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Cloning, characterization, expression and antifungal activity of an alkaline serine protease of *Aureobasidium pullulans* PL5 involved in the biological control of postharvest pathogens.

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23 **Cloning, characterization, expression and antifungal activity of an alkaline serine protease of**
24 ***Aureobasidium pullulans* PL5 involved in the biological control of postharvest pathogens**

25

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36 **Abstract**

37 An alkaline protease gene was amplified from genomic DNA and cDNA of the antagonistic yeast-like
38 fungus *Aureobasidium pullulans* PL5, a biocontrol agent effective against *Monilinia laxa* on stone
39 fruit and *Botrytis cinerea* and *Penicillium expansum* on pome fruits. An open reading frame of 1,248
40 bp encoding a 415-amino acid (aa) protein with a calculated molecular weight (M_r) of 42.9 kDa and
41 an isoelectric point (pI) of 4.5 was characterized. The *cDNAALP5* gene had an 18-amino acid signal
42 peptide, one *N*-glycosylation, one histidine active site, and one serine active site. The *ALP5* gene with
43 a M_r of 1,351 bp contained two introns. One intron was of 54 bp, while the other was of 50 bp. Protein
44 BLAST and phylogenetic tree analysis of the deduced amino sequences from the *cDNAALP5* gene
45 showed that the encoded protein had 100% homology to a protease enzyme (ALP2) of a sea strain of
46 *A. pullulans*, suggesting that the protein ALP5 was an alkaline serine protease. Expression of *ALP5* in
47 *Escherichia coli* BL21 (DE3), followed by identification with Western-blotting, purification with
48 Ni-NTA and analysis of enzymatic activity, yielded an homogeneous recombinant ALP5 which
49 hydrolysed the substrate casein and inhibited the mycelial growth of the pathogens. At its optimal pH
50 of 10.0 and reaction temperature of 50°C, the recombinant protease exhibited the highest activity
51 towards the substrate casein, though the highest stability was at lower temperatures and pH between
52 7.0 and 9.0. This study provided the direct evidence that extracellular proteases secreted by the
53 antagonist *A. pullulans* PL5 played a role in the biocontrol activities against some postharvest
54 pathogens of apple and peach.

55

56 **Keywords:** *Aureobasidium pullulans*, biological control, *Botrytis cinerea*, *Monilinia laxa*, *Penicillium*
57 *expansum*, postharvest.

58

59 **1. Introduction**

60 *Monilinia* spp., *Botrytis cinerea* and *Penicillium expansum* are among the most important
61 postharvest pathogens on fruit and vegetables. Three species of *Monilinia* can cause severe losses on
62 stone fruits, but *M. laxa* is the most dangerous in European countries (Pellegrino et al., 2009); *B.*
63 *cinerea* could cause grey mould on pome and stone fruits, and *P. expansum* can cause blue mould
64 decay, which is one of the most destructive disease of pears and apples and it is accompanied by the
65 production of patulin, a mycotoxin with immunosuppressive effects on humans (Moake et al., 2005;
66 Spadaro et al., 2008).

67 Biological control is an effective alternative to fungicidal treatment in controlling postharvest
68 diseases of fruits (Droby et al., 2009; Spadaro and Gullino, 2004). Knowledge about the modes of
69 action of biocontrol agents (BCAs) is essential for developing appropriate commercial formulations
70 and application methods to maximize the potential use of biological control (Janisiewicz and Korsten,
71 2002). For antagonistic yeasts or yeast-like fungi, the modes of action include nutrient competition
72 and site exclusion (Bencheqroun et al., 2007; Saravanakumar et al., 2008), induction of host resistance
73 (El-Ghaouth et al., 1998; Ippolito et al., 2000) and mycoparasitism (Wisniewski et al., 1991). Recently
74 more attention has been paid to studying the production of lytic enzymes by BCAs due to their roles
75 in breaking down the cell walls of pathogens and inhibiting the spore germinations (Masih and Paul,
76 2002; Smits et al., 2001).

77 The cell wall-degrading enzymes, mostly chitinases, glucanases, and proteases, are major lytic
78 enzymes that are secreted by biocontrol agents (Harman et al., 2004). Those enzymes attach the cell
79 wall of phytopathogenic fungi, causing cell lysis and subsequent death (Castoria et al., 1997; Tseng et
80 al., 2008). Although the mechanism of mycoparasitism is not completely known (Andrews et al.,
81 1994), this process has been assumed to involve the expression of extracellular cell wall-degrading

82 enzymes (Chan and Tian, 2005). So far, extensive research has been done on chitinases and
83 glucanases from microbial antagonists. Many chitinase genes have been cloned and characterized
84 from antagonistic *Trichoderma* spp. (Draborg et al., 1996; Garcia et al., 1994; Limon et al., 1995;
85 Matroudi et al., 2008), yeast (Saravanakumar et al., 2009) and bacteria (Gupta et al., 1995). Also some
86 glucanase genes from fungal (Cohen-Kupiec et al., 1999; El-Katatny, 2008), yeast (Chamberms et al.,
87 1993; Grevesse et al., 2003; Jijakli and Lepoivre, 1998; Zhang et al., 2011) and bacterial (Cheng et al.,
88 2009) biocontrol agents were cloned and biochemically studied. However, information on protease
89 from microorganisms is very limited and moreover, up to date, there are no reports on cloning and
90 characterizing protease genes from biocontrol agents.

91 The yeast-like fungus *Aureobasidium pullulans* De Bary (Arnaud) has been successfully applied to
92 control *B. cinerea*, *P. expansum* and *Rhizopus stolonifer* on apple, sweet cherry, grapes, strawberry
93 and peach (Bencheqroun et al., 2007; Ippolito et al., 2000; Lima et al., 1997; Schena et al., 2003).
94 Modes of action elucidated for *A. pullulans* include nutrient competition (Bencheqroun *et al.*, 2007),
95 induction of host resistance (Ippolito et al., 2000) and production of glucanase, chitinase and protease
96 (Zhang et al., 2010a).

97 Protease refers to a group of enzymes whose catalytic function is to hydrolyse (breakdown) peptide
98 bonds of proteins. Proteases are divided into four major groups according to the character of their
99 catalytic active site and conditions of action: serine proteinases, cysteine (thiol) proteinases, aspartic
100 proteinases, and metalloproteinases (Barrett et al., 2003). Attachment of a protease to a certain group
101 depends on the structure of catalytic site and the amino acid (as one of the constituents) essential for
102 its activity, and hence, proteases differ in their ability to hydrolyse various peptide bonds (Hedstrom
103 2002).

104 Besides their particular role in degrading cell wall of phytopathogenic fungi, proteolytic enzymes
105 occupy the most relevant position among industrial enzymes and are very important in digestion as
106 they breakdown the protein foods to liberate the amino acids needed by the body (Feijoo-Siota and
107 Villa, 2011). Moreover, proteolytic enzymes have been used for a long time in various forms of
108 therapy. Their use in medicine is gaining more and more attention as several clinical studies are
109 indicating their benefits in oncology, inflammatory conditions, blood rheology control, and immune
110 regulation (Hooper 2002; Silva and Malcata, 2005). In addition, the enzymatic hydrolysis of proteins
111 by using proteases is still one of the most important means to produce bioactive peptides (Kristinsson
112 and Rasco, 2000). Therefore, it is very important to seek for new protease-producing microbial
113 sources and to develop some new proteases. So far, the most commonly used proteases are obtained
114 from *Bacillus* sp., lactic bacteria, and marine yeasts (He et al., 2006; Ma et al., 2007; Minervini et al.,
115 2003; Okamoto et al., 1997). However, no report on protease-related genes obtained from terrestrial
116 yeasts was published.

117 The antagonistic yeast-like fungus *A. pullulans* strain PL5 isolated from the carposphere of fruits
118 showed a high efficacy in controlling *M. laxa* on stone fruits and *B. cinerea* as well as *P. expansum* on
119 pome fruits under semi-commercial conditions (Zhang et al., 2010a, 2010b). In our previous study, the
120 strain PL5 exhibited a high capability of producing protease activity which effectively hydrolysed the
121 substrate casein. Therefore, in this paper, the protease gene from *A. pullulans* strain PL5 was cloned,
122 characterized and its antifungal activity and role in the biocontrol were elucidated. This aspect could
123 greatly enhance postharvest biocontrol of fungal pathogens, by improving the selection of antagonists
124 with a protease activity.

125

126 **2. Materials and methods**

127 **2.1 Microorganisms, fruit, vectors and molecular kits**

128 *A. pullulans* strain PL5 was isolated from the carposphere of plum cv. Angeleno, harvested in
129 organic orchards located in Piedmont, Northern Italy, and identified by using molecular tools (Zhang
130 et al., 2010a). The strain PL5 was maintained on nutrient yeast dextrose agar (nutrient broth 8 g/L,
131 yeast extract 5 g/L, glucose 10 g/L and agar 20 g/L; NYDA) slants and grown in liquid medium YPD
132 (20 g/L dextro-glucose, 20 g/L peptone casein, 10 g/L yeast extract) at 25°C for 48 h on a rotary
133 shaker (ASAL, Italy) at 200 rpm. Several strains of *B. cinerea*, *P. expansum* and *M. laxa* were isolated
134 from rotted apples, identified by observing their morphology and by sequencing their ITS and 5.8 rDNA
135 regions, and selected for their virulence by inoculation in artificially wounded apples (*M. laxa*, in
136 peaches) and maintained on Potato Dextrose Agar (PDA; Merck, Darmstadt, Germany) at 4°C (Zhang
137 et al., 2010a). The conidia were harvested after the fungal strains were incubated on PDA in Petri
138 dishes at 25°C for 7 days. The required concentrations of the pathogen conidia were determined by a
139 Bürker chamber (Knittel, Germany).

140 The oligonucleotides and pGEM-T vector in this study were obtained from Promega (Madison, WI,
141 USA). *Escherichia coli* strains including DH5 α and BL21 as hosts for plasmids were purchased from
142 Invitrogen (Eugene, OR, USA). Bacterial cultures were grown according to the manufacturer's
143 instructions and standard methods. The kits for DNA and RNA manipulations were purchased from
144 Qiagen (Hilden, Germany). The kit "Gene Walking Made Easy" and the materials for enzyme assays
145 were purchased from Sigma-Aldrich (Italy).

146

147 **2.2 Pathogen mycelium inhibition by *A. pullulans* PL5 and its crude secreted enzymes**

148 The interactions between the antagonist and the pathogen hyphae were assessed in Petri dishes
149 containing PDA for *B. cinerea* and *P. expansum* or peach juice agar for *M. laxa*. The plates were
150 divided into three sections, 30 mm wide each, along the diameter. Pathogen mycelial plugs (5 mm in
151 diameter) were corked from a 4 day old PDA culture plate and fixed upon one point on the agar
152 surface. After 48h at 25±2°C, 50 µL aliquots of the antagonist cell suspension containing 10⁸ cells/mL
153 were streaked onto PDA and peach juice agar at 30 mm from the pathogen plug (Spadaro et al., 2002).
154 The dual cultures were washed with deionized water for about 2 min after 48h co-culture at 25±2°C.
155 The interactions of the antagonist and pathogen were directly observed under light microscope
156 (Axioskop 40, Germany). The experiments were repeated twice.

157 Purification of hydrolase proteins was carried out according to Tseng et al. (2008). Ammonium
158 sulphate (Merck, Germany) was added to the antagonist *A. pullulans* PL5 culture supernatant and
159 stirred at 4°C for overnight to give up to 75% saturation. Following centrifugation at 18,000 g for 30
160 min at 4°C, the precipitated protein pellets were resuspended in 3 mL deionized water. A 0.1%
161 protease inhibitor cocktail (Sigma, St Louis, MO, USA) was added, and samples were dialyzed
162 (dialysis membrane molecular weight cut off =12,000 kDa) against a 100-fold volume of deionized
163 water at 4°C for 24 h and then stored at -20°C for further studies.

164 To assess the activity of the purified enzyme against the pathogens, *B. cinerea* was selected for its
165 proper time of growth, not as fast as *P. expansum*, and not as slow as *M. laxa*. The pathogen was
166 incubated on PDA in Petri dish at 25°C for 4 days, and then two small wells were made near the
167 pathogen mycelia by removing the medium with a cork. A 100 µL purified enzyme solution was
168 added into one well and 100 µL uncultured medium was added into the other well, serving as a
169 control (CK). After incubation for two days, the inhibition of the pathogen mycelia was investigated.

170

171 **2.3 Determination of protease activity produced by *A. pullulans* PL5**

172 Proteolytic activity produced by *A. pullulans* PL5 was assayed against azocasein as described by
173 Inamura et al. (1985) with small modifications. Briefly, a linear rate of increase was obtained up to an
174 A_{440} of approximately 0.2. One unit of protease activity was reported as an amount which gave an
175 absorbance of 0.001 at 440 nm.

176

177 **2.4 Isolation of DNA and RNA from *A. pullulans* strain PL5**

178 Two ml of YPD culture of the strain PL5, grown at 25°C for 48 h, were centrifuged at 5,000 g for
179 10 min. DNA was extracted from the pellets with the DNeasy® extraction kit and RNA was extracted
180 with the RNeasy® extraction kit according to the manufacturer's instructions (Qiagen, Hilden,
181 Germany). The purification and concentrations were checked by the ratio of 260/280 nm and the
182 absorbance values at 260 nm with the spectrophotometer (Nanodrop 2000, Italy). Purified DNA and
183 RNA were stored in TE buffer (10 mM Tris-HCl; 0.1 mM EDTA; pH 8.0) at -20°C for further studies.

184

185 **2.5 Cloning the protease genes from the genomic DNA of *A. pullulans* strain PL5**

186 Degenerate primers for amplifying the partial sequences of protein genes were designed according
187 to the conserved protein sequences (GHGTHVAGT and TATNTISGTSMA) of alkaline proteases
188 already published (Fig. 1). The forward degenerate primer was designed as
189 5'-GNCANGGNCANCANGTNGCNGGNAC-3' and the reverse primer as
190 5'-CATRCTNGTNCCRCTDATNGTRTTNG-3'. The PCR reaction system (20 µL) was prepared by
191 mixing 1 µL of DNA template (50 ng), 200 mM of each deoxynucleotide triphosphate (dNTPs), 2 µL

192 of 10 X buffer (Taq DNA Polymerase, Qiagen, Hilden, Germany), 0.7 mM each degenerate primer,
193 and 1.0 U Taq DNA Polymerase. The conditions of PCR program were as followings: 95°C, 3 min; 32
194 cycles: 94°C, 15 s; from 55 to 35°C (-0.5°C as gradients), 45 s; 72°C, 30 s; 72°C, 10 min; 4°C. The
195 PCR products were subjected to agarose (2.0%, w/v) gel electrophoresis in TBE buffer stained with
196 SYBR-safe® (Invitrogen, Eugene, OR, USA), followed by excising from the gel and purifying by
197 QIAquick gel extraction kits (Qiagen, Hilden, Germany). The purified fragments were ligated into
198 pGEM-T cloning vector before transformation into chemically competent cells of *E. coli* strain DH5 α .
199 Transformants were grown at 37°C on Luria Broth (LB) agar containing ampicillin (100 μ g/mL),
200 IPTG (50 mM) and X-gal (80 μ g/mL) for blue / white screening of recombinant colonies.
201 Transformed *E. coli* strains were confirmed for the presence of insert using universal primers (M13F
202 and M13R).

203 To amplify and identify 5' and 3' flanking regions of the alkaline protease gene from the genomic
204 DNA of *A. pullulans* strain PL5, special primers and restriction digestion enzymes were designed
205 according to the obtained sequences and the chemical kit "Gene Walking Made Easy" (UVS1, Sigma,
206 St Louis, MO, USA). The specific process was performed according to the supplier's instructions. The
207 fragments from Vectors *Cla* I and *EcoR* I library of *A. pullulans* strain PL5 were purified and
208 ligated to pGEM-T cloning vector, followed by sequencing as described above. The obtained
209 sequences were then subjected to BLAST and ORF Finder program at NCBI to assemble the whole
210 sequence of the targeted gene.

211

212 **2.6 Cloning the protease gene from the cDNA of *A. pullulans* strain PL5**

213 In order to amplify the gene encoding alkaline protease by PCR, the forward primer (Pf) was
214 designed as 5'-ATGTGGAAGAAGAGTGTTC-3', and reverse primer (Pr) as 5'-TAACGACCG

215 CTGTTGTTGTAAAC-3' according to the whole sequence of the protease gene obtained from the
216 genomic DNA. The first cDNA was synthesized using Reverse Transcript kits (Qiagen, Hilden,
217 Germany) according to the manufacturer instructions. The PCR reaction system (50 μ L) was
218 composed by 5.0 μ L 10X buffer, 4.0 μ L (2.5 mM) dNTPs, 1.0 μ L (50 mM) Pf, 1.0 μ L (50 mM) Pr, 1.0
219 U Taq DNA Polymerase, 2.0 μ L (10.0 ng ml⁻¹) cDNA and 36.0 μ L H₂O. The conditions of PCR
220 program were as follows: 94°C, 3 min; 35 cycles: 94°C, 30 s; 58°C, 45 s; 72°C, 90 s; 72°C, 10 min;
221 4°C. To sequence the gene obtained from cDNA, the PCR fragments were ligated into pGEM-T
222 vector and transformed into *E. coli* strain DH5 α , as described above.

223

224 2.7 DNA sequence and computer analysis

225 BLAST and ORF Finder programs at the National Center for Biotechnology Information (NCBI)
226 were used for the nucleotide sequence analysis, deduction of the amino acid sequence and database
227 searchers. Multiple sequence alignments of DNA and amino acid sequence were performed using the
228 programs of DNA-MAN 6.0 and Clustal W (<http://www.ebi.ac.uk/Tools/es/Cgi-bin/clustalw2>). The
229 phylogenetic tree was generated using ClustalX-2.09 and MEGA-4.1 by neighbour-joining method.

230

231 2.8 Construction of plasmids and expression of the ALP5 gene in *E. coli* BL21

232 To further characterize the alkaline protease encoded by the ALP5 gene, the gene was transformed
233 into *E. coli* BL21 (DE3) and induced with IPTG. To amplify the ALP5 fragment without signal
234 peptide or terminator, the primers PF-*EcoR* I 5'-G/AATTCGCTGCTCCCGCCATTGAC -3' (bases
235 underlined encode *EcoR* I restriction site) and PR-*Hind* III
236 5'-A/AGCTTGCGACCGCTGTTGTTGTAAAC-3' (bases underlined encode *Hind* III restriction site)

237 were synthesized. The amplicons without stop codons or signal peptides were ligated into pET-23a(+) 238 with restriction sites of *EcoR* I and *Hind* III to generate the construct of pET-23a(+)-*ALP5*. The 239 expression construct was then inserted into *E. coli* BL21 (DE3). The transformants harbouring the 240 plasmid pET-23a (+) served as controls. The transformants were screened on Luria-Bertani (LB) broth 241 containing 100 µg/mL ampicillin and incubated on a rotary shaker (150 rpm) at 37°C until OD_{600nm} 242 reached 0.4-0.8, followed by induction with IPTG (final concentration 1.0 mM). The bacterial strains 243 were then grown at 37°C for 5-6 h. Diagrammatic representation of the expression of *ALP5* in *E. coli* 244 BL21 is shown in Fig. 2.

245

246 **2.9 SDS-PAGE, western-blotting and purification of the recombinant protease**

247 To characterize the recombinant proteases produced by the transformants of pET-23a(+)-*ALP5*, 248 sodium dodecyl sulphate polyacrylamide gel electrophoresis (SDS-PAGE) was performed as 249 described by Sambrook and Russell (2001). The bacterial strains were grown and induced with IPTG 250 as described above. The recombinant proteases (6×His-tagged fusion proteins) were then purified by 251 affinity chromatography with the kit of Ni-NTA (No. 102, Qiagen GmbH) according to the supplier's 252 instructions. For SDS-PAGE analysis, the concentration of stacking gel was 7% and the concentration 253 of separating gel was 12%. To further confirm the specific protein expressed by the *ALP5* gene, 254 western-blotting with monoclonal anti-polyhistidine as primary antibody and A1293-AlkPhos APA 255 Mouse Fab ads HIgG as secondary antibody was carried out by the methods described by Sambrook 256 and Russell (2001).

257

258 **2.10 Effects of temperature and pH on the activity and stability of the recombinant protease**

259 **ALP5**

260 The effect of temperature on the activity of recombinant alkaline serine protease was determined by
261 incubating the recombinant enzyme between 20-60°C using the standard assay conditions used for the
262 determination of the protease activity. In a similar way, the effect of pH values on the recombinant
263 protease activity was investigated by incubating the recombinant enzyme at different pH values
264 (4.0-12.0). The relative activity at different pH values and temperatures was calculated when the
265 recombinant ALP5 activity obtained at the pH of 10.0 and the temperature of 50°C was used as a
266 reference (relative activity was 100%).

267 The effect of temperature on the stability was examined by pre-incubating the enzyme at different
268 temperatures (0-60°C) for 24 h. The residual activity was measured immediately as described above.
269 The sample pre-incubated at 4°C was used as a reference (relative activity was 100%). The effect of
270 pH value on the stability was tested by 24 h pre-incubation of the recombinant enzyme in 0.05 M
271 potassium phosphate buffer (pH 4.0-12.0). The remaining activities of the recombinant enzyme were
272 measured immediately after this treatment with the standard method as described above. The relative
273 activity was calculated when the recombinant enzyme activity obtained at pH 7.0 pre-incubation was
274 used as a reference (relative activity was 100%). Three replicates for each treatment were prepared.

275

276 **2.11 Antifungal activity of the recombinant protease ALP5 against the postharvest pathogens**

277 The antifungal activity of the recombinant protease ALP5 in controlling the growth of *B. cinerea*, *P.*
278 *expansum* and *M. laxa* was assessed in PDB (Potato Dextrose Broth, Merck) under sterile conditions
279 as described by Lorito et al. (1993), with small modifications. The recombinant proteases were
280 obtained and purified as described before. The protein concentration of the purified enzyme solution

281 was determined according to Bradford (1976) by using bovine serum albumin (A1933, Sigma) as a
282 standard. Aliquots (300 μ L) of each pathogen conidial suspension (1×10^6 conidia/mL) in Ringer
283 solution were transferred to tubes containing 2.4 mL PDB. Then 300 μ L of the purified recombinant
284 enzyme solution (80 μ g/mL) was added to the tubes and reached a final concentration of 8 μ g/mL
285 PDB, serving as enzyme treatment (Pathogen+ Enzyme). Aliquots (300 μ l) of inactivated enzymes, by
286 boiling at 100°C for 10 min, or sterile distilled water instead of the enzyme solution were added to the
287 tubes and served as controls (Pathogen+ Inactivated enzyme, and Pathogen+ Water). After 18 h
288 incubation of the 45° sloping tubes at 25°C on a rotary shaker (200 rpm), 100 conidia per replicate
289 were observed microscopically and their germination rate (%) and germ tube length (μ m) were
290 measured. Three replications of three tubes were prepared for each treatment and the experiment was
291 repeated twice.

292

293 **2.12 Statistical analysis**

294 All the experiments were performed at least twice. Data from all the experiments were analyzed
295 using analysis of variance (ANOVA) and the SPSS version 12.0 (SPSS, 1989-2003). The means were
296 separated at 5% significance level, by using Duncan's Multiple Range Test (DMRT).

297

298 **Results**

299 **3.1 Pathogen mycelium inhibition by *A. pullulans* PL5 and its crude secreted enzymes**

300 After 7 days co-culture in PDA plates at $25 \pm 2^\circ\text{C}$, direct interaction *in vitro* was observed (Fig. 3 a,
301 b, c). *A. pullulans* PL5 significantly inhibited the hyphae elongation of the pathogens. However, no
302 attachment of fungal hyphae was observed.

303 After 2 days co-culture in the presence of purified crude enzymes produced by *A. pullulans* PL5 in
304 PDA plates at 25±2°C, an inhibition of the pathogen mycelia was observed. However, when
305 incubation was without crude enzymes (CK), the mycelium of *A. pullulans* PL5 grew normally (Fig. 3
306 d).

307

308 **3.2 Production of alkaline protease by *A. pullulans* PL5 and its activity**

309 As shown in Fig. 4, *A. pullulans* PL5 produced alkaline protease with high activities when grown in
310 LBMS medium with *M. laxa*, *B. cinerea* or *P. expansum* cell walls as sole carbon sources. When *A.*
311 *pullulans* PL5 was cultured in the LBMS medium, at 0 h incubation, no alkaline protease was
312 detected, while at 24 h incubation, a protease activity was detected. At 72 h, the maximum level of
313 protease activity was observed. At 96 h incubation, the activity began decreasing, after its maximum
314 level. Similar pattern of alkaline protease activity from 0 h to 96 h incubation was observed when *A.*
315 *pullulans* PL5 was grown in minimal salt medium with *M. laxa*, *B. cinerea* or *P. expansum* cell walls
316 as sole carbon sources, and the maximum activities in the three different LBMS medium were 116,
317 121 and 129 U/mg protein, respectively.

318

319 **3.3 Cloning alkaline protease genes from genomic DNA and cDNA of *A. pullulans* PL5**

320 To clone the partial sequences of the gene encoding extracellular alkaline protease in *A. pullulans*
321 PL5, degenerate primers were designed according to the conserved amino acid sequences of alkaline
322 proteases from different species of the yeast (Fig. 1). PCR amplification produced a reliable fragment
323 of about 600 bp (data not shown). Analysis of the sequence by BLAST program suggested that the
324 fragment showed a high identity (87%) to the alkaline serine protease gene *ALP2*, suggesting that the

325 putative alkaline protease gene was isolated. New primers were designed according to the sequence of
326 the obtained fragment (600 bp) of the putative alkaline protease gene in combination with the kit
327 “Gene Walking Made Easy”. The fragments obtained were sequenced, assembled, and analysed with
328 BLAST and ORF Finder programs. Finally, the whole gene of 1,351 bp (GenBank accession number
329 HQ113463) encoding the alkaline protease, named as *ALP5*, was cloned from the genomic DNA of
330 the antagonistic yeast strain PL5 (Fig. 5 and 6).

331 After PCR with the cDNA of the strain PL5 as template and the primers specific to *ALP5* gene, a
332 specific fragment of 1,248 bp was produced (Fig. 5 and 6). The *cDNAALP5* sequence presented 100%
333 identity to the corresponding coding sequence of the genomic DNA. The organization of the gene is
334 illustrated in Fig. 6. Comparison of *ALP5* gene with *cDNAALP5* revealed that there are two introns
335 inside *ALP5* gene. One intron was of 54 bp, while the other was of 50 bp in size. The two introns
336 divided the open reading frame of *cDNAALP5* into three parts. The size, percentage of (G+C) and
337 sequence characteristics of the introns were displayed in Table 1. The flanking sequences of the
338 second intron are consistent with the typical eukaryotic splice sites, including an invariant GT at 5
339 prime and an invariant AG at 3 prime of the introns, while the first intron had GA at its 5 prime and
340 GT at its 3 prime that are non-typical eukaryotic splice sites (Table 1).

341

342 **3.4 Protease ALP5 of *A. pullulans* PL5 and phylogenetic analysis**

343 As seen in Fig. 6, an open reading frame of 1,248 bp encoding a 415-amino acid (aa) protein with a
344 calculated molecular weight (M_r) of 42.9 kDa and an isoelectric point (pI) of 4.5 was characterized.
345 The protease ALP5 had a 18 amino acid signal peptide (positions from 1 to 18), one *N*-glycosylation,
346 one histidine active site, and one serine active site, suggesting that the protease ALP5 was an alkaline
347 serine protease.

348 To reveal the relationship of the protease ALP5 to proteases from other microorganisms, protein
349 BLAST and phylogenetic analysis were performed. As seen in Fig. 7, ALP5 and selected proteases
350 clustered into three groups. Among these proteases, ALP5 is close to proteases from *Aspergillus* spp.
351 and moreover, ALP5 deduced amino acid sequence shared 100% homology to the protease ALP2
352 (Genbank accession number: ABW86845.1) of the sea yeast, *A. pullulans* strain HN2-3, which has
353 been known as an alkaline serine protease, confirming that the protein ALP5 was alkaline serine
354 protease.

355

356 **3.5 SDS-PAGE, western-blotting and purification of the recombinant proteases**

357 As seen in Fig. 8a, SDS-PAGE showed that one specific recombinant protein at the size of about 43
358 kDa was produced from the positive transformants harbouring the gene *ALP5* as compared to controls
359 without containing the gene *ALP5*. The size of the recombinant proteins was the same as calculated
360 from the deduced amino acids of the protease gene *ALP5*. Western-blotting analysis of the proteins
361 from the positive transformants with his-tag monoclonal antibody showed that one specific protein
362 band of the same size obtained by SDS-PAGE was identified (Fig. 8b), indicating that the
363 recombinant protein was fused with His-tag. The recombinant proteases were purified with Ni-NTA
364 affinity chromatography and were subjected to SDS-PAGE analysis. Results showed that one specific
365 band with the molecular weight of about 43 kDa was identified (Fig. 8c), suggesting that the protein
366 was the recombinant ALP5. In addition, the results of Fig. 8a and Fig. 8c revealed that the
367 recombinant protein had an apparent molecular mass of 43 kDa.

368

369 **3.6 Effects of temperature and pH values on the recombinant ALP5 activities**

370 The effect of temperature on the recombinant ALP5 activity was investigated when the enzyme
371 reactions were performed at temperatures from 20°C to 60°C. As seen in Fig. 9a, the highest activity
372 of the recombinant ALP5 was observed when the enzyme reaction was performed at 50°C. During the
373 range of 20-50°C, the activity increased with an increase of the reaction temperature. But when the
374 enzyme reaction temperature exceeded 50°C, the activity started decreasing, indicating that the
375 optimal temperature of the recombinant ALP5 activity was 50°C. Similarly, the optimal pH of the
376 activity was also determined. As seen in Fig. 9b, the highest activity was detected when the reaction
377 system was at pH 10.0. At pH 4.0, the recombinant protein showed the lowest activity as compared to
378 those at other pH values.

379

380 **3.7 Effects of temperature and pH values on the recombinant protease ALP5 stability**

381 The recombinant protease ALP5 showed the highest residual activity when pre-incubated at pH 7.0
382 and 4°C (Fig. 10). Like other enzymes, the recombinant protease ALP5 showed a good stability when
383 pre-incubated at lower temperatures (Temperature \leq 10°C) (Fig. 10a). Moreover, when pre-incubated
384 at 20-50°C, the recombinant ALP5 still showed a high residual activity in hydrolysing the substrate
385 (Fig. 10 a). However, when pre-incubated at 60°C, the residual activity dramatically decreased. These
386 results suggested that the recombinant enzyme had a good thermal stability. As shown in Fig. 10b,
387 when the recombinant ALP5 was pre-incubated at the acid pH values (pH \leq 5.0) or at the extremely
388 strong alkaline pH values (pH \geq 11.0), residual activities were lower as compared to that at pH 7.0-8.0,
389 indicating that the recombinant ALP5 showed a poor stability at acidic or at extremely alkaline
390 conditions.

391

392 **3.8 Antifungal activity of the recombinant protease in controlling the growth of pathogens**

393 By co-culturing in liquid medium (PDB), the activity of the recombinant enzyme APL5 in
394 controlling the conidial germination and germ tube length of *B. cinerea*, *P. expansum* and *M. laxa* was
395 investigated (Table 2). No significant differences in germination percentage were observed on *B.*
396 *cinerea* or *P. expansum* treated by the recombinant protease, however, the germination percentage of
397 the pathogen *M. laxa* was significantly reduced from 98% to 50% in presence of the recombinant
398 ALP5. This result suggested that the responses to the lytic activity of the enzymes are various with
399 different pathogens. Among all treatments by the recombinant protease, the germ tube length of the
400 pathogen conidia was significantly lower as compared with those of controls. In the presence of the
401 recombinant protease ALP5, the germ tube lengths of *B. cinerea*, *P. expansum* and *M. laxa* were 68,
402 80 and 60 μm , respectively, while the germ tube length of their controls were 213, 186 and 125 μm ,
403 respectively. These results indicated that the recombinant protease ALP5 is highly active in reducing
404 the pathogen spore germination and germ tube elongation.

405

406 **4. Discussion**

407 The strain PL5 of *A. pullulans* secreted several enzymes with hydrolytic activity (Zhang et al., 2010a).
408 Protease was among them and of high activity. In the present investigation, the role of the protease
409 enzyme produced by the antagonist *A. pullulans* PL5 in controlling pathogens was studied. Moreover,
410 an alkaline serine protease gene was successfully cloned from the antagonist and expressed in *E. coli*
411 BL21. Understanding the modes of action is essential for developing appropriate commercial
412 formulations and application methods to maximize the potential use of microbial biocontrol agents
413 (Janisiewicz and Korsten, 2002). Production of lytic enzymes, especially glucanase, chitinase and

414 protease, has been proposed as an important mode of action of biocontrol agents against pathogens
415 (Castoria et al., 1997; Chan and Tian, 2005). Bar-Shimon et al., (2004) studied the role of
416 *exo-b-1,3-glucanase (CoEXGI)* in the biocontrol activity of *Candida oleophila* using the gene-knockouts
417 and over-producing transformants, and found that, compared to the wild type of yeasts, the biocontrol
418 activity of CoEXGI-over-producing yeasts was not significantly increased but the activity of
419 *CoEXGI*-knockouts yeasts was significantly decreased, suggesting that the production of *exo-glucanase* is
420 involved in the biocontrol of pathogens. This study demonstrated that the antagonist *A. pullulans* PL5
421 produced the high activities of extracellular proteases which significantly inhibited the mycelial
422 growth of pathogens. In addition, it was also demonstrated that the recombinant protease PL5
423 expressed in *E. coli* BL21 inhibited the pathogen mycelial growth *in vitro*. These results provided the
424 direct evidence that production of protease plays an important role in the activity of *A. pullulans* PL5
425 against pathogens. On the other hand, the elucidation of some gene functions is useful for the
426 registration of BCAs since the more information on BCAS is supplied, the easier their applications are
427 accepted by their consumers. Therefore, cloning and characterization of the protease genes from the
428 antagonistic yeast, *A. pullulans* PL5 is important to the registration and application of the yeast. This
429 discovery could greatly enhance biocontrol of postharvest diseases, by improving the future selection
430 of new antagonists characterized by a protease activity against the fungal pathogens.

431 Microbial proteases are classed into various groups, based on their activity under acidic, neutral,
432 or alkaline conditions and on the characteristics of the active site group of the enzyme. Among them,
433 the alkaline serine proteases, which are active in a neutral to alkaline pH range and have a serine
434 center, are the most important group of enzymes exploited commercially (Gupta et al., 2002).
435 Although proteases from bacteria (Gupta et al., 2002), and fungi (Macchione et al., 2008; Morita et

436 al., 1994) have been extensively investigated and used in different fields, only a few studies were
437 performed on the proteases and the protease-related genes from the yeasts. In this study, the protease
438 gene *ALP5* was cloned and characterized from the strain PL5 of *A. pullulans*, and the protease
439 encoded by the gene *ALP5* belongs to alkaline serine protease family.

440 The protease from the terrestrial yeast, *A. pullulans* PL5 shows an extremely high homology to that
441 from the sea yeast, *A. pullulans* strain HN2-3, suggesting that yeast enzyme genes are relatively
442 conserved among strains of the same species. Although the protease gene is not easy to be expressed
443 in prokaryotes, such as *E. coli*, as compared to eukaryotes, such as *Pichia pastoris* and
444 *Saccharomyces cerevisiae*, we successfully cloned and expressed the protease gene *ALP5* in *E. coli*
445 BL21 (DE3), without the signal peptide, in order to reduce the toxic effects (lytic activity) of the active
446 recombinant proteases on the growth of the bacterial host. The recombinant *ALP5* expressed from *E. coli*
447 showed lower activity than the native protease secreted by *A. pullulans* PL5, which maybe resulted
448 from the fusion of his-tag with the recombinant protease and the renaturation of extracted proteins
449 from conclusions. Previous studies (Moser et al., 1994) revealed that the refolded recombinant
450 protease had a lower level of proteolytic activity compared with that of the native protease and
451 proposed that the decrease in activity was most probably caused by refolding problems related to
452 leader sequences present in the proteases.

453 The activity and stability are the most important attributes of enzymes. In this study, the optimal
454 temperature and pH values of the recombinant protease *ALP5* were determined. In addition, the
455 effects of temperatures and pH values on the stability of the recombinant enzyme were investigated. It
456 was found that the recombinant enzyme performed the highest activity in hydrolysing substrate when
457 the reaction was at 50°C and pH of 10.0. These results observed on the terrestrial yeast, *A. pullulans*

458 strain PL5 were very similar to those on the sea yeast, *A. pullulans* strain HN2.3 (Ni et al., 2009) and
459 on the bacterium *Bacillus* sp. 103 (Joo et al., 2004), suggesting that most of alkaline protease from
460 different microorganisms shared similar optimal temperature and pH values. Actually, the optimum
461 temperature at 40-60°C and the high optimum pH of the enzyme activity is typical characteristics of
462 the most alkaline proteases (Gupta et al., 2002; Mehrotra et al., 1999; Ni et al., 2009).
463 In conclusion, the yeast *A. pullulans* strain PL5 produced high activity of proteases, which played an
464 important role in controlling fungal pathogens, and the protease gene *APL5* of *A. pullulans* strain PL5
465 was cloned and successfully expressed in *E. coli* BL21. ALP5 was identified as an alkaline serine
466 protease, with an important role in the biocontrol of postharvest pathogens of apples and peaches.
467 Future studies involve the use of protease gene-knockouts or gene-over-expressing transformants, to
468 better understand the role of the protease in the biocontrol activity.

469

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476

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624

625 **Tables**

626 **Table 1**

627 Size, percentage (G+C) and sequence characteristics of the introns of *ALP5* gene. The splice sites cleaving
628 the gene was marked with “/” and the flanking nucleotides of the introns were highlighted with a box.

| Intron | Flanking sequences of splice-sites | Size(bp) | G+C(%) |
|--------|--|----------|--------|
| 1 | AGGTgagtcttgggtcaactataatatctagtcatcaaccatactaattacaaacaggtCGCTG | 54 | 46.3% |
| 2 | TGGAgttaagattctttcttcattatgtcagccacatactaacaacgcatagTCCAGT | 50 | 46.0% |

629 **Table 2**

630 Antifungal activity of the recombinant protease ALP5 in controlling the growth of *B. cinerea*, *P. expansum* and *M. laxa* *in vitro*. The pathogen conidia at 1×10^5
 631 conidia/mL were co-cultured with the recombinant protease at 8 $\mu\text{g/mL}$ in PDB containing 100 $\mu\text{g/mL}$ ampicillin, serving as the enzyme treatment (Pathogen+
 632 Enzyme), and inactivated enzymes or sterile distilled water instead of the enzyme solution served as controls (Pathogen+ Inactivated enzyme, and Pathogen+
 633 Water). Three replications of three tubes were prepared for each treatment and the experiment was repeated twice.

| Treatments | <i>B. cinerea</i> | | <i>P. expansum</i> | | <i>M. laxa</i> | |
|-----------------------------|--------------------------|----------------|--------------------------|-----------------|--------------------------|----------------|
| | GTL (μm) ** | GP (%) ** | GTL (μm) ** | GP (%)** | GTL (μm) ** | GP (%) ** |
| Pathogen+enzyme | 68 \pm 9.0 a | 97 \pm 0.6 a | 80 \pm 9.0 a | 97 \pm 0.6 a | 60 \pm 6.6 a | 50 \pm 2.8 a |
| Pathogen+inactivated enzyme | 210 \pm 15.6 b | 99 \pm 2.0 a | 188 \pm 16.5 b | 100 \pm 0.0 a | 118 \pm 12.4 b | 96 \pm 1.0 b |
| Pathogen+water (Control) | 213 \pm 10.0 b | 99 \pm 0.8 a | 186 \pm 18.8 b | 100 \pm 0.0 a | 125 \pm 12.6 b | 98 \pm 0.6 b |

634 ** GTL: Germ tube length; GP: Germination percentage.

635 The results are the mean of two independent experiments. “ \pm ” stands for standard error of the means. Values of each column followed by different letters show
 636 significant difference ($P < 0.05$) according to analysis by Duncan’s Multiple Test (SPSS 13.0).

637 **Figures**

638

639 **Figure 1**

640 Alignment of the deduced amino acid sequence of five alkaline serine protease genes retrieved from NCBI
641 database: *Aureobasidium pullulans* alkaline serine protease (ABW86845.1); *Aureobasidium pullulans*
642 alkaline serine protease ALP2 (ABP82774); *Neosartorya fischeri* NRRL181 alkaline serine protease Alp1
643 (XP_001266852.1); *Aspergillus fumigatus* Af293 alkaline serine protease Alp1 (XP_751651.1);
644 *Aspergillus fumigatus* uncleaved alkaline protease (ALP) (CAA77666.1); Multiple sequence alignment of
645 proteins was performed by using the DNAMAN 6.0. Identical residues are highlighted by black boxes. The
646 potential conserved region (GHGTHVAGT and TATNTISGT SMA) marked with asterisks were used for
647 designing the degenerate primers for amplifying the partial sequence of alkaline serine protease gene from
648 *A. pullulans* strain PL5.

649

650 **Figure 2**

651 Diagrammatic representation of the construction of plasmid (pET23a-ALP5) and expression of ALP5 in *E.*
652 *coli* BL21.

653

654 **Figure 3**

655 Interaction of *A. pullulans* PL5 and three postharvest pathogens *in vitro*, and inhibition of *B. cinerea*
656 growth by purified extracellular crude enzymes produced by *A. pullulans* PL5: a) interaction of *A.*
657 *pullulans* PL5 and *B. cinerea*; b) interaction of *A. pullulans* PL5 and *M. laxa*; c) interaction of *A. pullulans*
658 PL5 and *P. expansum*; d) inhibition of *B. cinerea* hyphal growth by purified extracellular crude enzymes

659 produced by *A. pullulans* PL5.

660

661 **Figure 4**

662 Extracellular protease activities (EC. 3.4.21.63) of *A. pullulans* PL5 grown in LBMS medium
663 supplemented with 2 mg ml⁻¹ CWP (cell wall preparation of each pathogen: *M. laxa*, *B. cinerea*, or *P.*
664 *expansum*) as sole carbon source for 96 h at 25°C. Bars represented standard deviations of the means.

665

666 **Figure 5**

667 Amplification of the protease genes from cDNA and genomic DNA of *A. pullulans* PL5 by PCR. Line M is
668 DNA molecular standards (Cat. No. 239085, Qiagen); Lane1 is the PCR product with cDNA of *A.*
669 *pullulans* PL5 as template; Line2, the PCR product with genomic DNA as template; Line3, Blank control.

670

671 **Figure 6**

672 Nucleotide sequence of the alkaline serine protease *ALP5* gene of *A. pullulans* PL5 and deduced amino acid
673 sequence of the gene product. The start codon is in bold and the signal peptide was highlighted with the
674 inverted arrows. *N*-glycosylation site, histidine active site and serine active site were underlined with the
675 single line, respectively. The stop codon is marked with the asterisk. Two introns were highlighted with
676 lower case letters in grey color, respectively. The gene was designated as *ALP5* and the sequence has been
677 submitted to NCBI (accession number HQ113460).

678

679 **Figure 7**

680 Phylogenetic analysis, based on the deduced amino acid sequences, of *ALP5* and closely related proteases,

681 performed using the program MEGA 4.1. The numbers at node indicate the bootstrap percentages of 1000
682 resamples. The proteases retrieved from NCBI database are: *Aureobasidium pullulans* alkaline serine
683 protease (ABW86845.1); *Neosartorya fischeri* NRRL181 alkaline serine protease Alp1
684 (XP_001266852.1); *Aspergillus fumigatus* Af293 alkaline serine protease Alp1 (XP_751651.1);
685 *Aspergillus fumigatus* serine proteinase (AAB07672.1); *Aspergillus fumigatus* uncleaved alkaline protease
686 (ALP) (CAA77666.1); *Aspergillus clavatus* (ACX47962.1) alkaline protease; *Aspergillus clavatus* NRRL1
687 alkaline serine protease Alp1 (XP_001272038.1); *Trichoderma hamatum* (AAP15044.1) alkaline
688 proteinase; *Aspergillus oryzae* RIB40 hypothetical protein (XP_001820144.1); *Aspergillus oryzae*
689 preproalkaline protease (CAA38527.2); *Hypocrea virens* extracellular serine protease (AAO63588.1);
690 *Aspergillus fumigatus* (CAA75804.1) alkaline protease; *Aspergillus fumigatus* (CAA75806.1) alkaline
691 protease; *Aspergillus versicolor* extracellular alkaline serine protease (ADE74975.1); *Aspergillus* sp.
692 MK285 alkaline protease (AAT85628.1); *Aspergillus viridinutans* alkaline protease (AAT85626.1);
693 *Aspergillus viridinutans* alkaline protease (AAT85627.1); *Verticillium albo-atrum* VaMs.102 alkaline
694 proteinase (XP_003004413.1).

695

696 **Figure 8**

697 a) SDS-PAGE analysis of expression of *ALP5* in *E. coli* BL21 (DE3): line 1 and 2, total protein extracts
698 from IPTG-induced transformants harboring the plasmid pET23a-*ALP5*; line 3, protein extracts from *E.*
699 *coli* cell containing empty vector pET23a; line M, protein molecular weight markers; b) Western-blotting
700 confirmation of recombinant protein with monoclonal anti-polyhistidine as first antibody and
701 A1293-AlkPhos APA Mouse Fab ads HIgG as second antibody: line 4, protein extracts from IPTG
702 -induced transformants harboring the plasmid pET23a-*ALP5*; c) Line 5 and 6, recombinant alkaline

703 protease purified to homogeneity by affinity chromatography.

704

705 **Figure 9**

706 Effects of temperature (a) and pH (b) on the activity of recombinant alkaline protease assay. The activity
707 was measured and determined as described in the section 2. 10. Three replicates of each treatment were
708 prepared. Data are presented as means \pm SD, n=3.

709

710 **Figure 10**

711 Effects of temperature (a) and pH (b) on the activity of recombinant alkaline protease assay. The effect of
712 temperature on the stability was examined by pre-incubating the enzyme at different temperatures (0-60°C)
713 for 24 h. The residual activity was measured and determined as described in the section 2. 10. Three
714 replicates of each treatment were prepared. Data are presented as means \pm SD, n=3.