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Scleromatobacter humisilvae gen. nov., sp. nov., a novel bacterium isolated from oak forest soil

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Abstract

A novel bacterial strain, designated BS-T2-15^T, isolated from forest soil in close proximity to decaying oak wood, was characterized using a polyphasic taxonomic approach. Phylogenetic analyses based on 16S rRNA gene sequences as well as phylogenomic analyses based on coding sequences of 340 concatenated core proteins indicated that strain BS-T2-15^T forms a distinct and robust lineage in the *Rubrivivax–Roseateles–Leptothrix–Azohydromonas–Aquincola–Ideonella* branch of the order *Burkholderiales*. The amino acid identity and the percentage of conserved proteins between the genome of strain BS-T2-15^T and genomes of closely related type strains ranged from 64.27 to 66.57% and from 40.89 to 49.27%, respectively, providing genomic evidence that strain BS-T2-15^T represents a new genus. Its cells are Gram-stain-negative, aerobic, motile by a polar flagellum, rod-shaped and form incrusted white to ivory colonies. Optimal growth is observed at 20–22 °C, pH 6 and 0% NaCl. The predominant fatty acids of strain BS-T2-15^T are $C_{16:1}\,\omega7c$, $C_{16:0}$ and $C_{14:0}$ 2-OH. Its polar lipid profile consists of a mixture of phosphatidylethanolamine, diphosphatidylglycerol and phosphatidylglycerol and its main respiratory quinone is ubiquinone 8. The estimated size of its genome is 6.28 Mb with a DNA G+C content of 69.56 mol%. Therefore, on the basis of phenotypic and genotypic properties, the new strain BS-T2-15^T represents a novel genus and species for which the name *Scleromatobacter humisilvae* gen. nov., sp. nov., is proposed. The type strain is BS-T2-15^T (DSM 113115^T=UBOCC-M-3373^T).

INTRODUCTION

In forest ecosystems, wood decay is an important process that participates to the soil fertility through the action of a complex guild of decomposers [1, 2]. Among them, fungi are considered as important actors, while the role of bacteria is much less documented [3]. To fill this gap, the taxonomic diversity and the metabolic and functional potential of bacterial strains isolated from a soil-decaying-wood continuum have been investigated [4]. Overall, this study demonstrated a community dominated by representatives of the genera *Paraburkholderia* (*Betaproteobacteria*), *Streptomyces*, *Kitasatospora*, *Arthrobacter* and *Streptacidiphilus* (*Actinobacteria*), *Dyella* (*Gammaproteobacteria*) and by uncharacterized bacterial strains [4]. At the functional level, this study also revealed that soil bacterial communities have the potential to decompose organic matter and a stronger effectiveness than those isolated from decaying oak wood. The taxonomic assignation and functional screening allowed the identification of various strains of interest, among which strain BS-T2-15^T, one of the uncharacterized strains, was selected to be further characterized in the present study to clarify its taxonomic position within the *Rubrivivax–Roseateles–Leptothrix–Azohydromonas–Aquincola–Ideonella* branch of the order *Burkholderiales*, in the class *Betaproteobacteria*. To date, there is a taxonomic uncertainty regarding the classification of these genera at the family rank level. Recently, Liu *et al.* [5] proposed to refer to this branch as the closest-to-*Comamonadaceae* (CTC) group, as it forms a phylogenetically coherent group close to genera belonging to the *Comamonadaceae* family. They proposed to classify the CTC group as a new family, 'Sphaerotilaceae' fam. nov., based on phylogenomic analyses,

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Keywords: *Betaproteobacteria*; Burkholderiales; Comamonadaceae; oak forest soil; *Scleromatobacter humisilvae*.
Abbreviations: AAI, average amino acid identity; AF, alignment fraction; ANI, average nucleotide identity; COGs, cluster of orthologous groups; CTC, closest-to-*Comamonadaceae*; dDDH, digital DNA–DNA hybridization; DPG, diphosphatidylglycerol; GTDB, Genome Taxonomy Database; HPIC, high pressure ion chromatography; KEGG, Kyoto Encyclopedia of Genes and Genomes; MAG, metagenome assembled genome; ML, maximum-likelihood; MMN, mannitol–mobility–nitrate; MP, maximum-parsimony; NJ, neighbour-joining; OGRI, overall genome related indices; PE, phosphatidylethanolamine; PG, phosphatidylglycerol; POCP, percentage of conserved proteins; TSA, tryptic soy agar; TSB, tryptic soy broth.
The 16S rRNA gene sequence and the assembled genome sequences of strain BS T2-15^T have been deposited in GenBank under the accession numbers OM630150 and JAJLJH000000000, respectively.
Seven supplementary figures and nine supplementary tables are available with the online version of this article.

genome relatedness indices and phenotypic data. However, this new delineation is not yet recognized by the International Committee on Systematics of Prokaryotes. In addition, the same authors also proposed several taxonomic revisions at the genera and species levels. Among remarkable physiological features of the *Rubrivivax–Roseateles–Leptothrix–Azohydromonas–Aquincola–Ideonella* branch, some species are known to be involved in the biodegradation of petroleum compounds or in the reduction of chlorate to chloride under anaerobic conditions [6–8].

In the present study, we performed a polyphasic taxonomic characterization of strain BS-T2-15^T and provided phenotypic, phylogenomic and genomic evidences that it meets the criteria for delineating a new species of a new genus within the *Rubrivivax–Roseateles–Leptothrix–Azohydromonas–Aquincola–Ideonella* branch. We propose to name this new species *Scleromatobacter humisilvae* gen. nov., sp. nov.

ISOLATION AND ECOLOGY

Strain BS-T2-15^T is from a collection of 308 bacterial strains established as part of a study on the functional abilities of bacterial isolates from decaying wood and their comparison with the properties of bacteria from underlying soil [4]. The experimental set up consisted in oak discs that have been placed during 9 months on the soil surface of the forest experimental site of Champenoux (north-eastern France; 48.718420° N 6.346580° E; Alt: 248 m; 0.5 ha of surface). Strain BS-T2-15^T was isolated from the bulk soil in direct contact with decaying oak disc by serial dilutions on 1/10 diluted tryptic soy agar (TSA) medium [Difco's tryptic soy broth (TSB) 3 g l^{-1} and agar 15 g l^{-1}) containing cycloheximide (100 g l^{-1}, final concentration), with a pH adjusted to 5. The strain was then purified by three successive spreads on 1/10 diluted TSA plates at pH 5 to obtain a pure culture. Strain BS-T2-15^T was then grown routinely on 1/10 TSA or 1/10 TSB media adjusted to pH 5 over 3 days at 20 °C, under agitation (250 rpm). Its purity was routinely confirmed by microscopic observations, and by sequencing of its 16S rRNA gene and genome. Stock cultures were stored at −80 °C in 1/10 TSB medium supplemented with 5% (v/v) dimethylsulphoxide. Main chemical characteristics of the bulk soil samples were pH 4.65±0.10, 48.38±7.93 g kg^{-1} total carbon, 3.26±0.49 g. kg^{-1} total nitrogen, 0.17±0.01 g kg^{-1} phosphorus extracted according to the Duchaufour method and 83.80±13.92 g kg^{-1} organic matter [4].

Strain BS-T2-15^T (DSM 113115^T=UBOCC-M-3373^T) is available in the following public culture collections: Deutsche Sammlung von Mikroorganismen und Zellkulturen (DSMZ; www.dsmz.de/collection) and the UBO Culture Collection (UBOCC; www.univ-brest.fr/ubocc).

MORPHOLOGY AND PHYSIOLOGY

Colony morphology of the isolate BS-T2-15^T was observed on 1/10 TSA adjusted to pH 6. Cell morphology and motility were determined by light microscopy (Olympus BX60 and CX40) and TEM (JEOL JEM 1400). Motility was also observed by using mannitol–motility–nitrate (MMN) agar medium (composed of 10 g l^{-1} tryptic hydrolysate of casein, 1 g potassium nitrate, 7.5 g l^{-1} mannitol, 40 mg l^{-1} phenol red and 3.5 g l^{-1} agar), which was also used to evidence mannitol fermentation and nitrate reductase activity. Gram-staining was determined using standard procedures and confirmed with a KOH (3%) test. Catalase and cytochrome oxidase activities were respectively evaluated using H_2O_2 and strips of *N*,*N*,*N*′,*N*′-tetramethyl-*p*-phenylenediamine dihydrochloride (Bio-Rad). The oxidase test was repeated several times using independent cultures to confirm the result. Colonies of BS-T2-15^T are circular and rough with a colour between white and ivory. A major phenotypic feature is that its colonies are incrusted in the agar medium. To our knowledge, this was not yet reported in the literature for genera belonging to the *Rubrivivax–Roseateles–Leptothrix–Azohydromonas–Aquincola–Ideonella* branch. Cells are Gram-negative coccobacilli that divide by binary fission and occur mainly singly, but can also form aggregates (Fig. 1a, b). Cell size range from 0.59 to 0.93 µm wide (mean 0.78 µm; *n=45*) and from 1.71 to 2.73 µm long (mean 2.15 µm; *n=45*). Strain BS-T2-15^T is motile, as confirmed by growth observations on MMN agar medium and the observation of a single polar flagellum per cell by TEM (Fig. 1c, d). Refringent intracellular granules, which could be polyhydroxyalkanoates storage granules, were also observed (Fig. 1a). The strain is catalase positive and oxidase negative. The latter phenotypic feature clearly distinguishes strain BS-T2-15^T from other genera of the *Rubrivivax–Roseateles–Leptothrix–Azohydromonas–Aquincola–Ideonella* branch which are all oxidase positive. However, it is important to note that, cytochrome C oxidase complex was identified in its genome. This point is discussed later in the study.

Physiological characterization of the novel strain BS-T2-15^T was carried out aerobically, in triplicate, on 1/10 TSA or TSB adjusted to pH 6 at 20 °C and under agitation (250 r.p.m.). Determination of the temperature range for growth and salt tolerance were respectively tested over the range 0–45 °C, at 5 °C intervals and 0–10% NaCl (w/v), at 0.5% intervals, both for 10 days on 1/10 TSA at pH 6. Growth was observed from 4–30 °C with optimal growth between 20–22 °C. The optimal temperature for BS-T2-15^T growth is lower compared to the closest type strains (from 30–40 °C) (Table 1). Concerning salt tolerance, the strain grew only at 0.5% NaCl and exhibited optimal growth without sodium chloride. The pH range for growth was tested from pH 2.0 to 12 (at 20 °C), with increments of 1 unit in 1/10 TSB medium for 8 days. Cells were routinely enumerated by direct cell counting using a modified Thoma chamber (Preciss; surface: 0.0025 mm^2; depth: 10 µm). The following buffers (each at 20 mM, Sigma-Aldrich) were used to adjust the required pH: pH 4.0 and 5.0 with HOMOPIPES buffer, pH 6.0 with MES buffer, pH 7.0 with PIPES buffer,

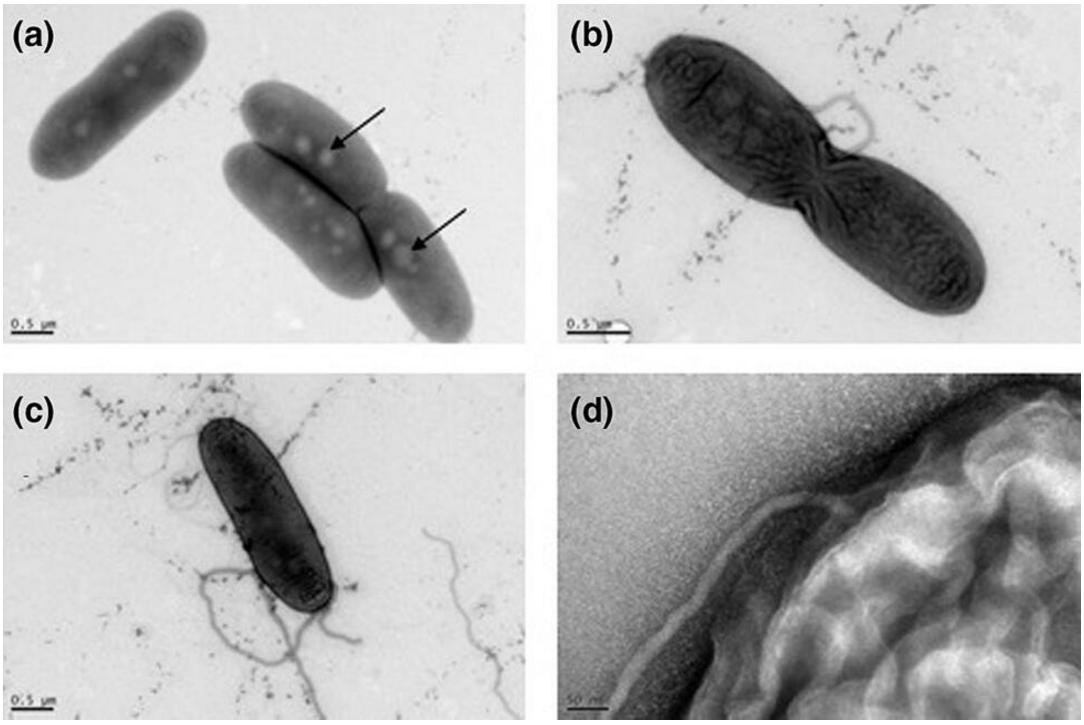

Fig. 1. Transmission electron microscopy image of cells of strain BS-T2-15^T showing (a) intracellular granules (indicated by black arrows), (b) a dividing cell (by binary fission), (c) a cell with its polar flagellum, and (d) the insertion point of the flagellum.

pH 8.0 with HEPES buffer, and pH 9.0 and 10.0 with CAPSO buffer. For pH 2.0, 3.0, 11.0 and 12.0, no buffer was used. Growth of strain BS-T2-15^T was observed from pH 2.0 to 12 with optimal growth at pH 6. This large pH tolerance was not observed for the closest type strains (Table 1). The growth kinetics of BS-T2-15^T under optimal conditions was then studied in triplicates, on 1/10 TSB adjusted to pH 6 at 22 °C with no NaCl salt, under agitation (250 r.p.m.) for 4 days. Cell growth was monitored by direct cell counting, every 3 h using a modified Thoma chamber, in order to determine the growth rate and doubling time of the strain under optimal culture conditions. The growth rate and the generation time of strain BS-T2-15^T are, respectively, 0.17 h^{-1} and 3 h 58 min.

Utilization of carbon sources was investigated using the mineral basis of 1/10 TSB medium containing 0.25 g l^{-1} KH_2PO_4 and adjusted at pH 6. Each substrate (lactose, mannose, ribose, maltose, glucose, *N*-acetylglucosamine, butyric acid, gluconate, citrate, benzoate, acetate, pyruvate and urea) was supplied at a final concentration of 20 mM. Utilization of nitrogen sources was investigated using 1/10 TSB medium adjusted to pH 6 with nitrate and ammonium supplied at a final concentration of 20 mM, while nitrite was supplied at a final concentration of 5 mM. Before inoculation, cells at the end of their exponential growth phase were harvested and washed three times with distilled water and then the bacterial suspension was adjusted to obtain a Mac Farland index value of 1. A medium composed of a mineral basis of the 1/10 TSB without a carbon source was used as negative control for each carbon utilization bioassay and a positive control was performed using 1/10 TSB medium adjusted at pH 6. The hydrolysis of cellulose was determined using carboxymethyl cellulose as described by Mieszkin *et al.* [4]. These tests were completed with liquid or solid cultures allowing to determine: (i) mannitol fermentation and presence of nitrate reductase (MMN agar medium); (ii) fermentative pathways (mixed acids or butane-2,3-diol pathways; Clark and Lubs liquid medium); (iii) glucose and lactose fermentation, gas and H_2S production (Kligler–Hajna agar medium); and (iv) citrate utilization (Simmons citrate agar medium). For these assays, culture media, cell cultures and washes and preparation of bacterial suspensions were performed as described above and by Mieszkin *et al.* [9]. Strain BS-T2-15^T is chemoorganoheterotrophic and grows by aerobic respiration. It catabolizes D-glucose, lactose and pyruvate, while moderate growth was obtained with D-ribose, *N*-acetylglucosamine, urea and gluconate. Weak growth was also observed with all the nitrogen substrates tested (nitrate, nitrite and ammonium). In addition, BS-T2-15^T is capable of using nitrate or nitrite as terminal electron acceptors showing that the nitrate reductase is functional (Table 1).

Volatile fatty acid production of strain BS-T2-15^T after growth in duplicate in 1/10 TSB was assessed by high-pressure ion chromatography [Dionex ICS-6000 HPIC; growth conditions: pH 6, 20 °C, under agitation (250 r.p.m.), for 3 days]. HPIC analyses showed that the strain consumed all the pyruvate present in the medium during its growth (approximately 930 µM), but did not produce acetate, lactate, pyruvate or oxalate under these culture conditions. This is consistent with previous results showing that it is capable to grow with pyruvate as sole carbon source.

Table 1. Differential characteristics of strain BS-T2-15^T and type strains of closely related genera

Strains: 1, BS-T2-15^T; 2, *Leptothrix mobilis* DSM 10617^T; 3, *Rubrivivax gelatinosus* DSM 1709^T; 4, *Ideonella dechloratans* CGUG 30977^T; 5, *Aquincola tertiaricarbonis* DSM 18512^T. Data are from Mieszkin *et al.* [4], Lechner *et al.* [7], Malmqvist *et al.* [8], Chen *et al.* [43], Sheu *et al.* [44], Spring *et al.* [45] and Willems *et al.* [46]. +, Positive; –, negative; NA, not available; W, weak growth. All strains are motile, positive for Tween 40 hydrolysis, and negative for urease activity and citrate utilization.

Characteristics	**1**	**2**	**3**	**4**	**5**
Colony colour	White-ivory	Dark-brown	Orange-brown	White	White
Cell size (µm)	0.6–0.9×1.7–2.7	0.6–0.8×1.5–12.0	0.4–0.7×1.0–3.0	0.7–1.0×2.5–5.0	0.8–1.1×1.2–2.3
Temperature range (optimum) for growth (°C)	4–30 (20–22)	10–37	10–45 (37–40)	15–30 (30)	4–40 (30)
pH growth range (optimum) for growth	2–12 (6)	6.5–8.5	5–9 (6–7)	6–8 (6–7)	5–9 (6–7)
NaCl tolerance (optimum) for growth (%, w/v)	0–0.5 (0)	NA	0–2 (1)	0–2	0–1 (0)
Carbon source utilization:					
Acetate	–	–	+	+	+
Butyrate	+	–	+	+	+
Gluconate	W	–	NA	–	+
Pyruvate	+	–	+	+	+
Arabinose	+	NA	–	–	NA
Cellobiose	+	NA	–	–	NA
CM-cellulose	–	NA	–	+	–
D-Glucose	+	–	–	+	+
Maltose	–	–	+	–	+
D-Mannose	–	–	–	+	+
D-Mannitol	–	+/-	–	–	+
N-Acetylglucosamine	W	–	–	–	+
Indole formation	–	–	+	–	–
Enzymatic activities:					
Catalase	+	NA	–	+	+
Oxidase	–	+	+	+	+
Nitrate reductase	+	NA	+	+	–
α-Glucosidase	+	NA	–	–	+
Quinone type	Q-8	Q-8	Q-8, MK-8	Q-8	Q-8
Diphosphatidylglycerol	+	–	+	+	+
Major fatty acids (%):*					
$C_{14:0}$ 2-OH	10.49	–	–	–	–
$C_{16:1}$ *cis*-9	–	53.04	–	–	39
$C_{16:1}\omega7c$	40.45	–	–	–	–
Summed feature 3†	–	–	42.8	40.2	–
DNA G+C content (mol%)	69.6	68	71.9	68.1	70.5
Isolation source	Forest soil	Freshwater sediment	Acetate enrichment	Activated sludge	Aquifer

*As all strains have not been grown under exactly the same conditions nor in the same media, percentages of fatty acids cannot be compared from one strain to another.
†Summed feature 3 comprises $C_{16:1}$ $\omega7c$ and/or $C_{16:1}$ $\omega6c$.

Strain BS-T2-15^T was not capable of using chlorate as sole terminal electron acceptor (at 20 mM), when grown anaerobically on 5 g l^{-1} NaCl, with 1 g l^{-1} tryptone as carbon and energy source (with respect to negative and positive controls).

Sensitivity to antibiotics of strain BS-T2-15^T was tested by the disc diffusion method after spreading cell suspensions (1 McFarland) on 1/10 TSA adjusted to pH 6 at 20 °C for 7 days. Discs were impregnated with antibiotic solutions to obtain a final quantity of antibiotic per disc of: kanamycin (40 µg), rifampicin (30 µg), novobiocin (30 µg), gentamicin (15 µg), ampicillin (10 µg), penicillin (10 U), oxacillin (5 µg), oxytetracycline (30 µg), chloramphenicol (30 µg) and streptomycin (10 µg). The discs were then placed on the agar surface. The inhibition zones were read after 3 days of incubation at 20 °C. Among the antibiotics tested, strain BS-T2-15^T was sensitive to kanamycin, novobiocin, gentamicin and streptomycin.

CHEMOTAXONOMY

In order to analyse respiratory quinones, polar lipids and fatty acids, cells of strain BS-T2-15^T were cultured in 1/10 TSB pH 6 at 20 °C under agitation (250 r.p.m.) and then harvested by centrifugation (800 *g*; 10 min) at the end of their exponential phase of growth. These analyses were carried out by the Identification Service of the DSMZ (Braunschweig, Germany) as described by Tindall [10, 11] and Kuykendall *et al.* [12]. The major respiratory quinone identified for strain BS-T2-15^T is ubiquinone 8 (Q-8).

The polar lipid profile of the novel isolate consisted in phosphatidylethanolamine (PE), diphosphatidylglycerol (DPG) and phosphatidylglycerol (PG). A common feature of the new strain and species belonging to the related genera *Leptothrix*, *Rubrivivax*, *Ideonella* and *Aquincola* is the high proportion of PE and PG, which is consistent with the family *Comamonadaceae* [13, 14]. However, a major characteristic of strain BS-T2-15^T is its high content of DPG, a polar lipid that is absent or only present in low proportions in the type strains of the closest genera (Table S1 and Fig. S1, available in the online version of this article).

The predominant cellular fatty acids (>10% of the total fatty acids) of strain BS-T2-15^T are $C_{16:1}$ ω7*c* (40.45%), $C_{16:0}$ (25.18%) and $C_{14:0}$ 2-OH (10.49%) (Table 2). Noticeably, the main saturated fatty acid detected (*i.e.*, $C_{16:0}$) appeared dominant and common among BS-T2-15^T and the four closely related genera (*Leptothrix*, *Rubrivivax*, *Ideonella* and *Aquincola*), while the hydroxyl fatty acid (*i.e.* $C_{14:0}$ 2-OH) was only detected in strain BS-T2-15^T (Table 1). In addition, the presence of the unsaturated fatty acid $C_{16:1}$ ω7*c* is another major feature of the new strain but could also be represented by summed feature 3 ($C_{16:1}$ *ω7c* and/or $C_{16:1}$ *ω6c*) in *Rubrivivax gelatinosus* DSM 1709^T and *Ideonella dechloratans* CGUG 30977^T.

16S rRNA GENE PHYLOGENY

A full 16S rRNA gene sequence (1512 nt) of strain BS-T2-15^T was extracted from the genome using the bacterial ribosomal predictor tseemann/barrnap on Galaxy version 1.2.1 [15]. Pairwise 16S rRNA gene sequence similarity was calculated using the global alignment algorithm implemented at the EzTaxon-e server (http://eztaxon-e.ezbiocloud.net/ [16]). Phylogenetic analyses were performed using the software Seaview version 4.7 for tree reconstruction by the neighbour-joining (NJ) and maximum parsimony (MP) methods [17–19]. The evolutionary distances were respectively calculated using the Kimura two-parameters and the Dnapars modes. The robustness of the inferred topology was assessed by bootstrap analyses based on 1000 replications. A third tree was build using the maximum-likelihood (PhyML) method with the subtree-pruning-regrafting algorithm (http://phylogeny.lirmm.fr/phylo_cgi/simple_phylogeny.cgi) [20, 21]. The 16S rRNA gene sequence analysis of strain BS-T2-15^T showed that it belongs to the class *Betaproteobacteria*, the order *Burkholderiales* and the family *Comamonadaceae*. The NJ and MP phylogenetic trees based on 16S rRNA gene sequences revealed that strain BS-T2-15^T does not form a monophyletic clade with any representatives of related taxa (Figs S2 and S3). However, most of the bootstrap percentages of the trees had a very low value (<70%). Concerning the PhyML tree, a clade was obtained with strain BS-T2-15^T and *Leptothrix mobilis* (Feox-1; X97071), but it was distantly related to most of the genera of the *Rubrivivax–Roseateles–Leptothrix–Azohydromonas–Aquincola–Ideonella* branch (Fig. S4).

Comparative analysis of the 16S rRNA gene sequence of the novel strain with relatives having validly published names showed that BS-T2-15^T is equidistant to species belonging to the genera *Ideonella* (96.6–95.8%), *Leptothrix* (96.5–95.5%), *Aquincola* (96.5–96.1%), *Rubrivivax* (96.4–95.9%) and *Aquabacterium* (96.1–95.5%). Its closest relative is *Ideonella azotifigens* 1a22^T (96.6%) followed by *Leptothrix mobilis* FeOx-1^T (96.5%), *Aquincola tertiaricarbonis* L10^T (96.5%), *I. dechloratans* CCUG 30898^T (96.5%), *Rubrivivax gelatinosus* ATCC 17011^T (96.4%) and *R. benzoatilyticus* JA2^T (96.4%).

Overall, these results demonstrate that the 16S rRNA gene-based phylogeny lacks sufficient resolution to evaluate with certainty the taxonomic position of strain BS-T2-15^T among the *Rubrivivax–Roseateles–Leptothrix–Azohydromonas–Aquincola–Ideonella* branch, as previously underlined by Liu *et al.* [5]. Genome-based phylogeny is therefore mandatory to gain a better resolution to assign with certainty the taxonomic position of the new strain BS-T2-15^T.

Table 2. Comparison of whole-cell fatty acid profiles (% of the total) of strain BS-T2-15^T with type strains of closely related genera

Strains: 1, BS-T2-15^T; 2, *Leptothrix mobilis* DSM 10617^T; 3, *Rubrivivax gelatinosus* DSM 1709^T; 4, *Ideonella dechloratans* CGUG 30977^T; 5, *Aquincola tertiaricarbonis* DSM 18512^T. Values are percentages of the fatty acids that were assigned to fatty acids in the peak-naming table of the MIS database (MIDI, Microbial ID). The nomenclature is as follows: the first number indicates the number of carbon atoms in the molecule; 'OH' and 'cyclo' indicate hydroxy or cyclic fatty acids; the second number following the colon indicates the number of double bonds present. The position of the double bond is indicated by the carbon atom position starting from the methyl (*ω*) end of the molecule. *c*, cis isomer. Data are from Lechner *et al.* [7], Malmqvist *et al.* [8], Sheu *et al.* [44] and Spring *et al.* [45]. Major fatty acids (>10% of the total fatty acids) are indicated in bold. –, Not detected.

Fatty acids*	1	2	3	4	5
$C_{10:0}$ 3-OH	5.99	4.54	4.8	2.4	2
$C_{12:0}$	–	2.43	3.7	2.1	4
$C_{12:0}$ 2-OH	0.47	–	–	2.5	–
$C_{12:0}$ 3-OH	3.17	–	–	4.1	–
$C_{14:0}$	3.14	0.77	5.4	1.5	2
$C_{14:0}$ 2-OH	**10.49**	–	–	–	–
$C_{15:0}$	–	–	–	–	3
$C_{15:1}$	–	–	–	–	2
$C_{15:1}$ *ω6c*	–	–	1.7	–	–
$C_{16:0}$	**25.18**	**30.29**	**33.1**	**31.5**	**37**
$C_{16:1}$ *cis*-9	–	**53.04**	–	–	**39**
$C_{16:1}$ *ω7c*	**40.45**	–	–	–	–
$C_{17:0}$	–	–	1.1	–	2
$C_{17:0}$ cyclo	–	–	–	–	2
$C_{17:0}$ cyclo *ω7c*	1.44	–	–	–	–
$C_{18:0}$	–	1.19	–	–	1
$C_{18:1}$	–	–	–	–	6
$C_{18:1}$ *cis*-9,11†	–	6.99	–	–	–
$C_{18:1}$ *ω7c*	9.68	–	4.5	**12.7**	–
$C_{19:1}$ *cis*-9,10‡	–	0.84	–	–	–
Summed feature 3§	–	–	**42.8**	**40.2**	–

*As all strains have not been grown under exactly the same conditions nor in the same media, percentages of fatty acids cannot be compared from one strain to another.
†Sum of both compounds: cis-9octadecenoic acid and cis-11-octadecenoic acid.
‡cis-9,10-methyleneoctadecanoic acid.
§Summed feature 3 comprises $C_{16:1}$ *ω7c* and/or $C_{16:1}$ *ω6c*.

GENOME FEATURES

Genomic DNA of strain BS-T2-15^T was extracted with a standard PCI (phenol–chloroform–Isoamyl Alcohol 25:24:1) protocol [22]. Whole genome sequencing was performed by the Novogene company (Cambridge, UK), using Illumina NovaSeq 6000 PE150 technology (2×150 bp paired-end reads). Read quality was then evaluated with Fast QC (version 0.11.9; www.bioinformatics.babraham.ac.uk/projects/fastqc/) [23]. The whole genome was assembled by using the Shovill pipeline with SPAdes and default parameters [24]. Genome completeness and potential contamination were estimated with CheckM on the MicroScope Microbial Genome Annotation and Analysis Platform (MaGe; https://mage.genoscope.cns.fr) [25]. The overall genome size was 6 276 266 bp (for 100% completion and 0% contamination) for 28 contigs and the G+C content was 69.56mol%. The N50 and L50 values were, respectively, 579 168 bp and three contigs. A total of 5712 coding DNA sequences (CDSs), three rRNA and 55 tRNA genes (corresponding to the 20 essential amino acids) were detected using the MaGe pipeline (Table 3 and Fig. S5). Most of the CDSs (78.29%) could be assigned to at least one cluster of orthologous groups (COGs). COGs categories related to metabolic processes were dominant (38.30% of the CDSs) and the main processes involved (>5% of the CDSs) were: (i) amino acid transport

Table 3. Genome statistics and overall genome relatedness indices between strain BS-T2-15^T and type strains of closely related genera and closely related metagenome assembled genomes

Strains: 1, BS-T2-15^T; 2, *Leptothrix mobilis* DSM 10617^T; 3, *Rubrivivax gelatinosus* DSM 1709^T; 4, *Ideonella dechloratans* CGUG 30977^T; 5, *Aquincola tertiaricarbonis* DSM 18512^T; 6, *Azohydromonas lata* NBRC 102462^T; 7, *Roseateles depolymerans* KCTC 42856^T; 8, MAG GCA_013289985.1; 9, MAG_GCA_903845345.1.

	1	2	3	4	5	6	7	8	9
Number of contigs	28	17	36	158	98	342	1	210	631
Size (Mb)	6.27	4.65	5.08	4.51	6.32	7.18	5.68	6	5.4
G+C content (mol%)	69.56	69.00	71.40	69.30	70.20	69.00	66.60	69.55	69.50
Number of CDS	5712	4019	4691	4172	5711	6349	4894	5441	5362
rRNA	3	6	3	7	3	4	12	3	1
tRNA	55	49	46	59	43	46	58	19	17
dDDH (%)	100	20.50	20.40	20.10	20.30	20.30	20.00	30.10	33.40
ANI (%)	100	79.50	79.70	79.70	79.60	78.60	78.50	87.80	88.90
AAI (%)	100	65.34	66.03	66.57	65.48	65.32	64.27	84.14	86.43
POCP (%)	100	43.17	44.84	47.33	49.02	40.89	49.27	72.60	74.76
Alignment fraction	1.0	0.42	0.48	0.43	0.40	0.32	0.29	0.71	0.80

and metabolism (E; 9.04%); (ii) carbohydrate transport and metabolism (G; 6.45%); inorganic ion transport and metabolism (P; 5.45%) and (iv) energy production and conversion (C; 5.38%). Then, 24.56% of CDSs were allocated to the COGs category related to cellular process and signalling and the following processes were dominant: signal transduction mechanisms (T; 7.64%) and cell wall, membrane and envelope biogenesis (M; 5.26%). Finally, 14.91% of the CDSs were predicted to be involved in the processes dedicated to the information storage and processing (Table S2).

In addition to phylogenetic trees based on the 16S rRNA sequences that do not provide robust phylogenetic reconstructions with this dataset, a phylogenomic tree was reconstructed based on 340 core gene clusters (gene clusters appearing once in each genome).

This tree encompassed 21 reference genomes representative of the *Rubrivivax–Roseateles–Leptothrix–Azohydromonas–Aquincola–Ideonella* branch and phylogenetically related to strain BS-T2-15^T (*Aquabacterium commune* DSM 11901^T, *Aquincola rivuli* KYPY4^T, *Aquincola tertiaricarbonis* DSM 18512^T, *Azohydromonas lata* NBRC 102462^T, *Ideonella azotifigens* DSM 21438^T, 'Ideonella benzenivorans' B7, *Ideonella dechloratans* CGUG 30977^T, *Ideonella livida* TBM-1^T, *Ideonella paludis* KCTC 32238^T, *Ideonella sakaiensis* 201-F6^T, *Leptothrix cholodnii* SP-6^T, *Leptothrix mobilis* DSM 10617^T, *Roseateles aquatilis* CCUG 48205^T, *Roseateles depolymerans* KCTC 42856^T, *Rubrivivax albus* ICH-3^T, *Rubrivivax benzoatilyticus* JA2^T, *Rubrivivax gelatinosus* DSM 1709^T, *Schlegelella brevitalea* DSM 7029^T, *Sphaerotilus hippei* DSM 566^T, *Sphaerotilus natans* ATCC 13338^T and *Sphaerotilus natans* subsp. *sulfidivorans* D-507^T), the target genome BS-T2-15^T and its two closely related Metagenome Assembled Genomes [MAGs; from the Genome Taxonomy Database (GTDB, https://gtdb.ecogenomic.org/); accession numbers GB_GCA_013289985.1 and GB_GCA_903845345.1] artificially classified as genus CAIMXF01. These closely related MAGs were respectively recovered from a forest soil [26] and from stratified freshwater lakes and ponds [27–29]. The phylogenomic tree was built as follows: (i) amino acid sequences were extracted, aligned and concatenated using command line *anvi-get-sequences-for-gene-clusters* on Anvi'o version 7.1 [30], then (ii) positions with over 0.5 gap frequency were masked, and finally (iii) a maximum-likelihood (ML) tree was computed using IQ-TREE (version 2.0.3 [31, 32]) under the model WAG [33] with 1000 ultrafast bootstrap replicates (see the supplementary information for more details). The tree was rooted using the genome of *Alcaligenes faecalis* ZD02 (GCA_000967305.2) as an outgroup. A second phylogenomic tree was built by placing BS-T2-15^T in the GTDB tree using GTDB-tk (version 2.1 [34]), then subsetting the tree to family *Burkholderiaceae* and genus *Escherichia*, extracting the amino acid alignment, masking positions with over 0.5 gaps and computing a ML tree with IQ-TREE under the model WAG as described above. This second tree was built with 229 MAGs and 60 cultivated bacterial strains from the *Rubrivivax–Roseateles–Leptothrix–Azohydromonas–Aquincola–Ideonella* branch.

The phylogenomic tree built with the 21 reference genomes and the two MAGs closely related to strain BS-T2-15^T, was very robust with high ultrafast bootstrap values, and showed a distinctly deeper branching of strain BS-T2-15^T with its two closely related MAGs and a close proximity to the *Ideonell*a clade (Fig. 2). A similar result was also obtained with the phylogenomic tree built with the 229 MAGs (Fig. S6). Therefore, these two phylogenomic trees indicate that strain BS-T2-15^T indeed represents a new

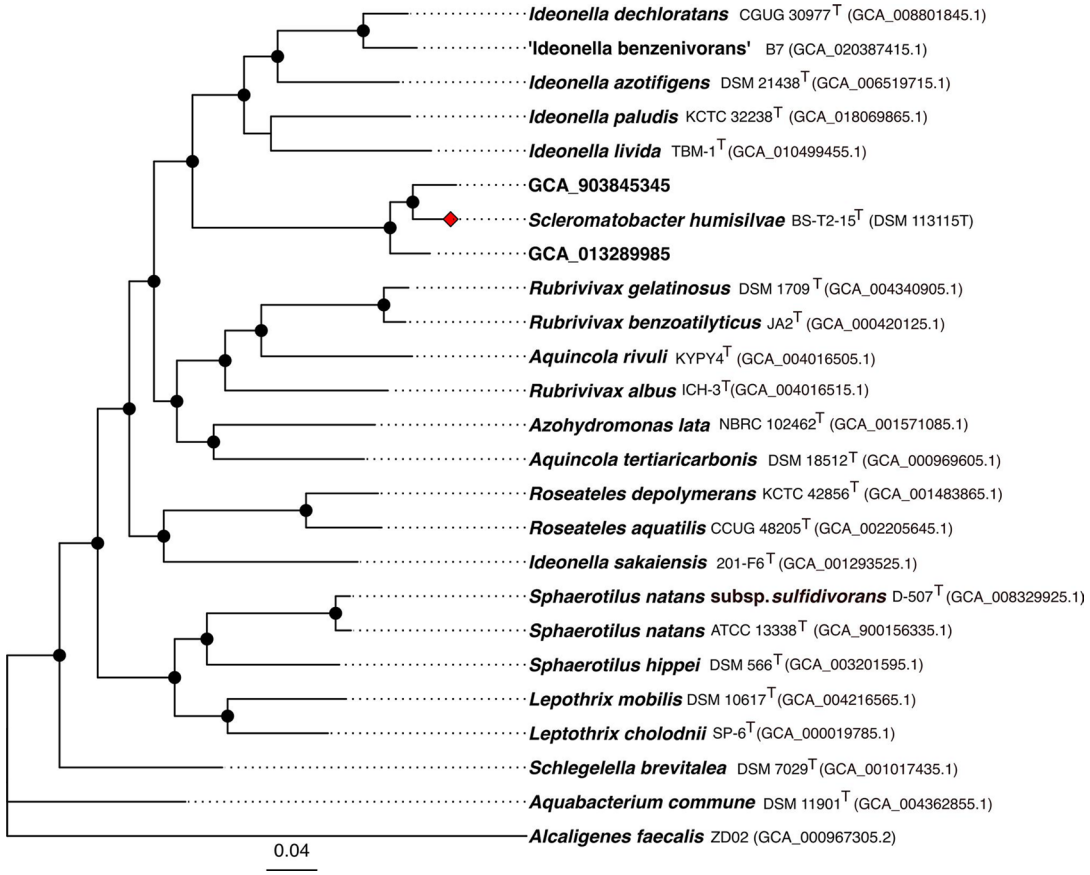

Fig. 2. Phylogenomic tree (concatenated alignment of 340 shared gene clusters) showing the phylogenomic position of strain BS-T2-15^T, its two closely related MAGs and representatives of other related taxa. The tree was built using IQ-TREE and the maximum-likelihood method with 1000 replicates for the calculation of the ultrafast bootstrap. Bootstrap values>95% are indicated at branching point by a dot. The tree was rooted using *Alcaligenes faecalis* ZD02 (GCA_000967305.2) as the outgroup. Bar, 0.04 substitutions per position.

genus of the *Comamonadaceae* family within the order *Burkholderiales*, and belongs to the *Rubrivivax–Roseateles–Leptothrix–Azohydromonas–Aquincola–Ideonella* branch.

In addition to the phylogenomic trees, Overall Genome Related Indices (OGRI) were obtained by pairwise calculations between genome of strain BS-T2-15^T, the two closely related MAGs of strain BS-T2-15^T and the 21 reference genomes. The average nucleotide identity scores (ANI) were obtained using the FastANI calculator tool from the GTDB web server (https://gtdb.ecogenomic.org/tools/fastani) [35]. In addition, the FastANI calculator provided the alignment fraction (AF) values between genomes. Digital DNA–DNA hybridization (dDDH) scores were determined by the Genome-to-Genome Distance Calculator (GGDC 2.1), using formula 2 [36]. The average amino acid identity (AAI) calculations between genomes were determined as described by Kim *et al.* [37] using the EzAAI pipeline (http://leb.snu.ac.kr/ezaai). The percentage of conserved proteins (POCP) was estimated as described by Qin *et al.* [38].

The dDDH and ANI values between strain BS-T2-15^T genome and the genomes of type strains of the closest genera ranged from 20.00 to 20.50% and from 78.50 to 79.70%, respectively (Table 3). These values are both far below the dDDH threshold level of 70% and the ANI value of 95–96% that are generally accepted for species delineation [39, 40]. Concerning the AAI and POCP values between the genome of strain BS-T2-15^T and genomes of the type strains of the closest genera, they ranged, respectively, from 64.27 to 66.57% and from 40.89 to 49.27% (Table 3). The AAI values are close to the 65% cutoff value generally accepted for delineating a new genus, while the POCP values are below the 50% threshold recognized for demarcating a new genus [38, 41]. Finally, the AF values ranged between 0.29 and 0.48 between the genomes of strain BS-T2-15^T and type strains of the closest genera (Table 3), and were observed in conjunction with low ANI values [42], which is not incompatible with the description of a new genus. In this case, POCP and, to a lesser extent, ANI, are the most relevant indices to demonstrate that strain BS-T2-15^T represents a new genus. Similar results were obtained when considering the 21 reference genomes (Fig. S7 and Table S3). In addition, all OGRI values obtained between the BS-T2-15^T strain genome and the genomes of its two closely related MAGs were higher compared to

the values obtained against genomes of cultured type strains. These OGRI values relative to the closest MAGs were respectively in the range of 30.10–40.40% and 87.40–88.90% for dDDH and ANI, and in the range of 84.14–86.43%, 70.43–74.76% and 0.70–0.80 for AAI, POCP and AF indices (Tab 3, S4–S8). These dDDH and ANI values are below the thresholds accepted for species delineation while the AAI, POCP and AF values are above the thresholds for a new genus delineation. Overall, these OGRI analyses clearly show that strain BS-T2-15^T and its two closely related MAGs (i) belong to the same genus, (ii) represent a new genus of the *Rubrivivax–Roseateles–Leptothrix–Azohydromonas–Aquincola–Ideonella* branch and, (iii) belong to three distinct genomic species. Furthermore, values of the different OGRI calculated between the species of the genus *Ideonella* and strain BS-T2-15^T and its two closely related MAGs are much lower than those obtained between strain BS-T2-15^T and its two closely related MAGs (Table S4-S8). Thus, OGRI values, as well as phylogenomic analyses, lead all to the conclusion that strain BS-T2-15^T represents a new species of a new genus of the *Rubrivivax–Roseateles–Leptothrix–Azohydromonas–Aquincola–Ideonella* branch.

For gene function prediction, genome annotations were performed with the MaGe platform using the KEGG and BioCyc databases. The genome of the new strain BS-T2-15^T encodes metabolic pathways for organoheterotrophic growth. Notably, the genome encodes a complete pentose phosphate pathway and a complete Entner–Doudoroff pathway. The tricarboxylic acid cycle pathway for aerobic respiration is almost complete (one enzyme missing). The genome of the novel isolate also encodes the nitrate VIII reduction pathway (dissimilatory) for anaerobic nitrate respiration, which has been shown to be functional experimentally. Degradation pathways for organic compounds such as amino acids (alanine, arginine, asparagine, serine, glutamine, glycine, histidine, cysteine, lysine, ornithine, taurine, threonine and tryptophan), carbohydrates (acetoin, chitin, glucose, glucose-1-phosphate, lactose, ribose and xylose), aromatic compounds (anthranilate, gentisate, phenylacetate and protocatechuate), alcohols (ethanol and glycerol), aldehyde (L-lactaldehyde), amines and polyamines (choline, 4-aminobutyrate, ethanolamine and urea) and carboxylates (gluconate, glutaryl CoA, glycolate and glyoxylate) are evidenced. The cytochrome C oxidase complex (EC number: 7.1.1.9; locus tags: COMBST215_v1_20371; 20374; 20375; 20376; 80152; 80156; 80157) was also identified despite oxidase activity not being demonstrated experimentally. The cyclopropane fatty acid biosynthesis *via* the cyclopropane-fatty-acyl-phospholipid synthase (EC number: 2.1.1.79; locus tag: COMBST215_v1_10589; 50189) and the arginine-dependent acid resistance (arginine decarboxylase; EC number: 4.1.1.19; locus tag: COMBST215_v1_10270) pathways are present and may give the strain a competitive advantage in acidic environments such as the forest soil ecosystem. The new strain BS-T2-15^T also has the genetic potential to detoxify arsenate using glutaredoxin (gene: arsC; EC number: 1.20.4.1; locus tag: COMBST215_v1_40055) and to degrade superoxide radicals [identification of superoxide dismutase (EC number: 1.15.1.1; locus tags: COMBST215_v1_20566; 40196; 50105) and catalase enzymes (EC number: 1.11.1.21; locus tag: COMBST215_v1_11754 and EC: 1.11.1.6; locus tags: COMBST215_v1_60157; 140122)]. In comparison with other closely related strains, the new strain BS-T2-15^T is the only one with the genetic potential to achieve the biosynthesis of betaxanthin (a secondary metabolite) and to degrade alanine and anthranilate (Table S9).

In conclusion, from the clear genotypic distance from the closest genera, the physiological similarities and some phenotypical and chemotaxonomic differences, we comply with the phylo-phenetic concept that currently prevails for the description of a new genus. Thus, we assigned strain BS-T2-15^T to a novel species, of a novel genus, for which the name *Scleromatobacter humisilvae* gen. nov., sp. nov. is proposed.

DESCRIPTION OF *SCLEROMATOBACTER* GEN. NOV.

*Scleromatobacter (*Scle.ro.ma.to.bac'ter. Gr. neut. n. *skleroma*, induration; N.L. masc. n. *bacter*, a rod; N.L. masc. n. *Scleromatobacter*, a rod from a hardened part; derived from the colonies that are incrusted in solid medium when the strain grows in Petri dishes).

Cells are Gram-negative, mesophilic, aerobic, chemoorganotrophic, straight rod-shaped (0.6–0.9×1.7–2.7 µm in size) and motile with presence of storage granules. Oxidase-negative and catalase-positive. The predominant fatty acids are $C_{16:1}$ ω7*c*, $C_{16:0}$ and $C_{14:0}$ 2-OH. The polar lipid profile consists of a mixture of phosphatidylethanolamine, diphosphatidylglycerol and phosphatidylglycerol and the main ubiquinone is Q-8. The estimated size of the genome is 6.28 Mb with a DNA G+C content of 69.56 mol%. Phylogenetically, on the basis of whole genome comparisons, the genus belongs to the family *Comamonadaceae*, order *Burkholderiales*. Overall, the genus belongs to the *Rubrivivax–Roseateles–Leptothrix–Azohydromonas–Aquincola–Ideonella* branch. The type species is *Scleromatobacter humisilvae* (BS-T2-15^T).

DESCRIPTION OF *SCLEROMATOBACTER HUMISILVAE* SP. NOV.

Scleromatobacter humisilvae (hu.mi.sil'vae. L. fem. n. *humus*, soil; L. fem. n. *silva*, forest; N.L. gen. fem. n. *humisilvae*; from forest soil; from the forest soil where the strain has been isolated).

Displays the following properties in addition to those given in the genus description: colonies are circular, rough and incrusted in the agar medium with a colour between white and ivory. Optimal growth occurs at 20–22 °C, pH 6 and 0% NaCl. Positive for nitrate reduction. Does not respire chlorate. The following carbon sources are used: L-arabinose, cellobiose, glucose, ribose, arabitol,

adonitol, butyrate, gluconate, pyruvate, L-leucine, L-proline, *N*-acetylglucosamine, *p*-hydroxy phenylacetic acid, bromo succinic acid, L-pyroglutamique acid, Tween 40 and 80, uridine, putrescine, and dextrine. On the contrary, unable to use: citrate, acetate, aspartate, benzoate, formate, methyl-pyruvate, mono-methyl-succinate, cis-aconitic acid, galactonic acid lactone, galacturonic acid, gluconic acid, glucosaminic acid, glucuronic acid, α-, β-, γ-hydroxy butyric acid, *p*-hydroxyphenylacetic acid, itaconic acid, α-keto butyric acid, α-keto glutaric acid, α-keto valeric acid, D,L-lactic acid, malonic acid, propionic acid, quinic acid, saccharic acid, sebacic acid, succinic acid, succinamic acid, L-aspartic acid, L-glutamic acid, glycyl-L-aspartic acid, glycyl-L-glutamic acid, L-pyroglutamic acid, γ-amino butyric acid, urocanic acid, phosphate, glucose-1-phosphate, glucose-2-phosphate, fructose, L-fucose, galactose, gentiobiose, CM-cellulose, psicose, raffinose, L-rhamnose, sucrose, maltose, trehalose, turanose, mannose, melibiose, lactose, lactulose, maltose, methyl β-glucoside, *myo*-inositol, xylitol, mannitol, i-erythritol, D-sorbitol, glycerol, D,L-α-glycerol, 2,3-butanediol, *N*-acetyl-glucosamine, *N*-acetyl-galactosamine, 2-aminoethanol, phenylethylamine, glucuronamide, L-alaninamide, D-,L-alanine, L-phenylalanine, L-alanyl-glycine, L-asparagine, L-histidine, L-ornithine, hydroxy-L-proline, D-,L-serine, L-threonine, D,L-carnitine, thymidine, α-cyclodextrin, inosine, glycogen, xylan, lignin and chitin. Produces α-glucosidase but is negative for urease.

The type strain, BS-T2-15^T (DSM 113115^T=UBOCC-M-3373^T) was isolated from bulk soil in direct contact with decaying oak placed for 9 months on the ground of the Champenoux forest experimental site (France).

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Conflicts of interest
The authors declare that there are no conflicts of interest.

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