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**Diversity and bioactivity of fungi associated with the marine sea cucumber *Holothuria poli*: disclosing the strains potential for biomedical applications**

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(Article begins on next page)

1 ***Diversity and bioactivity of fungi associated with the***  
2 ***marine sea cucumber *Holothuria poli*: disclosing the***  
3 ***strains potential for biomedical applications***

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21

22 **Running head:** Bioactive fungi of *Holothuria poli*

23

24 **Abstract**

25 Aims: Identification of the mycobiota associated to the marine echinoderm  
26 *Holothuria poli* and investigation of cytotoxic and pro-osteogenic potential of  
27 isolated strains.

28 Methods and results: Fungal strains were isolated from the animals body-wall,  
29 intestine, and faeces. The species identification was based on DNA barcoding  
30 and morphophysiological observations. Forty-seven species were identified, all  
31 Ascomycota and mainly belonging to *Aspergillus* and *Penicillium* genera.  
32 Sixteen strains were grown on three media for chemical extraction. Cytotoxic  
33 activity was tested on a hepatic cancer cell line (HepG2), the cells viability was  
34 evaluated after treatment using a resazurin based assay (AlamarBlue). Pro-  
35 osteogenic activity was tested on human Mesenchymal Stem Cell,  
36 differentiation was measured as the alkaline phosphatase production through  
37 reaction with *p*-nitrophenylphosphate or as the cells ability to mineralize calcium  
38 using a colorimetric kit (StanBio). Cytotoxic activity was recorded for four fungal  
39 species while five out of 48 extracts highlighted bioactivity toward human  
40 mesenchymal stem cells.

41 Conclusions: The presence of relevant animal-associated mycobiota was  
42 observed in *H. poli* and selected strains showed cytotoxic potential and pro-  
43 osteogenic activity.

44 Significance and importance of this study: Our work represents the first report  
45 of a Mediterranean sea cucumber mycobiota and highlights the isolates  
46 potential to synthesize compounds of pharmaceutical interest for regenerative  
47 medicine.

48

49 **Keywords:** Environmental mycology, Pharmaceuticals, Cytotoxicity, Marine  
50 Fungi, Sea cucumber, Mediterranean Sea

51

## 52 **Introduction**

53 Fungi are important actors of the marine ecosystem, studies on the molecular  
54 diversity of the micro-eukaryotic community shown that they inhabit most of the  
55 marine habitats with disparate ecological roles (Jones and Pang 2012). To  
56 date, 1,412 species have been documented in the marine environment (Jones  
57 et al. 2019) but information on unexplored habitats and DNA sequencing data  
58 collected over the past 20 years identified a possible further 10,000 (Jones  
59 2011). To overcome this lack of knowledge and encrypt the real microbial  
60 biodiversity existing in the sea, the isolation and identification of fungal  
61 communities living in association with new substrates is an essential task.  
62 Several studies investigated the mycobiota existing in the Mediterranean Sea,  
63 mainly focusing on algae, sponges and seagrasses (Garzoli *et al.* 2014; Gnavi  
64 *et al.* 2017; Bovio *et al.* 2019), describing particular marine fungal communities  
65 living in association with marine organisms. The up to date picture shows over  
66 200 fungal species isolated from Mediterranean substrates, with several  
67 recurring taxa such as *Aspergillus*, *Penicillium* and *Acremonium*. Common  
68 species such as *Penicillium chrysogenum*, *Trichoderma harzianum* and  
69 *Cladosporium sphaerospermum* were also identified, but the discovery of key  
70 species and trends in marine fungal populations strongly rely on the description  
71 of fungal communities from additional substrates.

72           Beside their ecological value, the description and isolation in pure culture  
73 of fungal strains from new marine substrates represent a valuable resource for  
74 biotechnological applications for their potentially unusual biochemical  
75 properties. Marine derived fungi had shown potential to synthesize  
76 pharmaceutical compounds such as anticancer, antibacterial, anti-  
77 inflammatory, antiviral, pro-osteogenic and others (Ebel 2012; Prince and  
78 Samuel 2015; Silber *et al.* 2016) as well as compounds with cosmeceutical and  
79 nutraceutical properties (Imhoff 2016). Marine drug discovery surveys had  
80 underestimated the microbial potential in the past, often focusing on bioactive  
81 molecules extracted from macro-organism without considering the substrate  
82 microbial colonization. This approach led to mistakenly assign the biosynthesis  
83 of chemotherapeutic Ecteinascidin to the marine tunicate *Ecteinascidia*  
84 *turbinata* (Rinehart *et al.* 1990) instead of the real producer, its bacterial  
85 endosymbiont (Schofield *et al.* 2015). To address the microbe as the metabolite  
86 producer instead of an animal or plant is very advantageous: once isolated, a  
87 fungus can be grown *in vitro*, allowing further studies with no more expensive  
88 and environmental-impacting sampling campaigns. Moreover, the development  
89 of fermenters for fungal cultivation allows industrial production and extraction  
90 of the metabolite from the biomass (Syed 2019).

91           *Holothuria poli* (Delle Chiaje, 1823) is a Mediterranean and oceanic sea  
92 cucumber, widely distributed in the Mediterranean Sea as well as in the  
93 northern Red Sea and in the Canary Islands Sea (WORMS 2020). It has been  
94 intensively studied for its secondary metabolites production, demonstrating a  
95 strong antifungal activity (Ismail *et al.* 2008), but never deeply analysed for its  
96 associated microbiome. A single study by Omran and Allam (2013) isolated one

97 strain of *Candida albicans* and a few bacteria associated with specimens  
98 collected in Egyptian Mediterranean sea, while a rich mycobiota was recorded  
99 by Pivkin (2000) on internal and external organs of three species of sea  
100 cucumbers sampled in the Pacific Ocean. A thorough study of the mycobiota  
101 associated to *H. poli* is particularly important for the wide distribution of this  
102 echinoderm in the Mediterranean area and for its ecological role as filter feeder.  
103 Given its remarkable production of antifungal compounds, the associated  
104 mycobiota might be specifically selected and contain strains with particular  
105 biochemical properties and potential producers of new pharmaceutically  
106 bioactive compounds.

107         In this study we describe the fungal community living in association with  
108 *H. poli*. The isolates biotechnological potential was investigated as their ability  
109 to synthesize metabolites for pharmaceutical applications. Investigated targets  
110 were the cytotoxicity against an hepatic cancer cell line (HepG2) and the  
111 bioactivity toward stem cell to promote their differentiation into bone or cartilage  
112 cell progenitors (Alves *et al.* 2011; Besio *et al.* 2019a, 2019b).

113

## 114 **Materials and methods**

### 115 ***Holoturia poli* collection**

116 Six individuals of *H. poli*, together with their faeces (rejected sand), were  
117 collected in September 2013 along the rocky coast of the Tabarka peninsula  
118 (Tunisia). Samples were maintained at 0-4°C during transportation. In order to  
119 evaluate the fungal colonization on different animal districts, specimens were  
120 firstly washed in sterile seawater, surface sterilized with 70% ethanol and then

121 underwent surgical manipulation in a sterile condition to separate the body wall  
122 (B), intestine (I) and faeces (S).

123

#### 124 **Isolation and identification of associated fungal strains**

125 Each sample was homogenized using steel beads and MM400 tissue lyzer  
126 (Retsch GmbH, Haan, Germany), then was diluted 1:10 w/v in phosphate  
127 buffer. An aliquot of each sample was dried to calculate the samples' number  
128 of colony forming units *per* gram of dry weight (CFU gdw<sup>-1</sup>). One ml of  
129 suspension was plated on Corn Meal Agar Sea Water (CMASW: 2g corn meal  
130 extract, 15g agar dissolved in 1l of sterilized artificial seawater, 2% w/v Sea  
131 Salts in ddH<sub>2</sub>O) added of an antibiotic mix (Gentamicin 80mg l<sup>-1</sup>, Piperacillin-  
132 Tazobactam 100mg l<sup>-1</sup> - Sigma-Aldrich, Saint Louis, USA). Three replicates *per*  
133 sample were performed (Panno *et al.* 2013; Gnavi *et al.* 2017). A total of 54  
134 plates were incubated at 24°C in the dark up to one month to allow the isolation  
135 of all fungi, including the slow-growing ones. Plates at days 2, 7, 14, and 21.  
136 Strains from each fungal morphotype and from each matrix (B, I, S) were  
137 isolated in axenic culture and preserved at the *Mycotheca Universitatis*  
138 *Taurinensis* (MUT – <http://www.mut.unito.it/en>).

139 Identification of the isolated fungi was carried out with a polyphasic approach,  
140 combining morpho-physiological and molecular methods. Fungi were firstly  
141 morphologically classified on the basis of specific taxonomical keys (Seifert *et*  
142 *al.* 2011; Samson *et al.* 2014a, 2014b). Subsequently, molecular analyses were  
143 performed by sequencing specific genomic regions (for details see Table S1).  
144 Taxonomic assignments were based on similarity to reference sequences

145 available at GenBank (nBlast; mismatch 1/-2; gap costs linear) and CBS  
146 databases. Molecular findings were confirmed morpho-physiologically. Newly  
147 generated sequences were deposited in GenBank database (Table S2)

148

#### 149 **Fungal chemical extraction**

150 Sixteen strains (Tab. 3), encompassing the most representative species  
151 isolated from *H. poli*, were cultivated following a preliminary OSMAC (One  
152 Strain Many Compounds – Bode *et al.*, 2002) approach. Fungi were cultured  
153 on different nutrient conditions to stimulate the production of different  
154 metabolites: each strain was inoculated in duplicate (two 9cm Petri dishes for  
155 each condition), onto three media containing different carbon and nitrogen  
156 sources and/or salinity. Based on pre-trials, media used were: Malt Extract Agar  
157 (MEA: agar 20g, glucose 20g, malt extract 20g, peptone 2g, dissolved in 1l  
158 ddH<sub>2</sub>O), Malt Extract Chloride Agar (MECIA: agar 20g, malt extract 20g, NaCl  
159 17g, dissolved in 1l ddH<sub>2</sub>O) and Soy Mannitol Agar (SMA: agar 20g, soy  
160 peptone 20g, mannitol 20g, NaCl 15g, dissolved in 1l ddH<sub>2</sub>O). Plates were  
161 incubated at 24°C for four weeks to allow fungal growth. After incubation, fungal  
162 biomass and medium were lyophilized and minced using an Ultraturrax device  
163 (IKA, Staufen, Germany), extracted adding 1:10 w/v of solvent mix (1:1  
164 methanol–dichloromethane) and stirred overnight. Suspensions were filtered  
165 and dried using Rotavapor (KNF, Freiburg, Germany). Using this procedure 48  
166 crude dry extracts were obtained.

167

#### 168 **Fungal extracts chemical fingerprinting**



169 Extracts chemical fingerprint was performed by analytical HPLC with a Waters  
170 Alliance 2695 (Waters Corporation, Milford, MA) using Luna C18 column  
171 (250×10mm id, 5µm Phenomenex Inc., Torrance, USA) coupled to a Diode  
172 Array Detector (DAD, Waters 996). The crude extracts were re-suspended at  
173 final concentrations of 10mg ml<sup>-1</sup> in CH<sub>2</sub>Cl<sub>2</sub>/MeOH (1:1, v/v), 20µl were injected  
174 and eluted with a gradient of H<sub>2</sub>O/MeCN/Formic acid (90:10:0.1 to 0:100:0.1 –  
175 flow 1ml min<sup>-1</sup>). Detection was performed by Sedex 55 evaporative light-  
176 scattering detector (SEDERE, Alfortville, France), wavelengths set at 214, 254  
177 and 280nm.

178

#### 179 **Extracts cytotoxicity assessment**

180 To assess the extracts cytotoxicity, a miniaturized high throughput assay was  
181 performed using an automated workstation (PerkinElmer, Waltham, USA). A  
182 liver cancer cell line (HepG2) was treated with seven extracts concentrations  
183 (200pg l<sup>-1</sup>, 2ng ml<sup>-1</sup>, 20ng ml<sup>-1</sup>, 200ng ml<sup>-1</sup>, 2µg ml<sup>-1</sup>, 20µg ml<sup>-1</sup> and 200µg ml<sup>-1</sup>):  
184 dry extracts were dissolved in dimethyl sulfoxide (DMSO, Sigma-Aldrich, Saint  
185 Louis, USA) and diluted in cell culture medium to reach the working  
186 concentrations.

187 Cells were cultured in Basic Medium (BM) containing: αMEM and 1%  
188 penicillin/streptomycin - Thermofisher, Waltham, USA plus 10% FBS – Sigma  
189 Aldrich, Saint Louis, USA. Culture flasks were maintained at 37°C, 5% CO<sub>2</sub> in  
190 humidified atmosphere. The screening was performed by seeding 5x10<sup>3</sup> cells  
191 in in each well of flat-bottom 96-well plates, incubated to settle overnight.  
192 Subsequently, treatment was performed by adding 100µl of BM with either

193 diluted extracts or controls, all conditions tested in triplicate. DMSO was kept at  
194 0.5% in the experimental wells. The positive control cells were treated with  
195 0.5% DMSO and negative controls with 10% DMSO to induce a cytotoxicity.  
196 Cells were then incubated at 37°C, 5% CO<sub>2</sub> for 72 h.

197 Cell viability after treatment was evaluated by measuring the cell reduction of  
198 the vital reagent resazurin (AlamarBlue - Thermofisher, Waltham, USA). A 10%  
199 v/v of reagent was added to the wells and plates incubated for 6 h at 37°C, 5%  
200 CO<sub>2</sub> to let the cells metabolize the reagent. After incubation, fluorescence was  
201 measured at 531nm excitation wavelength, 572nm emission wavelength, and  
202 Lethal Dose 50 (LD<sub>50</sub>) calculated.

203

#### 204 **Extracts pro-osteogenic bioactivity**

#### 205 **High Throughput Assay Procedure**

206 To assess the extracts pro-osteogenic activity a miniaturized high throughput  
207 assay was performed using an automated workstation (PerkinElmer, Waltham,  
208 USA). Human Mesenchymal Stem Cells (hMSCs) were isolated from the bone  
209 marrow of healthy donors at the Galway University Hospital after informed  
210 consent and ethical approval. Cells were cultured in growing medium  
211 containing  $\alpha$ -minimal essential medium ( $\alpha$ -MEM, Life technologies), 10% fetal  
212 bovine serum (FBS, Sigma) and 1% penicillin/streptomycin (P/S, Life  
213 technologies) supplemented with 1ng ml<sup>-1</sup> fibroblast growth factor-2 (FGF-2,  
214 Peprotech). Culture flasks were maintained at 37°C, 5% CO<sub>2</sub> in humidified  
215 atmosphere. Actively proliferating cells were detached from the flasks and  
216 resuspended in Basic Medium for osteogenesis (BM) containing phenol red

217 free Dulbecco's modified eagle medium low glucose (DMEM-LG, Life  
218 Technologies), 10% FBS and 1% P/S. Ten thousand cells were seeded in flat  
219 bottom 96-well plates (Sarstedt) and incubated overnight at 37°C, 5% CO<sub>2</sub>. To  
220 evaluate a promotion of differentiation, cells were treated with fungal extracts  
221 diluted in Osteogenic Medium (OM) containing BM with 100nmol l<sup>-1</sup>  
222 Dexamethasone, 100µmol l<sup>-1</sup> Ascorbic acid 2-Phosphate, 10mmol l<sup>-1</sup> β-  
223 glycerophosphate (Sigma-Aldrich, Saint Louis, USA). Crude extracts were  
224 tested at four non-toxic concentrations (based on the cytotoxicity screening  
225 results), DMSO was kept at 0.5% in experimental wells and controls. Positive  
226 control cells were treated with OM+0.5% DMSO and negative control cells with  
227 BM+0.5% DMSO. Cells medium was appropriately refreshed 72 h after  
228 treatment and early differentiation marker alkaline phosphatase (ALP)  
229 measured seven days after treatment. Cells intracellular ALP level was  
230 measured using an enzymatic assay involving the reaction enzyme-substrate  
231 (*para*-nitrophenilphosphate) as previously described (Bruder *et al.* 1997).

232

### 233 **Osteogenic hits re-screening**

234 Fungal extracts that showed to induce cells ALP expression higher than the set  
235 threshold (Ctr+ average + 3SD) were selected as positive hits and re-tested for  
236 bioactivity. Extracts were tested at 20µg ml<sup>-1</sup> in two media formulations: added  
237 to OM to evaluate promotion of differentiation or in Incomplete Osteogenic  
238 Medium (IOM: OM lacking β-glycerophosphate) to evaluate their ability to  
239 induce differentiation in absence of one essential component for *in-vitro* hMSCs  
240 osteogenic differentiation. Cell seeding and treatment was performed as

241 described before, the ALP level was measured after 7 days differentiation. The  
242 cell calcium mineralization was measured as a late differentiation marker after  
243 12 days treatment. Due to the longer incubation time, two additional medium  
244 changes were performed at days 7 and 10. The calcium mineralized in the  
245 extracellular matrix was solubilized in 1mol l<sup>-1</sup> HCl and quantified as previously  
246 described (Jaiswal *et al.* 1997) with a StanBio Calcium Liquicolour Kit (StanBio  
247 Calcium assay kit - Thermofisher, Waltham, USA).

248

## 249 **Statistical analyses**

250 Statistical analyses were performed using PRIMER 7.0 (Plymouth Routines In  
251 Multivariate Ecological Research; Clarke and Warwick, 2001). The fungal  
252 species biodiversity was evaluated calculating Shannon-Weaver's index (H')

253 and Gini-Simpson's index (1-Lambda). One-way ANOVA and *t*-test on  
254 bioactivity results were performed using GraphPad Prism version 7.0  
255 (GraphPad Software, La Jolla, California, USA). One-way ANOVA and  
256 Bonferroni post-test (significance level of 0.05) was used to compare the data  
257 in the osteogenic assessment and OSMAC effect.

258

## 259 **Results**

### 260 ***Holothuria poli* associated mycobiota**

261 From 18 samples, obtained by three districts of six animals, 498 fungal strains  
262 belonging to 17 taxa were obtained. The retrieved isolates were ascribable to  
263 16 genera, all belonging to the phylum Ascomycota (Table 1). *Aspergillus* and

264 *Penicillium* were the most represented genera (34% of the total species and  
265 65% of the total microbial load, 25.5% of the total species and 25% of the total  
266 microbial load – respectively). Species belonging to *Aspergillus* genus were  
267 mainly members of *A. flavipedes* section (*A. micronesiensis*, *A. poliporycola*  
268 and *A. spelaeus* - 18.7% of the *Aspergillus* species and 9.9% of the total  
269 microbial load), *A. niger* group (*A. awamori*, *A. foetidus*, *A. niger* and *A.*  
270 *tubingensis* - 31.2% of the *Aspergillus* species, 6.6% of the total microbial load)  
271 and *A. versicolor* group (*A. creber*, *A. fructus*, *A. protuberus*, *A. sidowii* and *A.*  
272 *versicolor* - 31.2% of the *Aspergillus* species and 6.4% of the total microbial  
273 load).

274 Other genera recorded with more than one species were *Chaetomium* (3  
275 species), *Acremonium*, and *Trichoderma* (2 species). All the animals were  
276 colonized by fungi and statistical analyses did not show significant differences  
277 amongst animals (p: 0.213, Figure 1).

278 Please insert here Figure 1

279 The fungal species occurrence on different animal specimens highlighted two  
280 most frequent species, *Aspergillus awamori* and *Penicillium steckii*, isolated  
281 from 5 out of 6 animals. Other species detected with high frequency were  
282 *Aspergillus insuetus* (4 animals) *A. fructus*, *A. niger*, *A. tubingensis*, *Penicillium*  
283 *brevicompactum*, *P. citrinum* and *Stachybotrys chartarum* (3 animals).

284 In regard to the three matrices under analyses (body wall, intestine, faeces),  
285 the number of isolated species ranged from 25 associated with the intestine to  
286 22 species isolated from the body wall and faeces. Eighteen of these were  
287 isolated from more than one matrix. In terms of global biodiversity, the Shannon

288 index ( $H'$ ) indicated a similar biodiversity level among the 3 districts. Gini-  
289 Simpson dominance index pointed out comparable and high species  
290 dominance in all the districts (1-Lambda - Table 2).

291 Please insert here Table 2

292 *Aspergillus* was the dominant genus, representing 65% of the total microbial  
293 load detected on the three districts and the only ubiquitous genus with 5 species  
294 (*A. awamori*, *A. fructus*, *A. ochraceus*, *A. tubingensis* and *A. versicolor*)  
295 detected on all districts. These species colonised with a higher rate faeces  
296 (average of  $304.5 \pm 81.9$  CFU  $gdw^{-1}$ ) and intestine content ( $268.7 \pm 95.7$  CFU  
297  $gdw^{-1}$ ), compared to the body wall ( $65.5 \pm 26.8$  CFU  $gdw^{-1}$ ). *Penicillium* was the  
298 other district-related dominant genus (25% of the total microbial load): *P. steckii*  
299 mainly colonised the faeces ( $761.7 \pm 71.8$  CFU  $gdw^{-1}$ ) and intestine ( $267.1 \pm 42$   
300 CFU  $gdw^{-1}$ ), *P. citrinum* colonised the same districts with a higher load in the  
301 faeces ( $118.8 \pm 17.2$  CFU  $gdw^{-1}$ ) compared to the intestine ( $11.9 \pm 2$  CFU  $gdw^{-1}$ ),  
302 and *P. brevicompactum* occurred with a higher load in the faeces ( $578.1 \pm 81.1$   
303 CFU  $gdw^{-1}$ ) than the body wall ( $15 \pm 2.5$  CFU  $gdw^{-1}$ ).

304 Please insert here Table 1

305

### 306 **Fungal extracts chemical analyses**

307 Sixteen fungal strains were grown for chemical extraction following a  
308 preliminary OSMAC approach. Fungi were cultured on two media with sodium  
309 chloride, one nutrient rich (SMA) and one nutrient poor (MECIA) and on one  
310 nutrient rich medium without sodium chloride (MEA). After four weeks at 24°C,  
311 fungal biomass and growing medium metabolites were extracted using both

312 polar and non-polar solvents. Average obtained raw extract dry mass on MEA  
313 was 153mg, 335mg on MECIA and 410mg on SMA.

314 The extracts chemical profiling was performed through HPLC: extracts  
315 belonging to nine strains generated different metabolic profiles on the three  
316 growing media (four examples in Figure 2). Qualitative changes in their  
317 metabolic profiles (i.e. peaks at different retention time in the chromatograms  
318 of the three media) were reported for all *Penicillium* strains analysed (*P.*  
319 *brevicompactum* MUT 1097, *P. chrysogenum* MUT 1115, *P. citrinum* MUT  
320 1071, and *P. citrinum* MUT 1105) as well as *Acremonium implicatum* MUT  
321 1055, *Acrostalagmus luteoalbus* MUT 1070, *Chaetomium globosum* MUT  
322 1013, *Chaetomium* sp. MUT 1035, and *Myrotecium verrucaria* MUT 1069. For  
323 these species, SMA medium chromatogram showed the highest number of  
324 peaks. Variation in the metabolites production based on the culture conditions  
325 was recorded for both different species of the same genus (*Aspergillus insuetus*  
326 and *A. protuberus*) and for different strains of the same fungal species (*P.*  
327 *citrinum*).

328 Please insert here Figure 2

329

### 330 **Fungal extracts cytotoxicity**

331 The fungal extracts' cytotoxicity was evaluated by exposing HepG2 cells to  
332 seven extracts' concentrations (200ng ml<sup>-1</sup> - 200µg ml<sup>-1</sup>) and measuring the  
333 viability after 72 h. The established threshold to consider an extract cytotoxic  
334 was set at 15% of induced cell death: results showed no extracts' cytotoxicity  
335 between 200pg ml<sup>-1</sup> and 20ng ml<sup>-1</sup>; two extracts were cytotoxic at 200ng ml<sup>-1</sup>;

336 thee extracts (0.6%) were cytotoxic at 2µg ml<sup>-1</sup>; 17 (34.4%) at 20µg ml<sup>-1</sup> and 46  
337 extracts (95.6%) were cytotoxic at 200µg ml<sup>-1</sup>. The LD<sub>50</sub> recorded (Table 3)  
338 ranged from 27.7 to 474.3µg ml<sup>-1</sup>: 46% of the extracts in the range of 0-100µg  
339 ml<sup>-1</sup>, 27% in the range 100-200µg ml<sup>-1</sup>, 19% in the range 200-300µg ml<sup>-1</sup>, 2% in  
340 the range 300-400µg ml<sup>-1</sup> and 6% in the range 400-500µg ml<sup>-1</sup>. The most  
341 cytotoxic extracts were produced by four species of which two belonged to  
342 *Chaetomium*, one *Acrostalagmus* and one *Myrotecium* genera (Figure 3).

343 The influence of growing medium on fungal synthesis of cytotoxic compounds  
344 (OSMAC effect) was also evaluated. Cell death induced by three extracts  
345 belonging to each single species were compared using one-way ANOVA  
346 statistical test. All 16 strains demonstrated statistically different cytotoxicity of  
347 extracts obtained from the three culture media, for at least one extract  
348 concentration tested (Figure S1).

349 Please insert here Figure 3

350 Please insert here Table 3

351

### 352 **Fungal extracts osteogenesis**

353 In order to evaluate the potential of fungal extracts to promote hMSCs  
354 osteogenic differentiation, the 48 extracts were tested using an automated HTS  
355 platform. Extracts diluted in DMSO were tested at the four highest nontoxic  
356 concentrations defined by the preliminary cytotoxic investigation (less than 15%  
357 cell death induced). Possible promoters of osteogenesis were detected from  
358 this screening selecting values above a threshold: ALP expression higher than  
359 positive control average + three times the standard deviation (Figure S2).



360 Using this method, 9 extracts were selected as osteogenic promoters and re-  
361 screened (MUT 1115-SMA; MUT 1071-SMA; MUT 1097-MEA; MUT 1086-  
362 SMA; MUT 1074-SMA; MUT 1091-SMA; MUT 1054-MEA; MUT 1069-MEA;  
363 MUT 1035-MECIA). These extracts were manually tested using the same  
364 procedure and miniaturized assays for ALP and calcium detection. Extracts  
365 were added to IOM to evaluate bioactivity as osteogenic inducers, in absence  
366 of  $\beta$ -glycerophosphate in the differentiation medium or added to OM to evaluate  
367 improvement of marker expression in presence of all the osteogenic  
368 differentiation factors. A significant increase in ALP expression after treatment  
369 was detected for four extracts when tested in IOM (Figure 4.A), showing to be  
370 able to induce differentiation in absence of  $\beta$ -glycerophosphate in the culture  
371 medium. When tested in OM (Figure 4.B), two of these extracts showed to  
372 promote a significant increase of ALP compared to the positive control cells  
373 treated with OM. In terms of calcium mineralization, no extract was able to  
374 induce differentiation when tested in IOM (Figure 4.C) while two extracts  
375 showed to improve the cell differentiation by increasing the quantity of  
376 mineralized calcium when tested in OM (Figure 4.D). Overall, extracts 1115-  
377 SMA and 1071-SMA belonging to *Penicillium chrysogenum* and *P. citrinum*,  
378 respectively, showed to improve the osteogenic marker expression ALP and  
379 calcium mineralization by hMSCs after treatment.

380 Please insert here Figure 4

## 381 **Discussion**

382 Our study demonstrates that the Mediterranean marine echinoderm *Holothuria*  
383 *poli* is widely colonized by fungi in its internal and external body sectors.

384 Isolated fungal strains all belonged to the phylum Ascomycota, confirming it as  
385 dominant in the marine environment (Jones *et al.* 2019). Our data show a  
386 significantly higher fungal diversity (47 species) compared to that reported from  
387 previously investigation on the same animal (Omran and Allam 2013) as well  
388 as to that reported from other species of sea cucumbers (Pivkin 2000). Omran  
389 and Allam (2013) reported only a single isolate, *Candida albicans*, associated  
390 with *H. poli* from the Egyptian Mediterranean Sea, a species not detected in our  
391 study. Pivkin (2000) studied sea cucumbers from the Pacific Ocean, reporting  
392 25 fungal species from *Eupentacta fraudatrix*, nine from *Apostichopus*  
393 *japonicus* and three from *Cucumaria japonica*. The higher diversity that we  
394 reported can probably be related to the isolation techniques adopted compared  
395 to the previous studies: Pivkin (2000) used agar with holothurian broth, with  
396 NaOH added; Omran and Allam (2013) used Sabouraud and blood agar media  
397 without the addition of salt. Our isolation strategy implemented the use of CMA,  
398 a nutrient rich medium previously reported as optimal for marine fungi isolation  
399 (Kossuga *et al.* 2011), added of sea salt to mimic the environmental conditions.  
400 In terms of species recurrence, Mediterranean *H.poli* showed four fungal  
401 species in common to the Pacific sea cucumber isolated by Pivkin (2000):  
402 *Alternaria alternata*, *A. versicolor*, *C. sphaerospermum* and *Penicillium*  
403 *commune*. In comparison with the mycobiota isolated from other Mediterranean  
404 substrates *H. poli* showed more similarities (Fig. 5): ten species in common with  
405 the brown algae *Padina pavonica* (Garzoli *et al.* 2018), nine in common with  
406 the green algae *Flabellia petiolata* (Gnavi *et al.* 2017), nine with the seagrass  
407 *Posidonia oceanica* (Panno *et al.* 2013), eight with the sponge *Psammocinia*  
408 sp. (Paz *et al.* 2010) and five with decaying woods (Garzoli *et al.* 2015). Most

409 common isolated fungal species from Mediterranean marine substrates are *T.*  
410 *harzianum* and *P. brevicompactum*, respectively isolated in the past from  
411 Oceanic sponges and ascidians (Yamada *et al.* 2014; Vacondio *et al.* 2015)  
412 and from Oceanic algae and sponges (Alves 2019; Bovio *et al.* 2019). Such  
413 common species are likely to be highly adapted to the marine environment  
414 showing a high potential in substrate colonization, therefore their specific role  
415 in association with animals, plants and algae should be thoroughly investigated  
416 to identify possible key marine species.

417 Please insert here Figure 5

418 Eleven species isolated in this study represent new records for the marine  
419 environment worldwide: *A. creber*, *A. foetidus*, *A. fructus*, *A. micronesiensis*, *A.*  
420 *spelaeus*, *Auxarthron ostraviense*, *Chaetomium subaffine*, *Emericella*  
421 *quadrilineata*, *Myriodontium. keratinophilum*, *P. adametzii*, and *Trichoderma*  
422 *epimyces*. Several of them have been previously described as soil inhabitants  
423 (Pitt 1979; Doveri *et al.* 2013; López-Quintero *et al.* 2013; Nováková *et al.* 2014)  
424 or present in house dust (Samson *et al.* 2014a). *Auxarthron ostraviense*, *M.*  
425 *keratinophilum* and *E. quadrilineata* are usually reported from soils and are  
426 described as weak human pathogens (Maran *et al.* 1985; Gugnani *et al.* 2007;  
427 Hubka *et al.* 2013). Further records on new substrates are needed to elucidate  
428 their presence in the marine environment.

429 The isolated fungal community was characterized by the dominance of  
430 *Penicillium* and *Aspergillus* genera, as previously detected on other  
431 Mediterranean substrates (Paz *et al.* 2010; Panno *et al.* 2013). Species  
432 belonging to these genera are highly sporulating and able to adapt to extremely

433 disparate environmental conditions such as Antarctica, Atacama desert or deep  
434 seas (Godinho *et al.* 2015; Nagano *et al.* 2017; Santiago *et al.* 2018), and  
435 therefore are likely to survive in shallow waters and colonize sessile  
436 echinoderms. The presence of recurrent species such as *A. awamori* and *P.*  
437 *steckii* suggests a higher adaptation of these taxa to live associated to an  
438 animal producing antifungal molecules and a possible selection of the  
439 mycobiota operated by the animal.

440 Our study confirms the pharmaceutical bioactivity of small molecule extracts  
441 obtained by fungal strains associated to *H. poli*. Cytotoxicity assessment  
442 against hepatocarcinoma cells (HepG2) showed the ability of several strains to  
443 produce highly cytotoxic metabolites, a concentration-related bioactivity and the  
444 medium influence in the biosynthesis of these compounds. Producers of the  
445 most cytotoxic extracts were members of the *Chaetomium* genus, previously  
446 reported to synthesize several azaphilones, molecules produced by  
447 *Chaetomium globosum* with selective cytotoxicity against leukemia HL60,  
448 leukemia L1210 and KB epidermoid carcinoma cell lines (Yamada *et al.* 2012).  
449 The marine fungi ability to synthesize human cells' cytotoxic compounds clearly  
450 show their potential for the treatment of cancer-based diseases. Future  
451 analyses on cytotoxic extracts will involve the investigation of bioactivity  
452 retention against other cancer cell lines and the extracts' chemical investigation  
453 to purify the molecules responsible of this bioactivity.

454 Regarding the fungal extracts' bioactivity toward human Mesenchymal Stem  
455 Cells, our initial high throughput screening showed nine extracts able to induce  
456 differentiation of hMSCs into bone cell progenitors. The positive hits validation  
457 was performed by re-testing the extracts and evaluating their specific bioactivity

458 as inducers or promoters of osteogenic differentiation. This was done by testing  
459 the extracts diluted in complete osteogenic medium containing the full cocktail  
460 of pro-osteogenic molecules for *in-vitro* differentiation or in incomplete  
461 osteogenic medium lacking  $\beta$ -glycerophosphate. Cells differentiation after  
462 treatment was evaluated by measuring two osteogenic markers: intracellular  
463 alkaline phosphatase production and cells calcium mineralization. Extracts  
464 obtained by *P. chrysogenum* (MUT 1115) and *P. citrinum* (MUT 1071) induced  
465 and promoted osteogenic differentiation as showed by increased level of  
466 intracellular ALP and increased amount of calcium mineralized in the  
467 extracellular matrix, process leading to bone formation, demonstrating great  
468 potential for the discovery of new drug candidates for regenerative medicine.  
469 While this is the first record for *P. chrysogenum* producing compounds with pro-  
470 osteogenic bioactivity, *P. citrinum* was previously reported to synthesize  
471 mevastatin (Endo *et al.* 1976), a molecule belonging to a class of metabolites,  
472 statins, known for their bioactivity as cholesterol-lowering and documented to  
473 stimulate the formation of new bone tissue (Mundy *et al.* 1999; Morse *et al.*  
474 2018).

475 The culture conditions' influence on fungal metabolite production (OSMAC  
476 effect) was demonstrated both with chemical profiling and detected extracts  
477 bioactivity. The variable cytotoxic bioactivity of extracts belonging to the same  
478 strain growing on different media was confirmed by the extracts chemical  
479 analyses that showed chromatograms variability. Most effective medium for the  
480 biosynthesis of bioactive compounds was SMA, responsible for the production  
481 of the most cytotoxic extracts in terms of number and induction of cell death,  
482 and the main medium where osteogenic metabolites were synthesized. Once

483 again is demonstrated that the discovery of new fungal secondary metabolites  
484 for biotechnological applications is strictly linked to the modification of culture  
485 conditions to trigger different metabolic pathways and induce the production of  
486 the widest fungal metabolome.

487 In this study we prove as demonstrated before (Lagarde *et al.* 2018) the fungal  
488 intraspecific variation in the production of bioactive compounds: different strains  
489 of *P. citrinum* isolated in this study showed different chromatographic profiles  
490 and different detected bioactivity as cytotoxicity and pro-osteogenic  
491 compounds. This evidence highlights the importance of strains evaluation for  
492 the discovery of new compounds for specific pharmaceutical applications in  
493 order to widen the chances to discover strains with pharmaceutical potential.

494 To the best of our knowledge, this is the first record on marine fungal extracts  
495 inducing hMSCs osteogenic differentiation in comparison to the established  
496 inducer,  $\beta$ -glycerophosphate, and potential producers of new molecules for  
497 regenerative medicine. Positive extracts will therefore be further analysed to  
498 identify the responsible molecules associated with the detected bioactivity and  
499 describe potential drug candidates. Further evidences of cytotoxic selectivity  
500 and hMSC osteogenic induction by the metabolites produced by our strains are  
501 needed to evaluate progression towards their use in targeted cell therapies,  
502 particularly in diseases such as cancer (Cragg *et al.* 2009), osteoporosis and  
503 osteogenesis imperfecta (Grunevald *et al.* 2014; Besio and Forlino 2015,  
504 Gagliardi *et al.* 2017). Furthermore, the optimized High Throughput assays  
505 developed in the present study allowed us to test our extracts library in a time  
506 and cost effective way and are a valuable tool to foster studies of cell-related  
507 bioactivity from wide natural compounds libraries.

508 To conclude, a peculiar fungal community with an interesting metabolic  
509 potential was recorded on *Holothuria poli*, increasing the knowledge about  
510 animal fungal association in the Mediterranean Sea, a marine biodiversity  
511 hotspot whose microbial community is substantially underestimated. The  
512 importance of culture based fungal community investigation in biodiscovery  
513 research was once again underlined: the development of future studies to  
514 unlock fungal biotechnological potential is strictly connected to the conservation  
515 of pure strains in culture.

516

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525

#### 526 **Conflict of Interest:**

527 The authors have no conflict of interest to declare

528

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706 2020-01-16

707

Table 1: Marine fungal species recovered from *Holothuria polii* in the Tunisian Sea

Taxa	MUT code	Animal*						Matrix*		
		1	2	3	4	5	6	B	I	S
<i>Acremonium alternatum</i> Link 1809	1054						17.02		17.0	
<i>Acremonium implicatum</i> (J.C. Gilman & E.V. Abbott) W. Gams 1975	1055				12.82			12.8		
<i>Acrostalagmus luteoalbus</i> Pethybr. 1919	1070 2130		14.95	21.22				14.9	21.2	
<i>Alternaria alternata</i> (Fr.) Keissl. 1912	856			63.66					63.6	
<i>Aspergillus awamori</i> Nakaz. 1907	2012 2060 2099 2191	86.29	384.6	487.8		163.4	17.02	86.2	483.	569.0
<i>Aspergillus creber</i> Jurjevic, S.W. Peterson & B.W. Horn 2012	1999 2026		53.41					14.9		38.46
<i>Aspergillus foetidus</i> Thom & Raper 1945	2035					100.5				100.5
<i>Aspergillus fructus</i> Jurjevic, S.W. Peterson & B.W. Horn 2012	2175 2187 2200 2203	44.86	130.34	466.8				32.2	466.	142.9
<i>Aspergillus insuetus</i> (Bainier) Thom & Church 1929	1085 2054 2092	15.47	29.91	21.22		24.74		42.1	49.1	
<i>Aspergillus micronesiensis</i> Visagie, Hirooka & Samson 2014	1990 1992	34.51	59.82					94.3		
<i>Aspergillus nidulans</i> (Eidam) G. Winter 1884	2165			21.22					21.2	
<i>Aspergillus niger</i> Tiegh. 1867	2082		1692.3	41.99			87.24			1821.
<i>Aspergillus ochraceus</i> G. Wilh. 1877	2036 2086 2096 2105		680.06	122.7				161.	295.	346.1
<i>Aspergillus polyporicola</i> Hubka, A. Nováková, M. Kolarík & S.W. Peterson 2015	1456					528.1				528.1
<i>Aspergillus protuberus</i> Munt.-Cvetk. 1968	1091					24.97			24.9	
<i>Aspergillus pseudodeflectus</i> Samson & Mouch. 1975	2040		38.46							38.46
<i>Aspergillus</i> sp.	2106			21.22		12.48			33.7	
<i>Aspergillus spelaeus</i> A. Nováková, Hubka, M. Kolarík & S.W. Peterson 2015	1457 1993					352.0	17.02		17.0	352.0
<i>Aspergillus sydowii</i> (Bainier & Sartory) Thom & Church 1926	2072 2102		14.95			12.48		14.9	12.4	
<i>Aspergillus tubingensis</i> Mosseray 1934	1074 2043 2047	41.41	76.92					33.0	34.0	118.3
<i>Aspergillus versicolor</i> (Vuill.) Tirab. 1908	1086 2052 2190		361.11	63.66				14.9	63.6	346.1



<i>Aureobasidium pullulans</i> (de Bary & Löwenthal) G. Arnaud 1918	2186					12.48			12.48	
<i>Auxarthron ostraviense</i> Hubka, Dobiášová & M. Kolařík 2012	1556		14.95						14.95	
<i>Cadophora luteo-olivacea</i> (J.F.H. Beyma) T.C. Harr. & McNew 2003	1073				31.49					31.49
<i>Chaetomium globosum</i> Kunze 1817	1013		14.95						14.95	
<i>Chaetomium</i> sp.	1035				21.22					21.22
<i>Chaetomium subaffine</i> Sergeeva 1961	1015				21.22			17.02		38.24
<i>Cladosporium sphaerospermum</i> Penz. 1882	1454	27.60								27.60
<i>Emericella quadrilineata</i> (Thom & Raper) C.R. Benj. 1955	2019 2025		271.28		21.22				44.87	247.63
<i>Myrothecium verrucaria</i> (Alb. & Schwein.) Ditmar 1813	1069		14.95						14.95	
<i>Myriodontium keratinophilum</i> Samson & Polon. 1978	1443				12.82		12.48		12.82	12.48
<i>Paecilomyces lilacinus</i> (Thom) Samson 1974	992		29.91						29.91	
<i>Penicillium adametzii</i> K.M. Zaleski 1927	2107		38.46							38.46
<i>Penicillium antarcticum</i> A.D. Hocking & C.F. McRae 1999	2125 2170	41.41						17.02		17.02
<i>Penicillium brevicompactum</i> Dierckx 1901	1097 2061 2097 2140		514.95		27.83	50.29			14.95	578.13
<i>Penicillium chrysogenum</i> Thom 1910	1115		29.91						29.91	
<i>Penicillium citreonigrum</i> Dierckx 1901	2062		269.23							269.23
<i>Penicillium citrinum</i> Thom 1910	1071 1105	13.80	11.91		104.99				11.91	118.79
<i>Penicillium commune</i> Thom 1910	2120		15.47						15.47	
<i>Penicillium corylophilum</i> Dierckx 1901	2173		69.01							69.01
<i>Penicillium oxalicum</i> Currie & Thom 1915	2094 2149		44.87		42.44				44.87	42.44
<i>Penicillium roseopurpureum</i> Dierckx 1901	2146		86.29						86.29	
<i>Penicillium steckii</i> K.M. Zaleski 1927	1453 2109		423.07		317.65	13.91	12.48	261.73	267.14	761.72
<i>Pleosporales</i> sp.	2081		38.46							38.46
<i>Stachybotrys chartarum</i> (Ehrenb.) S. Hughes 1958	1554 1555	13.80	38.46		12.82				12.82	52.26
<i>Trichoderma epimyces</i> Jaklitsch 2008	2022					12.48				12.48
<i>Trichoderma harzianum</i> Rifai 1969	2009		192.3							192.3
<b>Mean animal fungal load (CFU/gdw)</b>		40.83	203.1	111.3	16.05	101.5	62.65		38.34	92.12
<b>Number of detected species</b>		12	27	17	5	13	8		22	25

\*species detected in each animal (1 to 6) and matrix (B= Body wall; I= Intestine; S= Faeces)

Table 2: Biodiversity within districts:  
Shannon-Weaver's index (H') and Gini-  
Simpson's index (1-Lambda)

Matrix	N° Species	H'	1-Lambda
<b>B</b>	22	3.007	0.954
<b>I</b>	25	3.071	0.946
<b>S</b>	22	3.013	0.944

B=Body wall; I=Intestine; S=Faeces

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Table 3 Cytotoxicity of crude extracts on human hepatocarcinoma cell line (HepG2)

Species	MUT code	Growing medium		
		SMA	MECIA	MEA
<i>Acremonium alternatum</i>	1054	>200	>100	>200
<i>Acremonium implicatum</i>	1055	>200	>200	>200
<i>Aspergillus insuetus</i>	1085	>200	>100	62.1
<i>Aspergillus protuberus</i>	1091	93.6	>100	71.3
<i>Aspergillus tubingensis</i>	1074	>100	>100	>100
<i>Aspergillus versicolor</i>	1086	82.7	>400	70.4
<i>Cadophora luteo-olivacea</i>	1073	>100	>300	>400
<i>Chaetomium globosum</i>	1013	37.4	60.0	56.3
<i>Chaetomium</i> sp.	1035	49.7	>100	49.4
<i>Chaetomium subaffine</i>	1015	>100	>200	>200
<i>Myrotecium verrucaria</i>	1069	54.5	39.5	27.7
<i>Nectria inventa</i>	1070	41.9	74.3	53.0
<i>Penicillium brevicompactum</i>	1097	80.4	>100	55.0
<i>Penicillium chrysogenum</i>	1115	>100	60.9	70.8
<i>Penicillium citrinum</i>	1071	>100	>400	91.4
<i>Penicillium citrinum</i>	1105	>100	>200	82.7

Cells were treated for 72 hours with increasing concentration of crude extract (from 0.2ng ml<sup>-1</sup> to 0.2mg ml<sup>-1</sup>) or controls. Values are calculated as LD<sub>50</sub> in µg ml<sup>-1</sup>

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731 **Figure Captions**

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733 **Figure 1. PCA analyses of animals and districts.** Triangle pointing upward  
734 is Body wall (B); triangle pointing downward is Intestine (I); square is Sand  
735 (S).

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737 **Figure 2. Fungal extracts HPLC chromatographic profiles at 280nm.**  
738 Crude extracts obtained by fungal growth on different media (Soy Mannitol  
739 Agar, SMA; Malt Extract Chloride Agar, MECIA; Malt extract Agar, MEA) were  
740 analyzed by HPLC to detect variability in the metabolites content. In the figure  
741 are showed the extracts profiles on the different growing media of two strains  
742 belonging to the same genera (*Aspergillus insuetus*, *Aspergillus protuberus*)  
743 and two different strains of the same species (*Penicillium citrinum*).

744

745 **Figure 3. Fungal extracts cytotoxicity toward hepatocarcinoma (HepG2)**  
746 **cells.** The extracts' cytotoxicity of four of 16 fungal strains, encompassing the  
747 most cytotoxic, are here showed. Five thousand cells were seeded in 96-well  
748 plates and treated with fungal extracts for 72 hours at 37°C, 5% CO<sub>2</sub>. Extracts  
749 dissolved in DMSO were diluted in cell growing medium to reach seven  
750 increasing concentrations to treat the cells. Positive control cells (ctr+, dashed  
751 line) were treated with growing medium +0.5% DMSO while negative control  
752 cells (ctr-, dotted line) were treated with growing medium +10% DMSO. Cell  
753 viability after treatment was measured by adding 10% v/v of resazurin based  
754 dye (alamarBlue) and incubating at 37°C, 5% CO<sub>2</sub> for 6hours. Fluorescence  
755 was then read at 531nm excitation wavelength, 572nm emission wavelength.  
756 Light grey line with round dot is extract from MEA medium; dark grey line with  
757 triangle dot is extract from MECLA medium; black line with rhomboidal dot is  
758 extract from SMA medium.

759

760 **Figure 4. Positive hit extracts re-tested for osteogenic bioactivity.**  
761 hMSCs differentiation after fungal extracts treatment was evaluated by  
762 measuring two markers. Early differentiation marker alkaline phosphatase  
763 (ALP) expression was measured 7 days after treatment. Cells were exposed  
764 to 20µg ml<sup>-1</sup> fungal extract dissolved in Incomplete Osteogenic medium to  
765 evaluate their ability to induce differentiation in absence of β-  
766 glycerophosphate in the medium (A) or in Osteogenic Medium to evaluate an  
767 improvement on the differentiation induced by the standard differentiation  
768 medium (B). Late differentiation marker, matrix mineralized calcium, was  
769 measured 12 days after treatment. Cells were treated with extracts dissolved  
770 in IOM (C) or OM (D). The experiment was carried out on experimental  
771 triplicates. Results are presented as the mean ± SD of 3 technical replicates, \*  
772 = p ≤ 0.05 calculated using ANOVA one-way with Bonferroni post-test.

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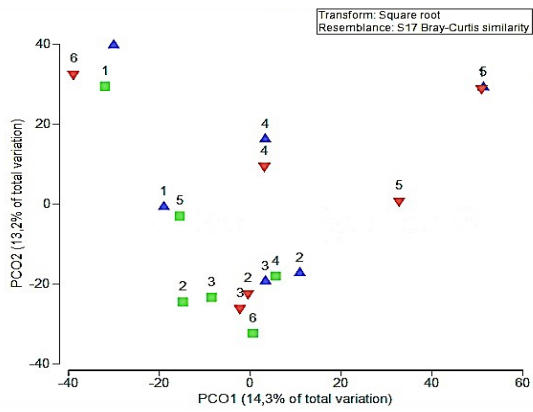
774 **Figure 5. Fungal species occurrence on Mediterranean substrates.** The  
775 Venn diagram highlights common fungal species between *Holothuria poli* and  
776 other Mediterranean substrates.

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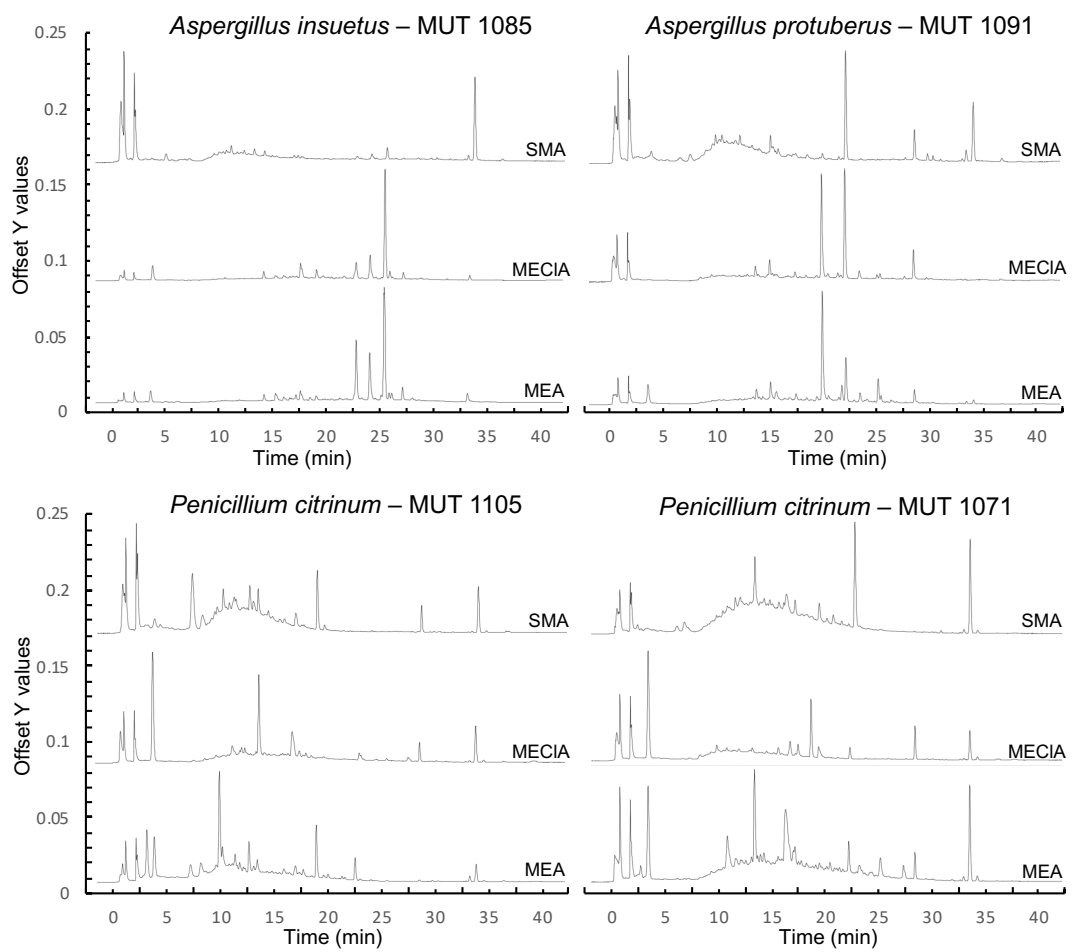
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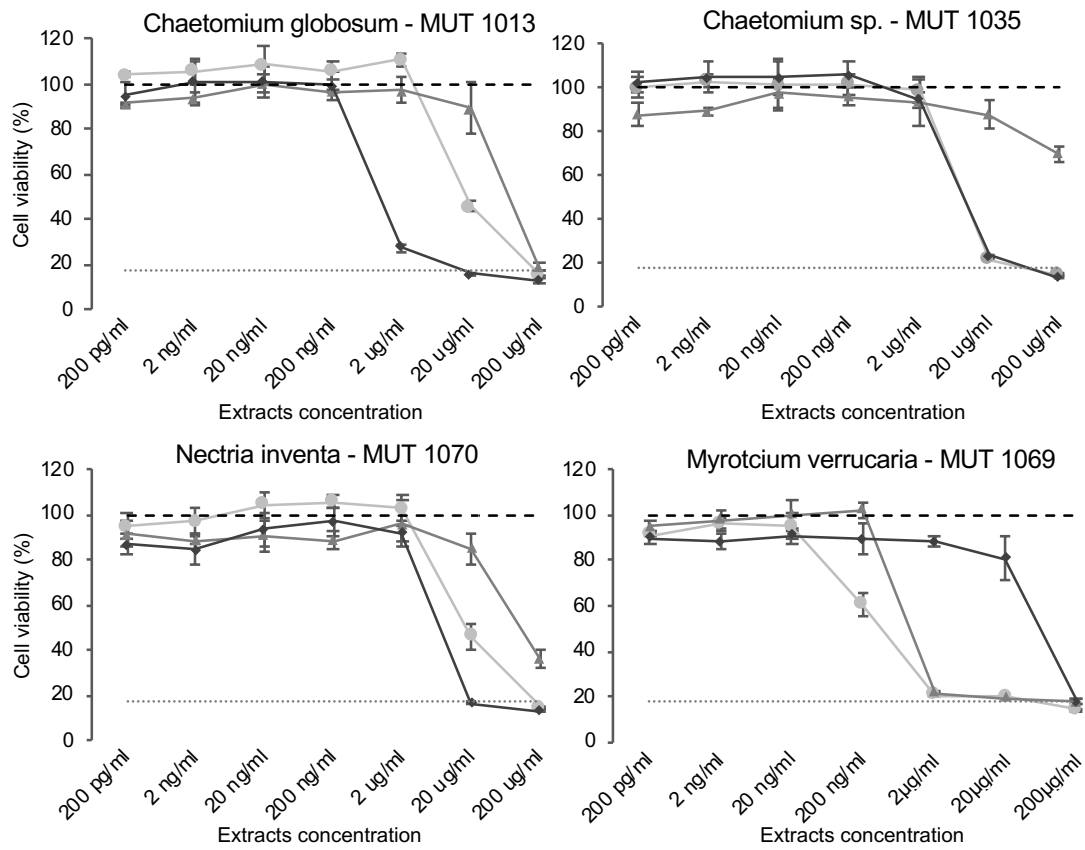
780 **Figures**



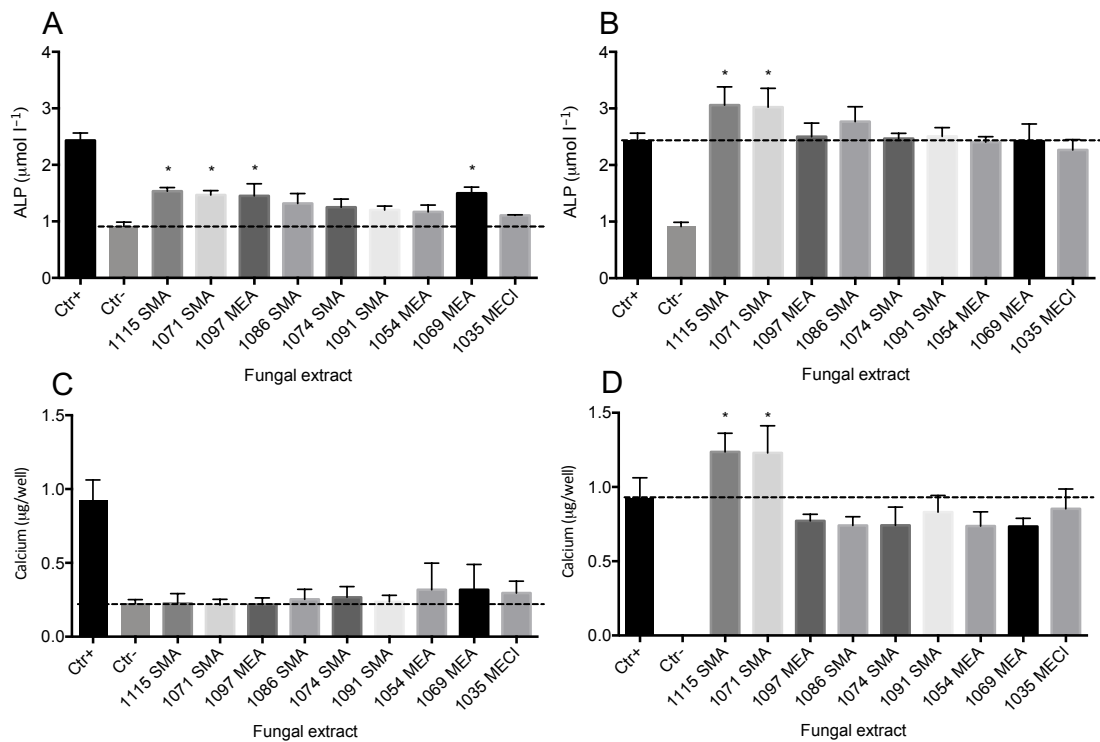
781 **Figure 1**  
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783 **Figure 2**  
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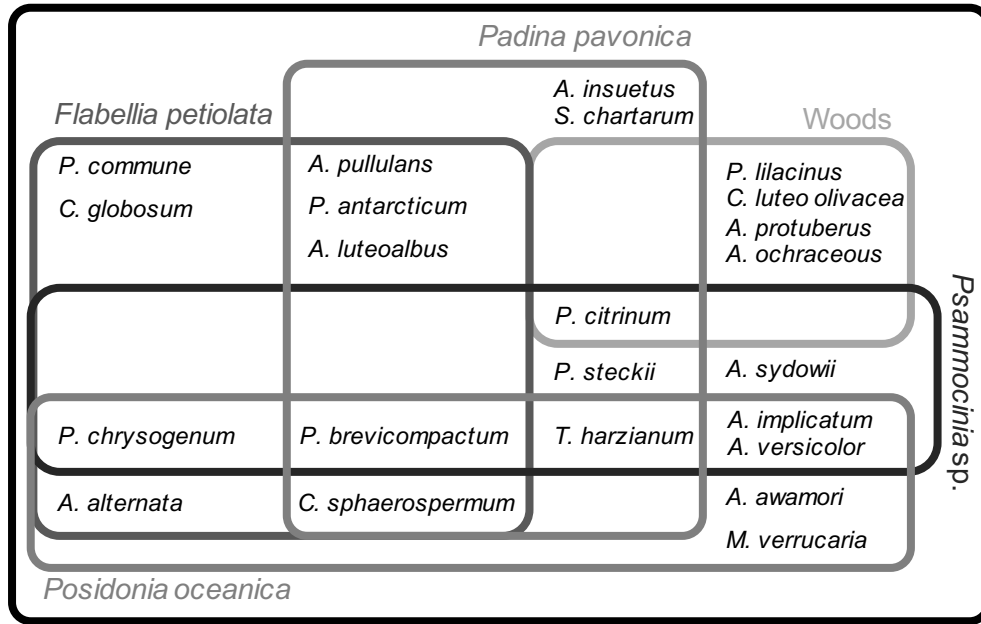


785 Figure 3  
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787 Figure 4  
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*Holothuria poli*



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Figure 5