrio ferrireducens* (Caccavo et al., 1996), an iron-reducing bacterium, can couple the oxidation of proline to sulphate reduction and dissimilatory Fe(III) reduction, respectively. The study of fermentative proline utilization by anaerobes has focussed on its use as an electron acceptor (McInerney, 1989). Strain TGO$^T$ might be able to convert proline to glutamate with the reverse reactions of proline synthesis via glutamate semialdehyde.
No growth of strain TGO$^T$ was observed in pure culture or in co-culture with Methanobacterium thermotrophicum Z-245 on aspartate, alanine, lysine, threonine, leucine, tyrosine, glycine, fumarate, malate, succinate, propionate, acetate, methanol, ethanol, propanol, butanol, acetone, benzoate, starch or H$_2$/CO$_2$. The following mixtures of amino acids were tested but were not utilized by the pure culture of strain TGO$^T$: alanine + glycine, alanine + arginine, alanine + proline, leucine + glycine, leucine + arginine, leucine + proline, H$_3$ + glycine, H$_4$ + arginine and H$_2$ + proline. The strain could not grow in the presence of traces of oxygen, nor could sulphate, sulphite, thiosulphate or nitrate serve as electron acceptors.

Strain TGO$^T$ could grow on glucose between 37 and 60 °C with an optimum at 50–55 °C. The pH range for growth was 5–5–8, with optimum growth at pH 7.

**Reconstitution of the original consortium from axenic cultures of strain TGO$^T$, strain TPO and Methanobacterium thermotrophicum Z-245**

In order to investigate glutamate utilization as originally observed in the propionate-oxidizing enrichment culture, we performed reconstitution experiments with three axenic cultures: strain TGO$^T$, strain TPO (the syntrophic propionate-oxidizing organism) and Methanobacterium thermotrophicum Z-245. In the original enrichment culture, glutamate was degraded to acetate, CH$_3$, NH$_3$ and CO$_2$, with the intermediate production of propionate (Fig. 2a). The stoichiometry of glutamate conversion was:

$$\text{Glutamate}^- + 3\frac{1}{2}\text{H}_2\text{O} \rightarrow \text{acetate}^- + 1\frac{1}{2}\text{CH}_4 + 1\frac{1}{2}\text{HCO}_3^- + \frac{3}{2}\text{H}^+ + \text{NH}_4^+$$

In the reconstitution experiments, glutamate was consumed according to the stoichiometry described above (Fig. 2b). This indicated that the axenic cultures of strain TGO$^T$ and strain TPO had the same physiological capabilities as in the original enrichment cultures.

**Phylogeny**

The nucleotide sequence (1725 bp) of the 16S rDNA of strain TGO$^T$ was analysed and it revealed that this organism belongs to the subphylum of Gram-positive, endospore-forming, thermophilic, anaerobic bacteria. Sequence alignment revealed that strain TGO$^T$ had additional loops in the V1, V7 and V9 helices of the 16S rDNA. There are examples of other organisms with 16S rDNA that exceeds the mean length of 1500 bp. In thermophiles, it is not unusual that the 16S rDNA is longer (Rainey et al., 1996). Dot-blot hybridizations with specific oligonucleotides against these regions showed no hybridization with 16S rRNA from strain TGO$^T$, Moorella glycerini, Moorella thermoacetica and Escherichia coli. The positive control with primer 538r reacted with all 16S rRNA molecules. This indicated that the loops were not transcribed from the 16S rDNA to the 16S rRNA. The 16S rRNA observed with the dot-blot hybridizations showed that the sizes were respectively 1700 and 1500 bp. This confirms the absence of the loops in the 16S rRNA observed with the dot-blot hybridizations (Fig. 3). It is unclear how the transcription of the rRNA is regulated.

Sequence analysis showed that strain TGO$^T$ is only distantly related to Moorella glycerini and Moorella thermoacetica (Slobodkin et al., 1997; Collins et al., 1994), with respective levels of similarity of 92 and 90%. The similarities were calculated with the use of the 16S rDNA sequence of strain TGO$^T$ without the additional loops. A phylogenetic tree showing the relationship of strain TGO$^T$ and other related species is depicted in Fig. 4.

The G+C content of strain TGO$^T$ was 33.8 mol %.

**Taxonomy**

Our findings indicate that strain TGO$^T$ differs physiologically and phylogenetically from previously described species. Strain TGO$^T$ is phylogenetically most similar to the genus Moorella (90–92% similarity), but

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Fig. 4. Phylogenetic tree showing the position of strain TGO among representatives of thermophilic, anaerobic spore-forming genera. The tree is based on a distance matrix of 16S rRNA sequences and was constructed using the neighbour-joining method corrected by the method of Felsenstein (1982). Bar, 0.1 (evolutionary distance).
the phylogenetic relationship is not sufficiently close to classify strain TGO<sup>T</sup> in this genus. Also, the ability of strain TGO<sup>T</sup> to form solely propionate from glutamate separates it from members of this genus. Therefore, we propose a novel genus and species, *Gelria glutamica* gen. nov., sp. nov.

**Description of *Gelria* gen. nov.**

*Gelria* (Gel.ri’a. N.L. fem. n. *Gelria* Gelre or Gelderland, one of the 12 provinces of The Netherlands, in which Wageningen is located).


**Description of *Gelria glutamica* sp. nov.**

*Gelria glutamica* (glu.ta’mi.ca. N.L. n. *acidum glutamicum* glumatic acid: N.L. fem. adj. glutamica referring to glutamic acid, on which the bacterium grows).

Cells are 0.5 × 0.5–6 μm, varying depending on the growth substrate. In pure culture, the cells can grow on pyruvate, lactate, glycerol, glucose, rhamnose and galactose. In syntrophic association with a hydrogenotrophic methanogen, the organism can utilize glutamate, α-ketoglutarate, proline, Casamino acids and a variety of sugars. Glutamate and proline are oxidized to propionate, H<sub>2</sub>, NH<sub>3</sub> and CO<sub>2</sub>. Sugars are converted to acetate, propionate, CO<sub>2</sub> and H<sub>2</sub> as main products. Growth occurs between 37 and 60 °C with optimum growth at 50–55 °C and at pH 5.5–8 (optimum pH 7). The DNA G + C content is 33–8 mol %.

The type strain is TGO<sup>T</sup> (= DSM 14054<sup>T</sup> = ATCC BAA-262<sup>T</sup>).

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**REFERENCES**


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