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Liu, Ze-hua; Maszenan, Abdul Majid; Liu, Yu; Ng, Wun Jern

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Ze-hua Liu^{ab}, Abdul Majid Maszenan^b, Yu Liu^{bc} & Wun Jern Ng^{bc}

^a College of Environment and Energy, South China University of Technology, Guangzhou 510006, China, Tel. +86 20 39380507

^b Advanced Environmental Biotechnology Centre, Nanyang Environment and Water Research Institute, Nanyang Technological University, CleanTech One, Singapore 637141, Singapore, Tel. +65 6513 7363 (A.M. Maszenan), +65 6790 4104 (Y. Liu), +65 6790 6813 (W.J. Ng)

^c School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore

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A brief review on possible approaches towards controlling sulfate-reducing bacteria (SRB) in wastewater treatment systems

Ze-hua Liu^{a,b,*}, Abdul Majid Maszenan^b, Yu Liu^{b,c}, Wun Jern Ng^{b,c}

^aCollege of Environment and Energy, South China University of Technology, Guangzhou 510006, China, Tel. +86 20 39380507; email: zehualiu@scut.edu.cn (Z.-H. Liu)

^bAdvanced Environmental Biotechnology Centre, Nanyang Environment and Water Research Institute, Nanyang Technological University, CleanTech One, Singapore 637141, Singapore, Tel. +65 6513 7363; email: CMaszenan@ntu.edu.sg (A.M. Maszenan), Tel. +65 6790 4104; email: CYLiu@ntu.edu.sg (Y. Liu), Tel. +65 6790 6813; email: WJNg@ntu.edu.sg (W.J. Ng)

^cSchool of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore

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ABSTRACT

Anaerobic processes in wastewater treatment and excess sludge digestion are desirable as these offer the prospect of energy recovery via the methane gas generated. However, hydrogen sulfide (H₂S) generated from reduction of sulfate by sulfate reducing bacteria (SRB) during the process, is inhibitory to the methane producing bacteria (MPB). The SRBs and MPBs also compete for utilization of a key substrate in methanogenesis, volatile fatty acids. For development of effective methods to mitigate the adverse impact of SRBs on methanogenesis, it is important there is better understanding of the SRBs and this can begin with knowing which species are likely to be present in wastewater treatment. With this objective in mind, species of SRBs isolated from wastewater treatment systems reported in the literature have been summarized in this paper and discussed.

Keywords: Anaerobic digestion; SRB species; Hydrogen sulfide; Wastewater treatment systems

1. Introduction

Anaerobic digestion (AD) is a method engineered to decompose organic matter by a variety of anaerobic micro-organisms under oxygen-free conditions. The process has a number of advantages related to cost of operation which is important to the industry. These advantages include much lower production of excess

sludge, and energy recovery via the biogas generated [1–3]. Notwithstanding these advantages there is a perception that AD processes are not easy to operate stably and this may be due to “unexpected” issues such as competition and inhibition [1,4]. An example is the inhibition caused by H₂S which may be produced by a group of micro-organism commonly referred to as the sulfate reducing bacteria (SRBs). Inhibition by H₂S is related to two aspects. Firstly

*Corresponding author.

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there can be competition for utilization of substrates, the volatile fatty acids (VFAs), between the SRBs and methane producing bacteria (MPBs), in which the SRBs are better able to compete [5]. With successful competition for the substrates, the SRBs generate H_2S and the undissociated form is more inhibitory to MPBs than SRBs [1]. Apart from inhibiting the MPBs, the gaseous H_2S in the biogas generated is strongly corrosive to the gas handling equipment which follows [6]. To reduce incidence of H_2S inhibition, chemical, and biological technologies are available. The chemical technologies include precipitation by addition of metal salts and addition of oxidizing reagents such as chlorine, hydrogen peroxide as well as potassium permanganate, to oxidize the sulfide. The biological methods include biological oxidation of H_2S by sulfide-oxidizing bacteria and activity inhibition of the SRBs [6]. Among these efforts, inhibition of SRB activity is theoretically most desirable as it would prevent formation of the sulfide ion in the first instance. To achieve this, better understanding of the SRBs such as its growth properties is necessary.

2. SRBs in wastewater treatment systems

SRBs comprise a metabolically versatile group of micro-organisms of many different families and genera. SRBs were formerly considered obligate anaerobic micro-organisms which use sulfate or other oxidized sulfur compounds as the terminal electron acceptor. However, this understanding is now considered not completely correct [7]. Since the 1990s, examples have been found of SRBs which could reduce oxygen and nitrate for energy in oxic conditions wherein their respirations only occurred in the microaerophilic environment and this would decline or halt at increased concentrations of oxygen [8,9]. Later it was proven that some SRBs favored use of oxygen as the electron acceptor, with nitrate/nitrite next, and sulfur compounds as the least favored [10].

SRBs include *Bacteria* and *Archaea*, with complex physiology, and various properties have been used in their classification [11]. Most of the SRBs described to date belong to one of five phylogenetic lineages: (a) the mesophilic δ -*Proteobacteria* with genera *Desulfovibrio*, *Desulfobacterium*, *Desulfobacter*, *Desulfobulbus*, *Desulfomicrobium*, *Desulfomonas*, *Desulfococcus*, *Desulfomonile*, *Desulfonema*, and *Desulfosarcina*; (b) the thermophilic gram-negative bacteria with the genus *Thermodesulfovibrio*, *Thermodesulfobacterium*, and *Thermodesulfobium*; (c) the gram-positive bacteria with the genus *Desulfotomaculum*, *Desulfosporosinus*, and *Desulfosporomusa*; (d) the *Euryarchaeota* with the genus *Archaeoglobus*; and (e)

the *Crenarchaeota* with the genus *Thermocladium* and *Caldirevira* [12–15]. Important parameters such as morphology, mobility, guanidine and cytosine (G+C) content of DNA, and growth properties are included in Table 1. Only species isolated from wastewater related sources have been included. SRBs belonging to the *Euryarchaeota* and *Crenarchaeota* have not been reported found in wastewater related sources.

3. Possible approaches towards controlling SRBs

Given the competition SRBs may pose to MPBs and that the H_2S generated by the SRBs has inhibitory, corrosive, and odorous properties, there is interest in methods which can be applied to control numbers of SRBs in a population or to control their activities. The following discussion is on three possible approaches and possibility of success:

- (1) The temperature and pH range suitable for SRB growth have been reported to be from 3 to 70°C, and 4.5 to 9.2, respectively. This would suggest that neither temperature nor pH can be effectively used to eliminate SRBs. It has been reported in the literature, to reduce competitive utilization of VFAs between SRBs and MPBs, a short-term low temperature shock at 12–15°C over 3 d was performed on an upflow anaerobic sludge bed reactor. No significant change in utilization of COD by the SRBs was noted. Changing the pH in the same reactor also had not helped [16].
- (2) The literature review (Table 1) has indicated all species reported other than *Desulfovibrio aerotolerans*, are obligate anaerobes. They had shown no growth but could tolerate an aerobic environment for at least 13 h. Their ability of reducing sulfate could be immediately recovered once the anoxic environment was re-established. The requirement for a strictly anaerobic growth condition offers possibility of an approach for inhibiting SRB growth and activity. In Tang et al. [17] study, inhibition of SRBs was successfully obtained through micro-aeration at a municipal solid-waste digester. H_2S in the biogas had then decreased from 680 to below 5 mg/L, while production of methane gas was little affected. Dissimilatory sulfite reductase genes associated with SRBs were, nevertheless, detected in the presence of the micro-aeration condition. This would suggest that H_2S was

Table 1
SRB isolated from wastewater

Category	Genus	Specie	Source	Shape	G+C (%)	Growth conditions		Substrate and electron transfer and other main conclusions	Ref.
						Temperature ^a	pH		
Mesophilic δ - <i>Proteobacteria</i>	<i>Desulfovibrio</i>	<i>Legallis</i>	Wastewater digester	Rod	55	22–43 (35) ^b	5–9.2 (7.3–7.5)	(1) Sulfate, sulfite, thiosulfate, elemental sulfur, and fumarate serve as electron acceptor instead of nitrate and nitrite;	[19]
								(2) Lactate, pyruvate, fumarate, ethanol, succinate, and hydrogen serve as electron donors in the presence of sulfate as terminal electron acceptor. Lactate is incompletely oxidized to acetate;	
								(3) Substrates that cannot be utilized include acetate, propionate, malate, valerate, formate, methanol, glycerol, mannitol, mannose, xylose, casamino acids, fructose, glucose, and ribose	
		<i>Marrakechensis</i>	Olive wastewater	Rod	65.1	20–50 (37)	6.5–8.5 (7)	(1) Sulfate, sulfite, thiosulfate, elemental sulfur, and fumarate serve as electron acceptor instead of nitrate and nitrite;	[20]
								(2) Strictly anaerobic, but with limited growth in the absence of sulfate under air in basal medium containing lactate and yeast extract;	
								(3) Hydrogen and formate can only be utilized in the presence of acetate	
		<i>Aminophilus</i>	Dairy wastewater	Vibrios	66	25–40 (35)	6.7–8 (7.5)	(1) In the presence of acetate as a carbon source, it is possible to grow on ethanol or H ₂ plus CO ₂ in the presence of sulfate;	[21]
								(2) Sulfate, sulfite, and thiosulfate serve as electron acceptor instead of elemental sulfur, fumarate, and nitrate	

(Continued)

Table 1
(Continued)

Category	Genus	Specie	Source	Shape	G+C (%)	Growth conditions			Substrate and electron transfer and other main conclusions	Ref.
						Temperature ^a	pH			
Mesophilic δ - <i>Proteobacteria</i>	<i>Desulfovibrio</i>	<i>Carbinolicus</i>	Food wastewater	Rod	65	5–44 (37–38)	5.3–8.7 (7–7.3)		(1) Instead of nitrate, nitrite, and fumarate, sulfite, thiosulfate, and elemental sulfur can serve as electron acceptor, and finally reduced to H ₂ S (2) It can grow on hydrogen, formate, and ethanol with acetate as carbon source in the presence of CO ₂ , while growth on methanol requires the presence of yeast extract	[22]
		<i>Mexicanus</i>	Cheese wastewater	Vibrio	66	20–40 (37)	6.3–8.2 (7.2)		(1) Sulfate, sulfite, thiosulfate, and elemental sulfur serve as electron acceptor instead of nitrate, nitrite, and fumarate; (2) Formate and H ₂ (with acetate), pyruvate, casamino acids, and ethanol can serve as electron donors in the presence of thiosulfate	[23]
		<i>Paquesii</i>	Wastewater	Vibrio to spiral	62.2	10–45	6.5–8.5		(1) Sulfate, sulfite, and thiosulfate reduced to H ₂ S under strict anaerobic condition, with incomplete oxidation of organics to acetate; (2) Hydrogen, formate, pyruvate, fumarate, lactate, succinate, malate, ethanol, and glycerol serve as electron donors in the presence of sulfate	[24]
		<i>Aerotolerans</i>	Activate sludge	Vibrio	57.2	3–37 (29)	6.4–7.8 (6.9)		(1) Sulfate, sulfite, thiosulfate, and elemental sulfur reduced to H ₂ S; (2) Nitrate, nitrite, and ferric ion are not utilized as electron acceptors; (3) Lactate, H ₂ , pyruvate, methanol, ethanol, glycerol can	[25]

<i>Desulfobulbus</i>	<i>Elongatus</i>	Mesophilic Industrial digester	Rod	59	20–40 (35)	6–7.8 (7)	[26]	be utilized as electron donors in the presence of sulfate; (4) Strict anaerobic growth, while its non-growth culture can tolerate oxygen for a short period of exposure (1) Instead of nitrate, sulfate, sulfite, and thiosulfate serve as electron acceptor and are reduced to H ₂ S; (2) Propionate, lactate, pyruvate, ethanol, propanol are incompletely oxidized to acetate in the presence of sulfate; (3) Hydrogen is used as electron donor in the presence of acetate and CO ₂ as carbon sources
<i>Desulfosporosira</i>	<i>Adipica</i>	Anaerobic digester	Rod	60	20–36 (35)	6.6–7.4 (7)	[27]	(1) Under strict anaerobic condition, sulfate, sulfite, thiosulfate, and elemental sulfur serves as electron acceptor instead of nitrate; (2) Pyruvate, lactate, C ₁ –C ₉ straight chain fatty acids, C ₄ –C ₆ iso-fatty acids, and C2–C9 straight chain primary alcohols can be completely oxidized in the presence of excess sulfate
<i>Desulfatirhabdium</i>	<i>Butyratizor</i>	Anaerobic reactor	Oval to rod	55.1	15–37 (28–30)	6.5–8.0 (7.0)	[28]	(1) Growth on H ₂ /acetate, formate, ethanol, pyruvate, propionate, propanol, 1-butanol, 2,3-butanediol, fumarate, and succinate in the presence of electron acceptor; (2) Sulfate and thiosulfate serve as electron acceptors instead of sulfite and nitrate; (3) No growth on H ₂ /CO ₂ , methanol, acetone, lactate, malate, glucose, or fructose

(Continued)

Table 1
(Continued)

Category	Genus	Specie	Source	Shape	G+C (%)	Growth conditions			Ref.
						Temperature ^a	pH	Substrate and electron transfer and other main conclusions	
Mesophilic δ -proteobacteria	<i>Desulfoglaeba</i>	<i>Alkanexedens</i>	Oily wastewater storage	Rod to oval end	53.6	17–50 (31–37)	4.5–8.2 (6.5–7.2)	(1) Tolerance to NaCl up to 55 g/L;	[29]
								(2) Sulfate and thiosulfate serve as electron acceptors, while alkanes (C ₆ –C ₁₂), pyruvate, butyrate, and hexanoic acid are electron donors	
Thermophilic δ -gram-negative bacteria	<i>Desulfobacca</i>	<i>Acetoxidans</i>	Anaerobic granular sludge	Oval to rod	51.1	27–47 (36–40)	6.5–8.3 (7.1–7.5)	(1) Acetate serves as the only electron donor and it is completely oxidized to CO ₂ ;	[30]
								(2) Sulfate, sulfite, and thiosulfate serve as electron acceptors, and reduced to H ₂ S	
	<i>Thermodesulfocibrio</i>	<i>Aggregans</i>	Sludge granules	Vibrios	35.2	45–70 (60)	6–8.5 (6.5–7)	(1) Lactate, hydrogen, formate and pyruvate serve as electron donors in the presence of sulfate (2) Organics are incompletely oxidized to acetate; (3) Sulfate and thiosulfate serve as electron acceptor in the presence of lactate, instead of sulfite, elemental sulphur, nitrate, and fumarate	[31]
Gram-positive bacteria	<i>Desulfotomaculum</i>	<i>Alcoholivorax</i>	Sewage sludge	Vibrios	34	45–60 (55)	6–8.5 (7–7.5)	(1) Lactate, hydrogen, formate and pyruvate serve as electron donors in the presence of sulfate; (2) Organics are incompletely oxidized to acetate; (3) Sulfate, sulfite, and thiosulfate serve as electron acceptor in the presence of lactate, instead of elemental sulfur, nitrate, and fumarate	[31]
								(1) Sulfate, sulfite, thiosulfate, and elemental sulfur serve as electron acceptors;	
Gram-positive bacteria	<i>Desulfotomaculum</i>	<i>Alcoholivorax</i>	Wastewater	Rod	48	33–53 (44–46)	6–7.5 (6.4–7.3)	(1) Sulfate, sulfite, thiosulfate, and elemental sulfur serve as electron acceptors;	[32]
								(1) Sulfate, sulfite, thiosulfate, and elemental sulfur serve as electron acceptors;	

<i>Carboxydifactorans</i>	Sludge in anaerobic reactor	Rod	45.6	30–68 (55)	6–8 (6.8–7)	[33]	(2) Alcohols and carboxylic acid are electron donors in the presence of sulfate; (3) Fermentative growth on pyruvate
							(1) CO (100% of the gas) can serve as the sole electron donor in the presence or absence of sulfate;
							(2) H ₂ /CO ₂ , pyruvate, lactate, glucose, fructose, maltose, ethanol, glycerol, alanine, and serine can be utilized in the presence of sulfate; (3) Sulfate, sulfite and thiosulfate are electron acceptors, instead of elemental sulfur

^a°C.

^bThe values in the parenthesis in columns of temperature and pH mean optimal points.

- produced but there was possibly sufficient O₂ caused by the micro-aeration to oxidize the sulfide. Micro-aeration would therefore be a possible approach for controlling SRB activity and mitigating their activity.
- (3) Fourteen out of the sixteen SRB species shown in Table 1 did not have nitrate/nitrite utilization capability. To prevent H₂S production, addition of nitrate to the wastewater treatment systems have been reported [6]. Heukelelelian attributed the method's success to the preferred reduction of nitrate over sulfate under oxygen deficient conditions [18]. However, since the bulk of the species identified did not have nitrate utilization, it is possible nitrate is inhibitory to SRBs but this would need to be confirmed.

Of the 3 approaches identified, manipulating temperature and pH had not been successful. This would then suggest that both mesophilic and thermophilic anaerobic systems can be affected by SRBs. Similarly 2-phase anaerobic systems with an acidogenic reactor preceding the methanogenic reactor can also be adversely impacted by SRBs. The use of nitrates to control SRB activity has been more successful and this can be applied to situations where septic conditions can develop—as in sewer lines on an “as needed” situation. This, however, unlikely can be a suitable method for application on an anaerobic reactor treating wastewater or a digester treating sludges. Nitrates applied continuously can adversely impact methanogenesis and there is also the growing concern associated with incomplete nitrate reduction and consequent production of nitrogen oxides. Of the 3 approaches identifies, it would therefore seem micro-aeration to be the most viable for control of SRBs in wastewater treatment systems.

4. Summary

Various species of SRBs isolated from sources associated with wastewater/waste treatment and reported in the literature have been identified. These belong to both mesophilic *δ-Proteobacteria*, and thermophilic gram-negative bacteria or gram-positive bacteria. The temperature range over which SRBs can be found would suggest both mesophilic and thermophilic systems can be affected. Their occurrence over a broad band of pH values would suggest manipulating pH is unlikely to be a successful control method. However, all 16 listed SRBs identified in this paper are obligate anaerobes, and 14 of the 16 SRB species cannot utilize nitrate/nitrite as electron acceptors. On the basis of

application costs (nitrates are likely more expensive than air) and lower risk of producing metabolites which may result in environmental issues (e.g. greenhouse gas), the obligate anaerobe characteristic may be better exploited. This may be done so via development of micro-aeration techniques for application on anaerobic systems for wastewater and wastes treatment.

References

- [1] Y. Chen, J.J. Cheng, K.S. Creamer, Inhibition of anaerobic digestion process: A review, *Bioresour. Technol.* 99 (2008) 4044–4064.
- [2] G. Kassab, M. Halalsheh, A. Klapwijk, M. Fayyad, J.B. van Lier, Sequential anaerobic-aerobic treatment for domestic wastewater—A review, *Bioresour. Technol.* 101 (2010) 3299–3310.
- [3] Y. Li, S.Y. Park, J. Zhu, Solid-state anaerobic digestion for methane production from organic waste, *Renew. Sust. Energ. Rev.* 15 (2011) 821–826.
- [4] O. Lahav, B.E. Morgan, Titration methodologies for monitoring of anaerobic digestion in developing countries—A review, *J. Chem. Technol. Biotechnol.* 79 (2004) 1331–1341.
- [5] D.R. Lovley, M.J. Klug, Sulfate reducers can outcompete methanogens at freshwater sulfate concentrations, *Appl. Environ. Microbio.* 45 (1983) 187–192.
- [6] L. Zhang, P. De Schryver, B. De Gussemé, W. De Muynck, N. Boon, W. Verstraete, Chemical and biological technologies for hydrogen sulfide emission control in sewer systems: A review, *Water Res.* 42 (2008) 1–12.
- [7] L.K. Baumgartner, R.P. Reid, C. Dupraz, A.W. Decho, D.H. Buckley, J.R. Spear, K.M. Przekop, P.T. Visscher, Sulfate reducing bacteria in microbial mats: Changing paradigms, new discoveries, *Sediment. Geol.* 185 (2004) 131–145.
- [8] W. Dilling, H. Cypionka, Aerobic respiration in sulfate-reducing bacteria, *FEMS Microbio. Lett.* 71 (1990) 123–128.
- [9] S. Dannenberg, M. Kroder, W. Dilling, H. Cypionka, Oxidation of H_2 , organic compounds and inorganic sulfur compounds coupled to reduction of O_2 or nitrate by sulfate-reducing bacteria, *Arch. Microbio.* 158 (1992) 93–99.
- [10] D. Krekeler, H. Cypionka, The preferred electron acceptor of *Desulfovibrio desulfuricans* CSN, *FEMS Microbio. Ecol.* 17 (1995) 271–277.
- [11] H.F. Castro, N.H. Williams, A. Ogram, Phylogeny of sulfate-reducing bacteria, *FEMS Microbio. Ecol.* 31 (2000) 1–9.
- [12] K. Mori, H. Kim, T. Kakegawa, S. Hanada, A novel lineage of sulfate-reducing microorganisms: *Thermodesulfobiaceae* fam. nov., *Thermodesulfobium narugense*, gen. nov., sp. nov., a new thermophilic isolate from a hot spring, *Extremophiles* 7 (2003) 283–290.
- [13] G. Muyzer, A.J.M. Stams, The ecology and biotechnology of sulphate-reducing bacteria, *Nature Rev. Microbio.* 6 (2008) 441–454.
- [14] R.K. Thauer, E. Stakebrandt, W.A. Hamilton, Energy metabolism and phylogenetic diversity of sulphate-reducing bacteria, in: L.L. Barton, W.A. Hamilton (Eds.), *Sulphate-reducing bacteria: Environmental and engineered systems*, Cambridge University Press, Cambridge, 2007, pp. 1–37.
- [15] F. Thevenieau, M.L. Fardeau, B. Ollivier, C. Joulain, S. Baena, *Desulfomicrobium thermophilum* sp. nov., a novel thermophilic sulphate-reducing bacterium isolated from a terrestrial hot spring in Colombia, *Extremophiles* 11 (2007) 295–303.
- [16] F. Omil, C. Bakker, L.H. Pol, G. Lettinga, Effect of pH and low temperature shocks on the competition between sulphate reducing bacteria and methane producing bacteria in UASB reactors, *Environ. Technol.* 18 (1997) 255–264.
- [17] Y. Tang, T.S. Ikbal, S. Morimura, K. Kida, The effects of micro-aeration on the phylogenetic diversity of microorganisms in a thermophilic anaerobic municipal solid-waste digester, *Water Res.* 38 (2004) 2537–2550.
- [18] H. Heukelekian, Effect of the addition of sodium nitrate to sewage on hydrogen sulfide production and BOD reduction, *Sewage Works J.* 15 (1943) 255–261.
- [19] O.B. Thabet, T. Wafa, K. Eltaief, J.L. Cayol, M. Hamdi, G. Fauque, M.L. Fardeau, *Desulfovibrio legallii* sp. nov.: A moderately halophilic, sulfate-reducing bacterium isolated from a wastewater digester in Tunisia, *Curr. Microbio.* 62 (2011) 486–491.
- [20] F. Chamkh, C. Sproer, P.C. Lemos, S. Besson, A.G. El Asli, R. Bennisse, M. Labat, M. Reis, A.I. Qatibi, *Desulfovibrio marrakechensis* sp. nov., a 1,4-tyrosol-oxidizing, sulfate-reducing bacterium isolated from olive mill wastewater, *Int. J. Sys. Evol. Microbio.* 59 (2009) 936–942.
- [21] S. Baena, M.L. Fardeau, M. Labat, B. Ollivier, J.L. Garcia, B.K.C. Patel, *Desulfovibrio aminophilus* sp. nov., a novel amino acid degrading and sulfate reducing bacterium from an anaerobic dairy wastewater lagoon, *Sys. Appl. Microbio.* 21 (1998) 498–504.
- [22] H.J. Nanninga, J.C. Gottschal, Properties of *Desulfovibrio carbinolicus* sp. nov. and other sulfate-reducing bacteria isolated from an anaerobic-purification plant, *Appl. Environ. Microbio.* 53 (1987) 802–809.
- [23] G. Hernandez-Eugenio, M.L. Fardeau, B.K.C. Patel, H. Macarie, J.L. Garcia, B. Ollivier, *Desulfovibrio mexicanus* sp. nov., a sulfate-reducing bacterium isolated from an upflow anaerobic sludge blanket (UASB) reactor treating cheese wastewaters, *Anaerobe* 6 (2000) 305–312.
- [24] B.H.G.W. van Houten, R.J.W. Meulepas, W. van Doesburg, H. Smidt, G. Muyzer, A.J.M. Stams, *Desulfovibrio paquesii* sp. nov., a hydrogenotrophic sulfate-reducing bacterium isolated from a synthesis-gas-fed bioreactor treating zinc- and sulfate-rich wastewater, *Int. J. Sys. Evol. Microbio.* 59 (2009) 229–233.
- [25] G.L. Mogensen, K.U. Kjeldsen, K. Ingvorsen, *Desulfovibrio aerotolerans* sp. nov., an oxygen tolerant sulphate-reducing bacterium isolated from activated sludge, *Anaerobe* 11 (2005) 339–349.
- [26] E. Samain, H.C. Dubourguier, G. Albagnac, Isolation and characterization of *Desuljobulbus elongatus* sp. nov. from a mesophilic industrial digester, *Sys. Appl. Microbio.* 5 (1984) 391–401.
- [27] K. Tanaka, E. Stackebrandt, S. Tohyama, T. Eguchi, *Desulfovira adipica* gen. nov., sp. nov., an adipate-degrading, gram-negative, sulfate-reducing bacterium, *Int. J. Sys. Evol. Microbio.* 50 (2000) 639–644.

- [28] M. Balk, M. Altinbas, W.I.C. Rijpstra, J.S. Sinninghe Damste, A.J.M. Stams, *Desulfatirhabdium butyrativorans* gen. nov., sp. nov., a butyrate-oxidizing, sulfate-reducing bacterium isolated from an anaerobic bioreactor, *Int. J. Sys. Evol. Microbio.* 58 (2008) 110–115.
- [29] I.A. Davidova, K.E. Duncan, O.K. Choi, J.M. Suflita, *Desulfoglaeba alkanexedens* gen. nov., sp. nov., an n-alkane-degrading, sulfate-reducing bacterium, *Int. J. Sys. Evol. Microbio.* 56 (2006) 2737–2742.
- [30] S. Oude Elferink, W.J.C. Vorstman, A. Sopjes, A.J.M. Stams, Characterization of the sulfate-reducing and syntrophic population in granular sludge from a full-scale anaerobic reactor treating papermill wastewater, *FEMS Microbio. Ecol.* 27 (1998) 185–194.
- [31] Y. Sekiguchi, M. Muramatsu, H. Imachi, T. Narihiro, A. Ohashi, H. Harada, S. Hanada, Y. Kamagata, *Thermodesulfovibrio aggregans* sp. nov. and *Thermodesulfovibrio thiophilus* sp. nov., anaerobic, thermophilic, sulfate-reducing bacteria isolated from thermophilic methanogenic sludge, and emended description of the genus *Thermodesulfovibrio*, *Int. J. Sys. Evol. Microbio.*, 58 (2008) 2541–2548.
- [32] A.H. Kaksonen, S. Spring, P. Schumann, R.M. Kroppenstedt, J.A. Puhakka, *Desulfotomaculum alcoholivorax* sp nov., a moderately thermophilic, spore-forming, sulfate-reducer isolated from a fluidized-bed reactor treating acidic metal- and sulfate-containing wastewater, *Int. J. Sys. Evol. Microbio.* 58 (2008) 833–838.
- [33] S.N. Parshina, J. Sipma, Y. Nakashimada, A.M. Henstra, H. Smidt, A.M. Lysenko, P.N.L. Lens, G. Lettinga, A.J.M. Stams, *Desulfotomaculum carboxydivorans* sp. nov., a novel sulfate-reducing bacterium capable of growth at 100 % CO, *Int. J. Sys. Evol. Microbio.* 55 (2005) 2159–2165.