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## Identification and Characterization of a Halotolerant, Cold-Active Marine Endo- $\beta$ -1,4-Glucanase by Using Functional Metagenomics of Seaweed-Associated Microbiota

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1 **Functional screening of a metagenomic library of seaweed-associated**  
2 **microbiota: identification and characterization of a halotolerant, cold-**  
3 **active marine endo- $\beta$ -1,4-endoglucanase**

4

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13

14 Running head: Functional screening of an algal biofilms metagenomic library

15

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17 **Abstract**

18 A metagenomic library was constructed from microorganisms associated with the  
19 brown alga *Ascophyllum nodosum*. Functional screening of this library revealed  
20 thirteen novel putative esterase genes and two glycoside hydrolase genes. Sequence  
21 and gene cluster analysis showed the wide diversity of the identified enzymes and  
22 gave an idea of the microbial populations present during the sample collection period.  
23 Lastly, an endo- $\beta$ -1,4-endoglucanase having less than 50% identity to sequences of  
24 known cellulases was purified and partially characterized, showing activity at low  
25 temperature and after prolonged incubation in concentrated salt solutions.

26

27 **Keywords**

28 Microbial enzymes; *Ascophyllum nodosum*; metagenomics; plates tests; biomass  
29 hydrolysis ; cellulase ; beta-glucosidase; esterase; functional screening, GH5

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31

## 32 **Introduction**

33 Previous surveys have revealed that less than 1% of existing microorganisms can be  
34 studied by traditional culturing methods. This leaves most microorganisms and their  
35 by-products unknown and unexploited (1, 2) and explains why metagenomics, a  
36 culture-independent approach using total microbial genomes from environment  
37 samples, has met with great success over the past decade (3, 4). Sequence-based  
38 metagenomics has already provided information about the composition, organization,  
39 functioning, and hierarchy of microbial communities in particular habitats (5). On the  
40 other hand, functional genomics applied to metagenomic libraries from diverse  
41 environments has led to the discovery of many new enzymes and bioactive  
42 compounds and to substantial enrichment of genome databases. To date, most of the  
43 enzymes brought to light through metagenomics have been derived from soil (6–9)  
44 and gut (10–13) samples.

45 Marine microorganisms represent great candidate sources of original biocatalysts, as  
46 they are exposed to extreme conditions of temperature, pressure, salinity, nutrient  
47 availability, etc. Hence, functional screening of marine microbial populations should  
48 yield new enzymes with specific and unique physiological and biochemical  
49 properties, produced by organisms far different from those usually described in  
50 terrestrial environments (14). New enzymes have already been identified in marine  
51 metagenomic libraries from seawater samples (15, 16) and from microorganisms in  
52 symbiosis with marine organisms such as sponges and corals (17). To our knowledge,  
53 however, nobody has yet performed functional screening of metagenomic libraries  
54 from algal microbial communities. As algal microbial biofilms are in constant  
55 interaction with algal biomass, they represent an interesting source of enzymes and  
56 other active compounds (18). Sequence-based studies have already revealed the

57 importance and functions of microbial communities living on the surfaces of algae,  
58 showing tight interdependence between algae and their biofilms (19–21).  
59 Furthermore, many genes coding for enzymes involved in hydrolyzing algal biomass,  
60 such as cellulases, xylanases,  $\alpha$ -amylases, and specific algal polysaccharidases (e.g.  
61 agarases, carrageenases, and alginate lyases) have been identified from cultivable  
62 marine bacteria (22, 23). Only a few such enzymes have been found again in marine  
63 metagenomes by functional screening. For example, no cellulase gene has yet been  
64 identified by marine metagenomics, although cellulase genes have been identified in  
65 the genomes of cultivable marine bacteria such as *Caldocellum saccharolyticum* (24),  
66 *Paenibacillus* sp. BME14 (25), *Marteella mediterranea* (26), and *Marinobacter* sp.  
67 MS1032 (27). Cellulases are widely used in biotechnological applications (e. g. in the  
68 pulp and paper, textile, and food industries) and their capacity to convert cellulosic  
69 biomass is increasingly exploited in sustainable applications and bioprocesses (28).  
70 Although several cellulases are already in use, there is an increasing demand for  
71 cellulases with better or special industrial properties (29). Here we describe the  
72 construction and functional screening of a metagenomic library from microorganisms  
73 living on the annual brown alga *Ascophyllum nodosum*. The library was screened for  
74 particular hydrolytic enzymes. The screen has yielded genes encoding new esterases  
75 belonging to diverse lipolytic enzyme families, a novel beta-glucosidase, and a novel  
76 cellulase. These discoveries highlight the utility of seeking original biocatalysts in  
77 algal biofilm populations. We have purified and characterized the identified new  
78 cellulase. To our knowledge, no functional screening of a metagenomic library from  
79 alga-associated microbial biofilms has been realized before, and no cellulase has  
80 already been identified by functional metagenomics in a marine environment.

## 81 **Material and methods**

### 82 **Environmental Sample Collection**

83 Several plants (~ 100g) of *Ascophyllum nodosum* were collected from the foreshore  
84 (48° 43' 36.07" SE, -3° 59' 22.96") in Roscoff (Brittany, France), at the start of  
85 February 2012. Samples were collected in triplicate and put in sterile plastic bags. The  
86 algae were rinsed three times with sterile seawater to remove loosely associated  
87 microorganisms and cut into smaller sections. Washed and cut algae were freeze-dried  
88 at -80°C in new sterile plastic bags until DNA extraction.

### 89 **Microbial Genomic DNA Extraction**

90 Bacterial DNA was extracted by swabbing the algal surfaces with sterile cotton tips  
91 followed by classic DNA extraction (30). Six cotton tips were used per 25 g of algae.  
92 Microbial DNA was extracted from the cotton tips with 6.75 ml lysis buffer (100 mM  
93 Tris-HCl; 0.5 M EDTA; 100 mM sodium phosphate; 5 M NaCl; 10% CTAB) and  
94 incubated with 50 µl proteinase K (10 mg/ml) at 37°C. After one hour, 750 µl of 20%  
95 SDS was added and the cotton tips were incubated for 2 h at 65°C, with manual  
96 inversion every 20 minutes. After centrifugation, 1 volume of chloroform-isoamyl  
97 alcohol (v:v, 24:1) was added to the supernatant and the mixture centrifuged. The  
98 aqueous phase was recovered and DNA was precipitated with 0.6 vol isopropanol for  
99 one hour at room temperature. DNA was recovered by centrifugation (30 min –  
100 10.000g) at 4°C, washed with 70% ethanol, and the pellet was air dried and  
101 resuspended in 100 µl Tris-EDTA. The DNA extracted from triplicate samples was  
102 pooled for DNA library construction. The quantity of DNA was measured with a  
103 Qubit® (Invitrogen) and its quality was checked on a 0.8% agarose gel.

### 104 **Library Construction and functional screening**

105 The pool of DNA obtained from triplicate samples was partially cut with DpnII (New  
106 England Biolabs). A PEG/NaCl size-selective precipitation was done according to

107 Biver et al. (6) in order to remove small DNA inserts. An equal volume of 6.5%  
108 PEG/0.4M NaCl was added to the restriction fragments (final DNA concentration: 20  
109 ng/μl) and the mixture was incubated for 2 h at RT. The DNA was purified by  
110 migration through a 1% low-melting-point agarose gel (Promega) and DNA inserts  
111 between 1.5 and 7 kb were recovered by AgarACE digestion (Promega). The inserts  
112 were ligated into the BamHI (Roche) linearized and dephosphorylated (Roche) shuttle  
113 vector YEp356 (Novagen) with T4 DNA ligase (Roche). Electrompetent Electromax  
114 *E. coli* cells (Life Technologies) were finally transformed with the ligation product.  
115 The average DNA insert size was estimated by isolation and purification of 20  
116 randomly chosen plasmids. The transformants were pooled and the metagenomic  
117 library was plated and screened for lipolytic activity on 3% tributyrin 2xYT agar  
118 plates containing 100 μg/ml ampicillin. Beta-glucosidases were sought on 2xYT agar  
119 containing 0.5% esculin (Sigma—Aldrich) and 0.1% ammonium iron (III) citrate  
120 (Sigma—Aldrich) (12). Cellulolytic activity was detected by plating the library on  
121 2xYT agar plates containing 1 g/l insoluble synthetic AZCL-HE-cellulose  
122 (Megazyme) and 100μg/ml ampicillin. A blue halo was observed around colonies  
123 exhibiting cellulase activity. The plasmids of positive clones were extracted and used  
124 for activity confirmation in DH5α *E. coli* subcloning cells (Life Technologies). Insert  
125 sizes were estimated with restriction enzymes cutting at both extremities of the DNA  
126 insert (*HindIII* and *EcoRI*, Roche).

#### 127 **DNA sequencing and sequence analysis**

128 DNA inserts of positive clones were sequenced at GATC Biotech (Germany).  
129 Sequence similarity searches were carried out with the NCBI BlastP program.  
130 Phylogenetic trees were produced by the neighbor-joining method with MEGA6.06.  
131 Signal peptides were predicted with the SignalP 4.1 server (31). All putative proteins

132 corresponding to the identified ORFs in the inserts were analyzed with BlastP against  
133 the GenBank non-redundant database and Swissprot (curated database). The putative  
134 esterases were also analyzed with Pfam (32).

#### 135 **Overexpression and purification of the CellMM5.1 cellulase**

136 The coding sequence of the *Cell5.1\_3* gene was amplified, without its putative peptide  
137 signal, with Platinum *Pfx* DNA Polymerase, 0.5x PCRx Enhancer Solution  
138 (Invitrogen), 5'- gggaattcCATATGCAAACCTCTGACAGCTATGTTCCGC -3' as  
139 forward primer, and 5'-

140 cgcGGATCCTCATCAGTGGTGGTGGTGGTGGTGGCGCCCAAGCAAGGCGT  
141 -3' as reverse primer. The restriction sites (NdeI, BamHI) used for subcloning are  
142 underlined and the histidine tag sequence appears in bold. PCR products were cloned  
143 into the pET30b(+) vector (Novagen) and the resulting plasmids were introduced into  
144 *E. coli* Rosetta 2 (DE3) cells (Novagen). The cellulolytic activity of the obtained  
145 transformants was evaluated by spotting 5 µl overnight culture (grown at 37°C in  
146 liquid 2xYT medium, 30 µg/ml chloramphenicol and 30 µg/ml kanamycin) onto solid  
147 2xYT medium supplemented with 10 µM isopropyl β-D-1-thiogalactopyranoside  
148 (IPTG) (Fermentas), 1g/l AZCL-HE-cellulose (Megazyme), and appropriate  
149 concentrations of antibiotics (30 µg/ml chloramphenicol and 30 µg/ml kanamycin).  
150 The bacteria were allowed to grow at 37°C for 3 days. To purify the recombinant  
151 cellulase, an overnight culture of transformed *E. coli* Rosetta cells was diluted to  
152 OD<sub>600nm</sub>=0.005 in a 1-l shake flask containing 200 ml 2xYT medium and the  
153 corresponding antibiotics. The cultures were grown at 37°C under shaking at 160 rpm  
154 until the OD<sub>600nm</sub> reached about 0.4. Overproduction was induced by addition of 1 µM  
155 IPTG followed by incubation at 16°C for ~20 h. The cells were harvested by  
156 centrifugation and lysed at 37°C for 30 min in 17 ml lysis buffer (20 mM Tris-HCl



157 buffer pH 8 containing 0.3 M NaCl, 1 ml/l Triton X-100, and 5 mg/ml lysozyme)  
158 according to Biver et al (33). After sonication on ice (4 cycles of 5 s, 100 W, Sonifier  
159 250, Branson), the lysate was centrifuged at 10,000g for 20 min (4°C) to separate  
160 insoluble (I0) from soluble (S0) proteins. To solubilize the recombinant cellulase  
161 found mostly in the resulting pellet (I0), the latter was incubated at 4°C for 4 h in 5 ml  
162 solubilization buffer (20 mM Tris-HCl pH 8, 0.5 M NaCl, 20 ml/l Triton X-100, 2 M  
163 urea). The partly resuspended fraction was then centrifuged again to collect the  
164 soluble fraction (S1) now containing a sufficient amount of His-tagged cellulase,  
165 which was next purified by Ni-NTA affinity chromatography (Qiagen). The soluble  
166 fraction was diluted 10 times in 20 mM Tris-HCl pH 8 and 0.5 M NaCl to reduce the  
167 urea and Triton X-100 concentrations to 0.2 M and 2 ml/l, respectively, and then  
168 incubated overnight at 4°C with 200 µl Ni-NTA agarose pre-equilibrated with binding  
169 buffer (20 mM Tris-HCl pH 8, 0.5 M NaCl, 2 ml/l Triton X-100, 0.2 M urea). The  
170 resin was recovered by centrifugation at 800 g for 5 min and washed twice with 1 ml  
171 washing buffer 1 (20 mM Tris-HCl pH 7.5, 0.5 M NaCl, 1 ml/l Triton X-100, 10 mM  
172 imidazole) and twice with 1 ml washing buffer 2 (20 mM Tris-HCl pH 7.5, 0.5 M  
173 NaCl, 1 ml/l Triton X-100, 20 mM imidazole) before elution with 2 ml of 20 mM  
174 Tris-HCl pH 7.5, 0.5 M NaCl, 250 mM imidazole. After analysis by SDS-PAGE, this  
175 first eluate (E1) was repurified by Ni-NTA chromatography (E2) and then dialyzed at  
176 4°C against 50 mM sodium phosphate pH 6.8 containing 50 mM NaCl.

### 177 **Cell5.1\_3 cellulase activity characterization**

178 Enzymatic activity was quantified by measuring the quantity of generated reducing  
179 sugars with the 3',5'-dinitrosalicylic acid reagent (DNSA, Sigma) (34). The  
180 enzymatic assay was performed with 1% (w/v) carboxymethylcellulose (CMC) (Ultra  
181 low viscosity, Fluka), 50 mM phosphate buffer pH 7 for 10 minutes at 40°C in a total

182 volume of 390  $\mu\text{l}$ , to which 10  $\mu\text{l}$  suitably diluted enzyme was added. Then an equal  
183 volume (400  $\mu\text{l}$ ) of DNSA was added and the mixture heated for 10 minutes at 99°C.  
184 After cooling on ice, the absorbance was read at 540 nm (Multiskan Go,  
185 ThermoScientific). The concentration of reducing sugar was determined against a  
186 glucose standard. Cell5.1\_3 activity was measured in  $\mu\text{moles}$  of glucose released per  
187 minute. All assays were performed in triplicate. The temperature range tested was  
188 from 0°C to 70°C. The tested pH ranges were from pH 4 to pH 6 (in sodium acetate  
189 buffer), from pH 6 to pH 8 (in sodium phosphate buffer), from pH 8 to pH 9 (in  
190 Tris/HCl buffer), and from pH 8 to pH 10 (in glycine/NaOH buffer). The temperature  
191 and pH stability were estimated, respectively, by incubating the enzyme for 1 hour at  
192 the appropriate temperature or for 24 h at the appropriate pH (in the appropriate  
193 buffer). Residual activities were then measured under standard conditions.  
194 Halotolerance was determined by measuring the residual activity after 1.5, 5, and 24 h  
195 of incubation in 3 M KCl or 4 M NaCl. Substrate specificity was determined by  
196 replacing CMC in the standard assay with 1% (w/v) lichenan (1-3,1-4- $\beta$ -D-glucan,  
197 Megazyme), laminarin (Sigma), xyloglucan (Megazyme), mannan (1,4- $\beta$ -D-mannan,  
198 Megazyme), or crystalline cellulose (Avicel, Sigma). For the insoluble substrates  
199 mannan and Avicel, the reaction time was extended to 5 h at room temperature, with  
200 automatic inversion. Effects of metal ions on the activity of the Cell5.1\_3 cellulase  
201 were determined under standard conditions with the metal ion of interest at 1 mM  
202 final concentration. Effects of the chemicals EDTA (10 mM), SDS (1%), ethanol  
203 (10%), Triton (5%), glycerol (15%), and DMSO (15%) were also tested under  
204 standard conditions. Kinetic parameters ( $K_m$  and  $k_{cat}$ ) were determined from a  
205 Lineweaver-Burk plot obtained by varying the concentration of CMC (0.5 – 4%) in  
206 assays performed under standard conditions.

207 **Accession numbers**

208 The DNA insert sequences of *LipMM5.1*, *LipMM5.3*, *LipMM5.5*, *LipMM5.7*,  
209 *LipMM5.8*, *LipMM5.11*, *LipMM5.12*, *LipMM5.13*, *LipMM5.14*, *LipMM5.15*,  
210 *LipMM5.19*, *CellMM5.1*, and *BglucMM5.1* have been submitted to GenBank under  
211 accession numbers KF726988, KF726989, KF726990, KF726991, KF726992,  
212 KF726993, KF726994, KF726995, KF726996, KF726997, KF726998, KF726999,  
213 and KJ499810, respectively (see also TABLE 1).

214 **Results**

215 **DNA extraction, library construction, and functional screening**

216 Bacterial DNA was first extracted according to Burke et al. (35) with a tri-enzymatic  
217 cleaner (ANIOS PlaII, France). As this procedure resulted in co-extraction of  
218 polyphenols, present in brown algal cell walls (36), the DNA could not be purified  
219 (data not shown). Therefore, a method described by Lachnit et al. (30), consisting of  
220 swabbing the algal surfaces with sterile cotton tips followed by classic DNA  
221 extraction, was tried. DNA quality was checked by migration through an agarose gel.  
222 High-molecular-weight DNA, without any visible degradation smear, was observed  
223 (data not shown). An average of 0.11 µg DNA per gram of *Ascophyllum nodosum* was  
224 recovered with this method. As 75 g of algae were swabbed, approximately 8 µg of  
225 microbial DNA was recovered and used to construct the metagenomic library. The  
226 DNA was restricted and small DNA fragments were removed by PEG/NaCl  
227 precipitation followed by agarose purification. DNA fragments with a size between 3  
228 and 10 kb were ligated into the YEp356 cloning vector and the resulting recombinant  
229 plasmids were inserted into electrocompetent DH10b *E. coli* cells. The generated  
230 metagenomic library was plated, resulting in approximately 40,000 clones (180 Mb)  
231 with an average DNA insert size of 4.5 kb (estimated on 20 randomly chosen

232 recombinant plasmids). The recombinant clones were pooled and screening was done  
233 by plating the library several times on 2xYT agar plates containing tributyrin,  
234 esculetin, or AZCL-HE-cellulose (for detection of lipase (clear halo), beta-glucosidase  
235 (brown precipitate), or cellulase (blue halo) activity, respectively). The screens  
236 yielded respectively 20, 1, and 1 candidate(s). Activity was confirmed by extraction of  
237 their recombinant plasmids and transformation of DH5 $\alpha$  *E. coli* cells. The novel  
238 recombinant clones were then plated again on selective media: from the 20 candidates  
239 showing lipase activity, 11 plasmids were found to confer lipolytic activity  
240 (*LipMM5.1*, *LipMM5.3*, *LipMM5.5*, *LipMM5.7*, *LipMM5.8*, *LipMM5.11*, *LipMM5.12*,  
241 *LipMM5.13*, *LipMM5.14*, *LipMM5.15*, *LipMM5.19*), and the plasmids assumed to  
242 carry a cellulase gene (*CellMM5.1*) or a beta-glucosidase gene (*BglucMM5.1*)  
243 accordingly conferred the corresponding activity.

#### 244 **DNA Sequence analysis**

245 The DNA inserts of the positive clones were sequenced. ORFs on the DNA inserts  
246 were sought with ORF Finder. On the DNA insert of each positive candidate, 3 to 7  
247 ORFs were indentified. Each ORF gene product was analyzed with BlastP against the  
248 GenBank non-redundant database and Swissprot (a curated database). The putative  
249 esterases were also analyzed with Pfam (32) (Supplementary Data, DATASET S1).  
250 In each cluster, we identified at least one ORF whose predicted product shows  
251 sequence similarity to the amino acid sequence of a known esterase, beta-glucosidase,  
252 or cellulase (shown in TABLE 1). Putative esterase genes were assigned to four  
253 carboxyesterase families by amino acid sequence alignment (data not shown).  
254 Lip5.8\_1 shows sequence similarity to members of bacterial esterase family II (37,  
255 38). Lip5.1\_5, Lip5.3\_3, Lip5.5\_4, Lip5.13\_3, Lip5.14\_3, and Lip5.19\_3 belong to  
256 family IV, Lip5.13\_1 to family V, and Lip5.11\_3 and Lip5.15\_3 to family VIII. The

257 gene products of *Lip5.7\_2* and *Lip5.12\_2* could not be assigned to any esterase family  
258 described by Arpigny (37) nor to one of the novel families EstA (39) and LipG (16).  
259 However, these gene products could be assigned to the Pfam alpha/beta-hydrolase  
260 family (subfamilies 6 and 5, respectively), which contains numerous esterases. In fact,  
261 the esterase families IV and V correspond to alpha/beta-hydrolase subfamilies 3 and  
262 6, respectively (32).

263 On the DNA insert of the beta-glucosidase-positive clone, the following were  
264 identified: an incomplete ORF encoding a putative glycoside hydrolase (GH), an  
265 incomplete ORF encoding a putative xylulokinase, and a complete ORF encoding a  
266 putative esterase (GDSL). The incomplete glycoside hydrolase gene (*Bgluc5.1\_1*) was  
267 probably responsible for the beta-glucosidase activity and was assigned to family  
268 GH3 of the CAZyme database (40). The esterase gene (*Bgluc5.1\_2*) encodes a  
269 putative GDSL lipolytic protein assigned to family II by amino acid sequence  
270 alignment (37, 38).

271 On the *CellMM5.1* candidate, we identified an ORF (*Cell5.1\_3*) of 359 amino acids  
272 showing 42% sequence identity to a glycoside hydrolase of *Hirschia baltica* ATCC  
273 49814 (GenBank: YP\_003060354.1). A GH5-family protein signature was also  
274 identified. Phylogenetic analysis showed that the enzymes most similar to the  
275 *Cell5.1\_3* putative cellulase are subfamily-GH5\_25 enzymes of proteobacteria such as  
276 *Hirschia baltica*, *Caulobacter sp.*, and *Ramlibacter sp.* (41) (FIG 1). A signal peptide  
277 was also predicted. As no other cellulase has been identified to date by functional  
278 metagenomics in a marine environment, we chose to purify and characterize the  
279 putative cellulase gene (*Cell5.1\_3*) product.

280 It is difficult to attribute a specific biological function to the different gene clusters on  
281 the basis of gene annotations, especially for the clusters containing esterases. In

282 contrast, curated gene annotations give insights into the taxonomic affiliation of the  
283 *Ascophyllum*-associated bacteria, at least at the level of the class or order. In most of  
284 the clusters, the different genes have a consistent taxonomic affiliation (based on the  
285 bacterial origin of the closest homologous proteins). The *LipMM5.1* insert is an  
286 exception: its affiliation is ambiguous, with homologous genes found among the  
287 *Firmicutes*, *Actinobacteria*, and *Gammaproteobacteria*. The *LipMM5.7* and  
288 *LipMM5.13* inserts seem to come from representatives of the *Betaproteobacteria* and  
289 *Gammaproteobacteria*, respectively. The remaining inserts originate from  
290 *Alphaproteobacteria* members, mainly of the order *Rhodobacterales*. Interestingly,  
291 several inserts seem to belong to bacteria close to *Robiginitomaculum antarcticum*, a  
292 marine *Rhodobacterales* species isolated from Antarctic seawater (42).

#### 293 **Cellulase purification and activity characterization**

294 The recombinant Cell5.1\_3 cellulase, without its signal peptide, was produced in *E.*  
295 *coli* Rosetta 2 (DE3) from the pET30b vector and purified by Ni-chromatography.  
296 SDS-PAGE of the eluted fractions showed a clear band between 30 and 40 kDa  
297 (Figure 2), in accordance with the predicted molecular mass (38 kDa). The activity of  
298 the Cell5.1\_3 enzyme was tested by the DNSA method on CMC. Its optimal  
299 temperature was found to be about 40°C, although the enzyme proved unstable after a  
300 1-hour incubation at this temperature (FIG 3A). At 40°C, the optimal pH was pH 7,  
301 and the cellulase appeared stable over a wide pH range when pre-incubated for 24 h at  
302 4°C in different buffers (FIG 3C, D). The kinetic parameters determined for the  
303 reaction with CMC, at optimal pH and temperature, were  $K_m = 8.37 \mu\text{M}$  and  $k_{\text{cat}} =$   
304  $10.35 \text{ s}^{-1}$ . Halotolerance was also observed: the activity of the enzyme remained  
305 unchanged, under standard conditions, after a 24-hour pre-incubation with 4 M NaCl  
306 or 3 M KCl (FIG 3B). The specificity of the enzyme was tested in the presence of

307 different substrates (TABLE 2). The Cell5.1\_3 cellulase failed to hydrolyze the  
308 insoluble substrates crystalline cellulose (Avicel) and mannan, even when incubated  
309 for 5 h at 20°C. Among the soluble substrates tested, it showed no activity against  
310 xyloglucan, low activity against laminarin, and higher activity against CMC and  
311 lichenan ( $\beta$ -1,3;1,4-glucan). The activity of the enzyme was enhanced by  $Mn^{2+}$  and  
312  $Cd^{2+}$  but clearly inhibited by  $Cu^{2+}$ ,  $Zn^{2+}$ , and  $Fe^{2+}$  (Figure 3E). Triton X-100 was  
313 found to increase the activity of the enzyme to 350%, while the other tested additives  
314 were found to reduce (EDTA, glycerol) or totally inhibit (SDS, EtOH, DMSO) its  
315 activity (FIG 3E).

## 316 **Discussion**

317 Microorganisms on algae, in the context of their numerous interactions with the host,  
318 are known to produce diverse hydrolytic enzymes. Furthermore, the complexity of the  
319 marine environment in which these microorganisms live leads to the production of  
320 specific enzymes with original biochemistry (18). Here we have constructed a  
321 metagenomic library from the genomic DNA of the bacterial communities associated  
322 in February 2012 to the brown alga *Ascophyllum nodosum* (*Fucales* order) and have  
323 screened it for diverse hydrolytic enzymes. From this library we have identified a  
324 range of new esterase genes and two new glycoside hydrolase genes, thus  
325 demonstrating the pertinence of seeking new enzymes in such microbial communities  
326 by functional metagenomics. All these hydrolase genes can most likely be assigned to  
327 the phylum *Proteobacteria* and essentially to the class *Alphaproteobacteria*, and a few  
328 to the classes *Betaproteobacteria* and *Gammaproteobacteria*. This is consistent with  
329 previous findings on the bacterial community associated in January 2007 with another  
330 *Fucales* species, *Fucus vesiculosus*, as this bacterial community appeared dominated  
331 by *Alphaproteobacteria* and *Gammaproteobacteria* species (20). Nonetheless,

332 *Bacteroidetes* and *Planctomycetes* species are also relatively abundant on brown algal  
333 surfaces (20, 43), and one can be surprised that our functional metagenomic screen  
334 yielded no genes identified as originating from these phyla. An explanation might be  
335 that our *E. coli* expression strain (*Gammaproteobacteria*) does not readily recognize  
336 gene promoters of *Bacteroidetes* and *Planctomycetes* species.

337 Esterases are the category of enzymes most frequently isolated by functional  
338 metagenomics. Here we have identified 13 esterase-encoding genes by screening a  
339 relatively low number of Mb: approximately 180 Mb, which makes on the average 1  
340 esterase per 14 Mb screened. This is much higher than in other metagenomic studies  
341 (see review of Steele et al. (44)). The 13 esterase genes identified here can be assigned  
342 to four esterase families. Six of them (*Lip5.1\_5*, *Lip5.3\_3*, *Lip5.5\_4*, *Lip5.13\_3*,  
343 *Lip5.14\_3*, *Lip5.19\_3*) have been assigned to family IV. This esterase family appears  
344 highly represented in marine metagenomes, as out of 34 esterases identified in 8  
345 screens of marine metagenomes, 27 have been classified as family-IV esterases (39,  
346 45–51). We have assigned one of the esterase genes identified here (*Lip5.13\_1*) to  
347 esterase family V, which appears to count relatively few members. Esterases of this  
348 family have been found in microorganisms displaying very different growth-  
349 temperature ranges, such as *Sulfolobus* (thermophilic archaea), *Psychrobacter*  
350 (psychrophiles), and *Moraxella* (mesophiles) species (37, 38). Only two esterases of  
351 marine origin (FJ483459, FJ483468), identified in a metagenomic library from marine  
352 sediments, have been assigned to this family previously (48). The *Lip5.11\_3* and  
353 *Lip5.15\_3* esterases have been classified as family-VIII esterases. Members of family  
354 VIII show no typical  $\alpha/\beta$ -hydrolase fold but are very similar to  $\beta$ -lactamases.  
355 Furthermore, they have a typical molecular weight around 42 kDa (38). The predicted  
356 *Lip5.11\_3* esterase shows sequence identity to  $\beta$ -lactamases and has an estimated



357 molecular weight of 41.4 kDa. The predicted Lip5.15 esterase has an estimated  
358 molecular weight of 41.5 kDa. To our knowledge, no marine-metagenome-derived  
359 esterase has previously been assigned to this family. We have identified conserved  
360 domains of the SGNH superfamily (family-II esterases) in the esterase gene  
361 (*Bgluc5.1\_2*) found on the DNA insert of the beta-glucosidase candidate *BglucMM5.1*  
362 and in the esterase gene (*Lip5.8\_1*) of *LipMM5.8*. Only one marine-metagenome-  
363 derived esterase (AB432912), identified in a sponge-associated bacterial metagenome  
364 (50), has been classified previously as a member of this family. SGNH hydrolases are  
365 a subgroup of the GDSL family II esterases. GDSL esterases have thioesterase,  
366 protease, lysophospholipase, and arylesterase activities (52). In the BLAST results for  
367 both *Bgluc5.1\_2* and *Lip5.8\_1*, we found sequence identities to thioesterases and  
368 lysophospholipases.

369 Finally, the two thioesterase genes identified on *LipMM5.11* (*Lip5.11\_4* and *\_5*) seem  
370 to be in an operon. The first gene (*Lip5.11\_4*) has sequence identity to a thioesterase  
371 of *Caulobacter* sp. K31 (Caul\_4896, YP\_001686513.1), located with another  
372 thioesterase in a 3'-5' oriented operon (Caul\_4895, YP\_001686512.1). The other  
373 thioesterase gene (*Lip5.11\_5*) has sequence identity to a thioesterase gene of  
374 *Parvibaculum lavamentivorans* DS-1 (Plav\_0440, YP\_001411720.1), which is also in  
375 a 3'-5' oriented operon with another thioesterase (Plav\_0441, YP\_001411721.1). The  
376 thioesterases and carboxylesterases constitute separate enzyme groups, although a few  
377 proteins classified as carboxylesterases also show thioesterase activity. Despite careful  
378 annotation of the esterase-containing gene clusters, it is difficult to predict the exact  
379 biological function of these esterases on the basis of the genomic context.

380 Because (i) we have found thirteen genes encoding esterases, (ii) we have assigned  
381 these genes to four esterase families, and (iii) most of the predicted protein sequences

382 are less than 50% identical to known esterases, we conclude that this library  
383 constructed from algal biofilms can be considered rich and diverse in novel microbial  
384 genes and enzymes.

385 As compared to esterase genes, few cellulase genes have been identified by functional  
386 metagenomics. To our knowledge no cellulase has been identified by metagenomics  
387 in a marine environment before. All of the cellulases identified by analysis of soil  
388 (53–56) or rumen (57, 58) metagenomes display more than 50% sequence identity to  
389 known cellulases, in contrast to our cellulase, which is only 42% identical to the  
390 closest known cellulase. Hence, our cellulase appears new and only distantly related  
391 to known cellulases. We have assigned the Cell5.1\_3 cellulase to endo- $\beta$ -1,4-  
392 glucanase family GH5, subfamily 25. Although most cellulases identified by  
393 metagenomics have been classified as GH5-family enzymes (8, 54, 57–59), only one  
394 of them (ABE60714.1), identified in a pulp sediment metagenome from a paper mill  
395 effluent, belongs to subfamily 25 (60). The other members of this subfamily were  
396 identified in cultivable microorganisms such as *Caulobacter*, *Clostridium*,  
397 *Dictyoglomus*, *Fervidobacterium*, and *Thermotoga* species isolated from diverse  
398 environments (CAZyme database, [www.cazy.org](http://www.cazy.org)). Only two subfamily-25 enzymes  
399 have been characterized so far: *Tm\_Cel5A* (Q9X273) of *Thermotoga maritima* (61,  
400 62) and *FnCel5A* (A7HNC0) of *Fervidobacterium nodosum* (63). Both of these  
401 appear thermostable. Cell5.1\_3, in contrast, shows low thermostability: when pre-  
402 incubated for 1 hour at various temperatures, it began to show decreased CMC-  
403 hydrolyzing activity when the pre-incubation temperature exceeded 25°C, and when  
404 the pre-incubation temperature exceeded 40°C, no activity was observed. Under our  
405 assay conditions, its activity was highest at 40°C, which is relatively low as compared  
406 to the enzymes *Tm\_Cel5A* and *FnCel5A*, identified in the thermophile *Thermotogales*

407 (around 80°C for both). On the other hand, our enzyme retained 11.8% of its  
408 maximum activity at 0°C and 28.7% at 10°C. According to Asperborg et al. (64), most  
409 of the endoglucanases of this subfamily have been derived from thermophiles, but  
410 interestingly, the here-identified cold-active cellulase Cell5.1\_3 would appear to come  
411 from a mesophilic (or even psychrophilic) bacterium. A cold-active cellulase (CelX)  
412 identified in *Pseudoalteromonas sp.* DY3 shows very similar optimal temperature and  
413 thermostability (65). However, Cell5.1\_3 is active over a broad pH range, from 5 to 8,  
414 and is stable at pH values from 4 to 10 (it is still active after a 24-hour pre-incubation  
415 in this pH range), which is not the case of the cold-active CelX (65). What's more,  
416 other metagenome-derived GH5 cellulases show stability only at acidic (4-6.6, (59))  
417 or alkaline (6-10, (55)) pH. Another advantage of Cell5.1\_3 is its halotolerance, as it  
418 retains 93% of its activity after a 24-hour pre-incubation in 3 M KCl, and 97% of its  
419 activity after a pre-incubation in 4 M NaCl. These remaining activities are much  
420 higher than those reported for other halotolerant GH5 enzymes. For example, Cel5A,  
421 isolated from a soil metagenome, retains approximately 87% activity after a 20-h pre-  
422 incubation in 3M NaCl or 4M KCl (54), and a GH5 endoglucanase of the  
423 thermophilic eubacterium *Thermoanaerobacter tengcongensis* MB4 retains less than  
424 15% of its activity after a 12-hour pre-incubation in 4 M NaCl (66). As GH5  
425 endoglucanases hydrolyze a wide range of cellulose substrates (64), we have tested  
426 the substrate specificity of Cell5.1\_3. The enzyme appears to degrade CMC and  
427 mixed glucans (lichenan ( $\beta$ 1,3- $\beta$ 1,4) and laminarin ( $\beta$ 1,3- $\beta$ 1,6)), but not  $\beta$ -1,4 linked  
428 xyloglucan. Other metagenome-derived cellulases either fail to degrade laminarin  
429 (53–55, 58) or, like the GH5 enzyme described by Juan et al., show very low specific  
430 activity (approximately 0.002 U/mg) (59). In agreement with its classification as an  
431 endoglucanase, Cell5.1\_3 failed, in our assay, to degrade the insoluble substrates

432 Avicel and mannan. Triton X-100 enhances significantly the activity of Cell5.1\_3.  
433 Zheng et al (67) reported three main hypothesis explaining the enhancement of  
434 enzymatic cellulose hydrolysis in the presence of non-ionic surfactants: 1) they  
435 stabilize the enzyme by reducing thermal and/or mechanical shear forces; 2) they  
436 change the substrate structure, enhancing the substrate accessibility; and 3) they affect  
437 enzyme-substrate interaction, preventing enzymes inactivation due to non-productive  
438 adsorption when hydrolyzing for example lignocellulosic substrates. This last  
439 hypothesis doesn't concern the substrate we used (CMC) and as, generally, no  
440 significant (positive or negative) effect of Triton X-100 has been observed on other  
441 bacterial cellulase activities characterized with CMC (9, 54, 63, 68), the second  
442 hypothesis must not be the reason why Cell5.1\_3 activity increases to 350% in the  
443 presence of Triton X-100. However, Cell5.1\_3 is probably more stable, and therefore  
444 more active on CMC, in the presence of Triton X-100.

#### 445 **Competing interests**

446 The authors declare no competing interests.

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- 667

668 **FIG 1** Neighbor-joining phylogenetic tree of subfamily GH5\_25 and classification of  
669 the cellulase gene *Cell5.1\_3*. Bootstrap values higher than 50% are indicated at  
670 branch points (1,000 replicates). Reference sequences from the GenBank database are  
671 added.

672

673 **FIG 2** SDS-PAGE analysis of the recombinant cellulase. **MW**: Molecular weight, **T**:  
674 Total extract. **I0** and **S0** show the insoluble and soluble fractions obtained by  
675 sonication, followed by centrifugation, of *E. coli* cells overexpressing the cellulase  
676 gene *Cell5.1\_3*. As the GH was mostly present in the insoluble fraction (I0), we  
677 resuspended it for 4 h in a solubilization buffer and centrifuged it, aiming to obtain a  
678 higher, and sufficient, amount of our cellulase in the soluble fraction (S1). This  
679 fraction was then purified twice by chromatography (E1 and E2)

680

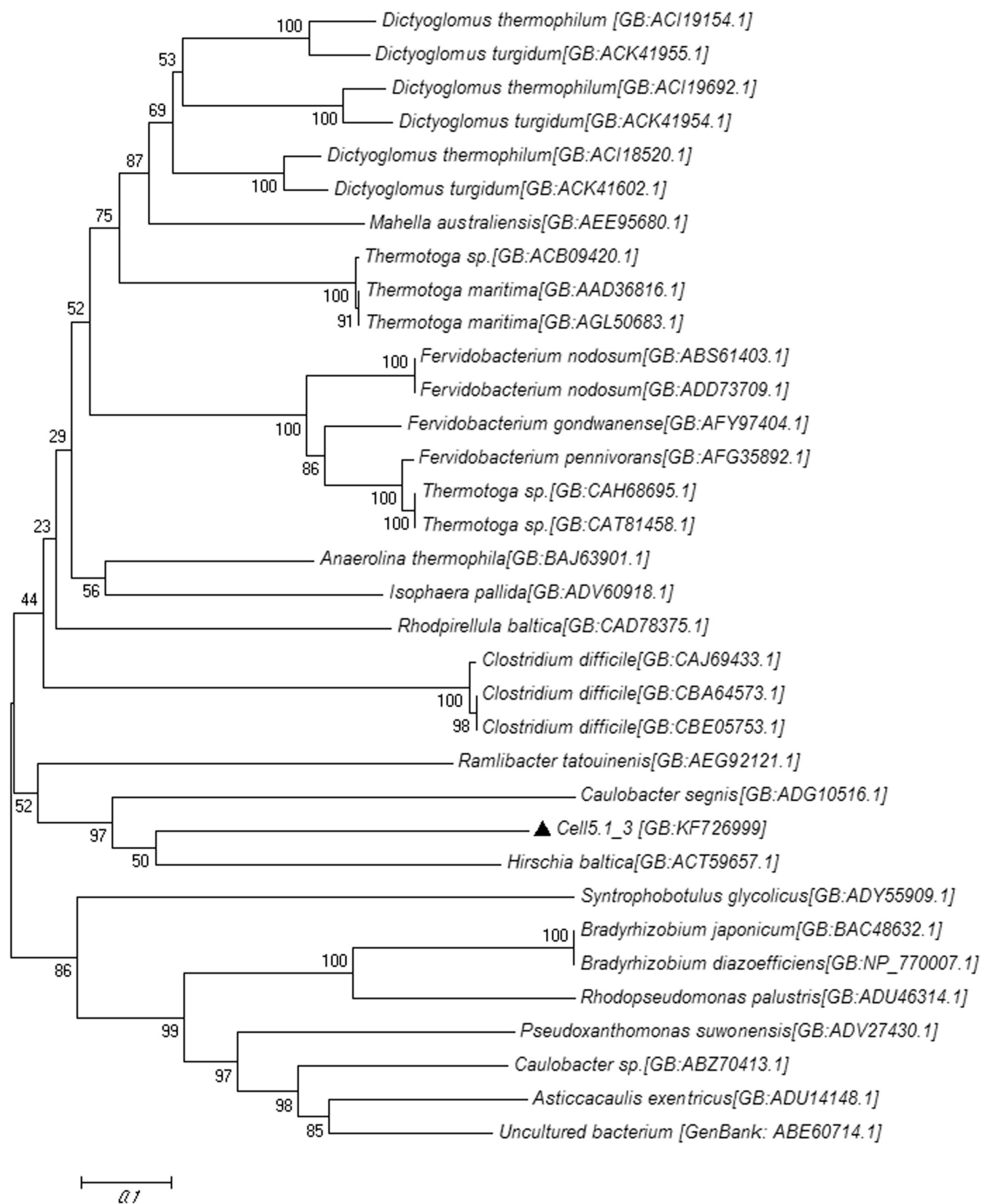
681 **FIG 3** Characterization of the activity of Cell5.1\_3. (A) Influence of temperature on  
682 Cell5.1\_3 activity (●) and thermostability after one hour incubation at indicated  
683 temperature (■) (B) Halotolerance of Cell5.1\_3 (C) Influence of pH on Cell5.1\_3  
684 activity (D) Residual activity of Cell5.1\_3 after a 24-hour incubation at the indicated  
685 pH, (Ac : acetate Buffer, Ph: phosphate buffer, Tris : Tris-HCl buffer, Gly : glycine-  
686 NaOH buffer) (E) Effects of ions and other additives on the activity of the Cell5.1\_3.

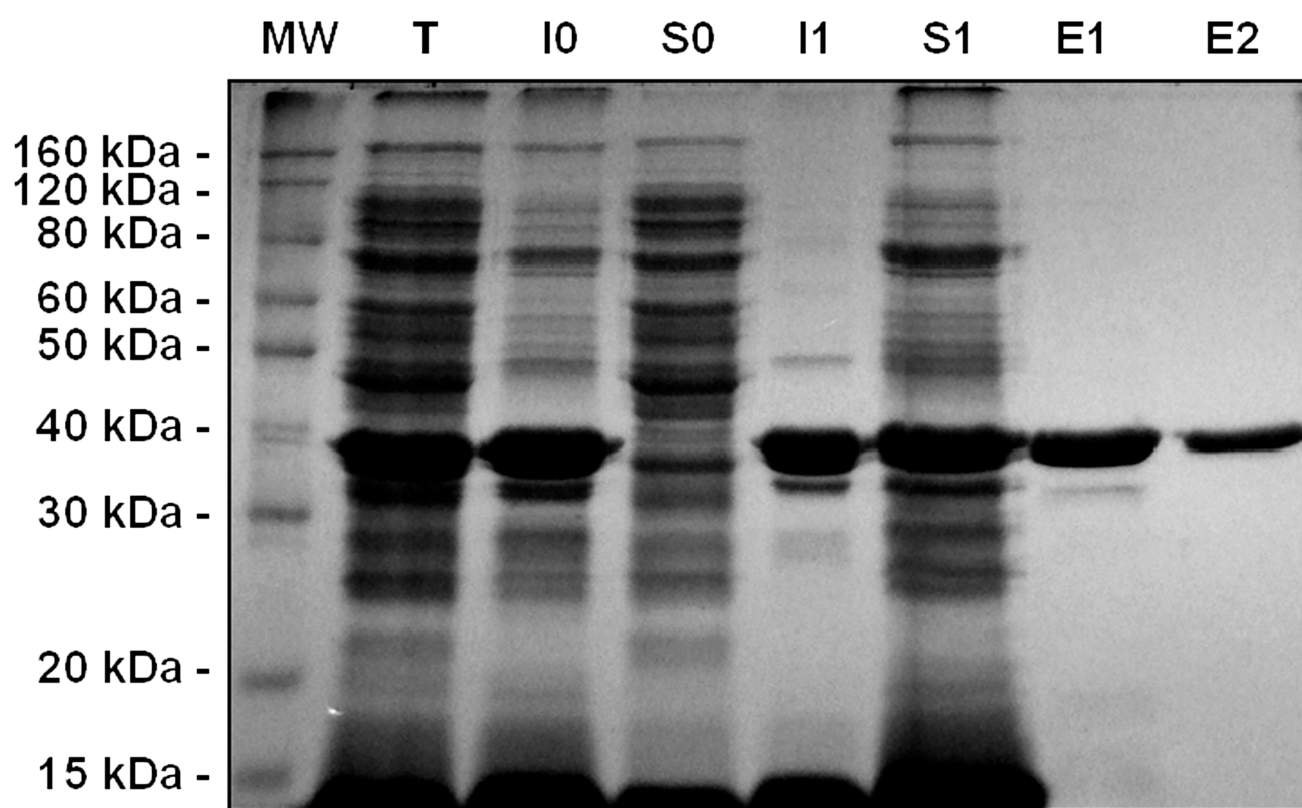
687

688 **TABLE 1** ORFs on the esterase-, cellulase-, and beta-glucosidase-encoding plasmids,  
689 showing sequence identities to known esterases and glycoside hydrolases.

690

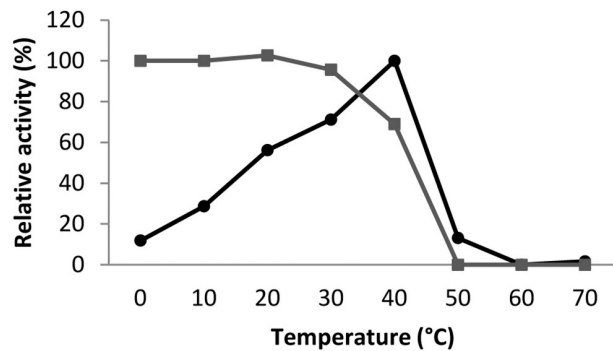
691 **TABLE 2** Substrate specificity of Cell5.1\_3.



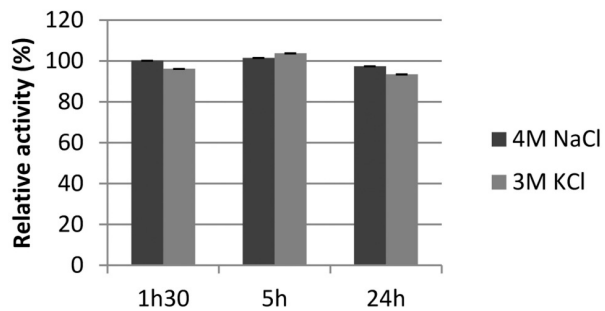




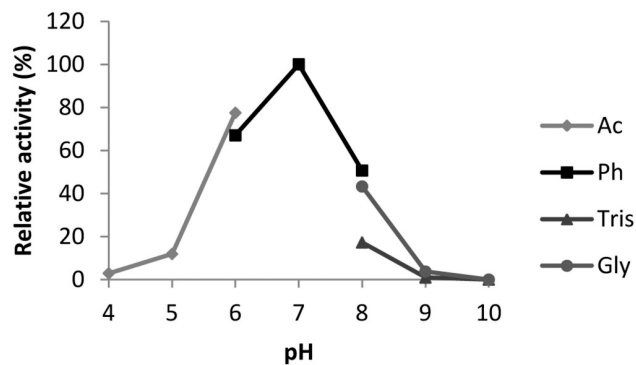
(A)



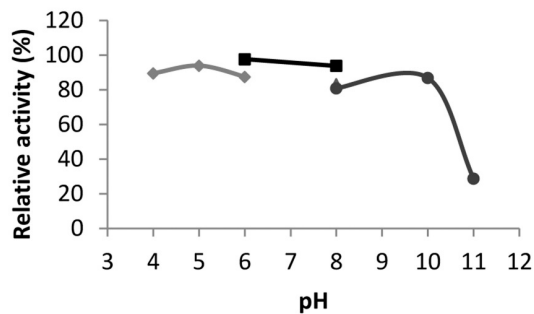
(B)



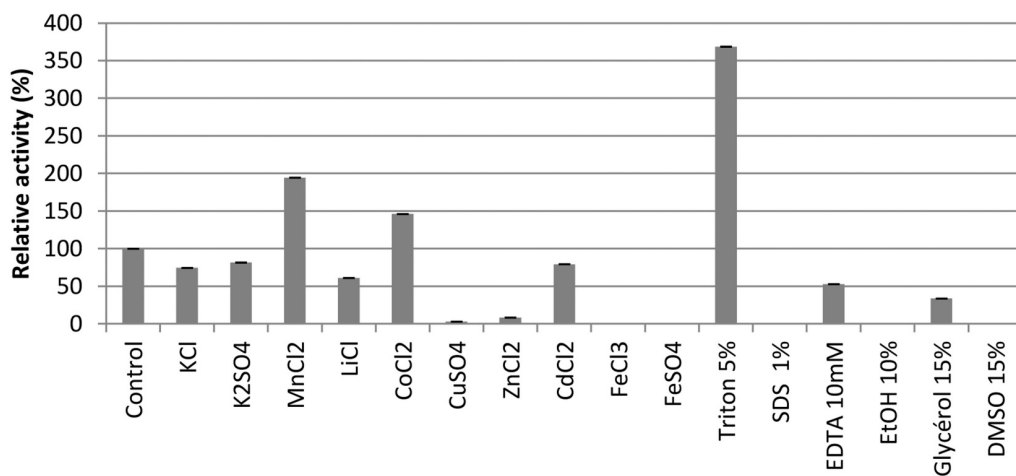
(C)



(D)



(E)



**TABLE 1** ORFs on the esterase-, cellulase-, and beta-glucosidase-encoding plasmids, sequences showing sequence identities to known esterases and glycoside hydrolases.

Activity	Candidate name	Gene name	ORF size (amino acids)	Best hit against GenBank (Source organisms)	Sequence Identity (%)	Family assignment	Accession number	
Carboxyesterase	<i>LipMM5.1</i>	<i>Lip5.1_5</i>	295	Lipase/esterase [uncultured bacterium] ACZ16567	58	Est IV	KF726988	
	<i>LipMM5.3</i>	<i>Lip5.3_3</i>	314	Alpha/beta hydrolase [ <i>Hirschia baltica</i> ATCC 49814] YP_003058522	41	Est IV	KF726989	
	<i>LipMM5.5</i>	<i>Lip5.5_4</i>	328	Alpha/beta hydrolase [ <i>Maricaulis maris</i> ] YP_757536.1	36	Est IV	KF726990	
	<i>LipMM5.7</i>	<i>Lip5.7_2</i>	414	Lysophospholipase [ <i>Burkholderia</i> sp. KJ006] YP_006332790	33	/	KF726991	
	<i>LipMM5.8</i>	<i>Lip5.8_1</i>	237	Hydrolase GDSL [ <i>Ponticaulis koreensis</i> ] WP_006609299.1	46	Est II	KF726992	
		<i>Lip5.8_2</i>	221	ABC Transporter [ <i>Erythrobacter litoralis</i> HTCC2594] YP_458689.1	57	/		
		<i>Lip5.8_3</i>	844	Putative ABC-type transport system involved in lysophospholipase L1 biosynthesis, permease component [ <i>Caulobacter vibrioides</i> ] WP_004617736.1	41	/		
	<i>LipMM5.11</i>	<i>Lip5.11_3</i>	378	Penicillin-binding protein, beta-lactamase class C [ <i>Caulobacter vibrioides</i> ] WP_004621811	51	Est VIII	KF726993	
		<i>Lip5.11_4</i>	153	Thioesterase superfamily protein [ <i>Caulobacter</i> sp. K31] YP_001686513	49	/		
		<i>Lip5.11_5</i>	138	Thioesterase superfamily protein [ <i>Parvibaculum lavamentivorans</i> DS-1] YP_001411720.1	52	/		
	<i>LipMM5.12</i>	<i>Lip5.12_2</i>	288	Esterase [uncultured bacterium] ACF49126.1	38	/	KF726994	
	<i>LipMM5.13</i>	<i>Lip5.13_1</i>	332	Alpha/beta hydrolase [ <i>Pseudomonas pseudoalcaligenes</i> ] WP_004422344.1	34	Est V	KF726995	
		<i>Lip5.13_3</i>	348	Lipase/esterase [uncultured sludge bacterium] ADC79145.1	47	Est IV		
	<i>LipMM5.14</i>	<i>Lip5.14_3</i>	314	Alpha/beta hydrolase [ <i>Hirschia baltica</i> ATCC 49814] WP_017932623.1	41	Est IV	KF726996	
	<i>LipMM5.15</i>	<i>Lip5.15_3</i>	383	Esterase [ <i>Glaciecola nitratreducens</i> FR1064] YP_004870252.1	57	Est VIII	KF726997	
	<i>LipMM5.19</i>	<i>Lip5.19_3</i>	283	Esterase [ <i>Erythrobacter litoralis</i> HTCC2594] YP_458833.1	48	Est IV	KF726998	
	Beta-glucosidase	<i>BglucMM5.1</i>	<i>Bgluc5.1_1</i>	749*	1,4-beta-D-glucan glucohydrolase [ <i>Xanthomonas campestris</i> ] WP_017932269	56	GH3	KJ499810
			<i>Bgluc5.1_2</i>	244	G-D-S-L family lipolytic protein [ <i>Hirschia baltica</i> ATCC 49814] YP_003059731.1	37	Est II	
			<i>Bgluc5.1_4</i>	521*	Xylulokinase [ <i>Novosphingobium</i> sp. PP1Y] YP_004534688	60	/	
Cellulase	<i>CellMM5.1</i>	<i>Cell5.1_3</i>	359	Glycoside hydrolase family protein [ <i>Hirschia baltica</i> ATCC 49814] YP_003060354.1	42	GH5	KF726999	

\* Incomplete ORF

**TABLE 2** Substrate specificity of *Cell5.1\_3*

<b>Substrates</b>	<b>Main linkage type</b>	<b>Specific activity<sup>a</sup> (U/mg)</b>
<u>Soluble substrates</u>		
Carboxymethylcellulose	$\beta$ -1,4-glucan	10.22 $\pm$ 0.002
Lichenan	$\beta$ -1,3/1,4-glucan	12.61 $\pm$ 0.008
Laminarin	$\beta$ -1,3/1,6-glucan	5.08 $\pm$ 0.004
Xyloglucan	$\beta$ -1,4-xyloglucan	UD
<u>Insoluble substrates<sup>b</sup></u>		
Mannan	$\beta$ -1,4-mannan	UD
Avicel	$\beta$ -1,4-glucan	UD

UD, Undetectable

<sup>a</sup> One unit of enzyme activity (U) corresponds to 1  $\mu$ mole of glucose released in 1 min. Measurements were performed in triplicate and standard deviations were calculated.

<sup>b</sup> For these substrates, the reaction time was extended to 5 h at 20°C, with automatic inversion.