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Effects of disinfectants on inactivation of mold spores relevant to the food industry: a review.

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Abstract

Due to the dissemination of airborne conidia and spores, molds can contaminate various surfaces. In the food industry sector, their presence and development can have health and economic implications. In order to control these undesirable microorganisms, various approaches can be used but the main one relies on the use of disinfectants. The objective of this review is to report the existing studies on the effect of various disinfectant molecules (i.e., sodium hypochlorite, chlorine dioxide, ethanol and other alcohols, hydrogen peroxide, peracetic acid, and quaternary ammonium compounds) on the inactivation of fungal spores. These studies were sorted depending on the targeted fungal species. Noteworthy, in the food industry, four log and three log reductions are required to claim a fungicidal activity for suspension (European Standard 1650, 2019) and surface (European Standard 13697/IN1, 2019) treatments, respectively. Most of the presented studies concerned *Penicillium* and *Aspergillus* species (44 and 31% of the literature, respectively). In general, for a given disinfection procedure, ascospores were more resistant than conidia, and *Aspergillus* conidia were more resistant than *Penicillium* ones. However, the variability of encountered molds (e.g. species, strains, physiological state) and disinfection procedures (e.g. molecules, concentrations, contact time) affected the efficacy of disinfectants.

1. Introduction

Quality is a major issue for food industries as various hazards can affect food products. Among microbiological hazards, fungal contamination is a major spoilage source of many food products such as fruits, vegetables, bakery and dairy products. Mold development leads not only to modification of organoleptic properties but can also have safety implications in the case of a mycotoxigenic species. Consequently, food spoilage by fungi is synonymous of economic losses for producers, and food waste and health risk for the consumer (Bryden, 2007; Coton and Dantigny, 2019; Dagnas and Membré, 2013; Sengun *et al.*, 2008). As for the medical sector, pathogenic strains of *Candida* and *Aspergillus* species are the primary cause of hospital-acquired fungal infections (Seeliger and Schröter, 1984), and in recent years these infections have been recognized as serious threats to immunocompromised patients (Bodey *et al.*, 1992; Morrison *et al.*, 1994; Wildfeuer *et al.*, 1998). Moreover, other mold-associated infections have constantly increased over the last decades (e.g. mucormycosis, Morin-Sardin et al., 2017).

In order to prevent microbial contamination, food manufacturers mainly use disinfectants. Due to the presence of at least one active ingredient with antimicrobial activity, disinfectants are microbiocidal products. Antimicrobial activity is defined as the ability of a biocide to reduce the number of viable cells. More generally, disinfectants have a broad activity range, such as a bactericidal, virucidal, sporicidal, yeasticidal and fungicidal activity.

Fungicidal activity is determined by means of the log reduction of the number of viable mold spores. This is a key factor in the choice of a disinfectant. This activity is evaluated according to specific standards drawn up by international or national agencies, and specifying standardized test methods (van Klingeren *et al.*, 1998). In Europe, standards for assessing fungicidal activity have been established by the European Committee for Standardization (CEN/TC 216). These standards indicate various experimental factors such as

the species and strains, the culturing and harvesting methods, the test procedure (contact time, concentrations, temperature...), the enumeration method as well as the criteria for assessing the antimicrobial activity of the tested biocide.

The fungicidal effect of disinfectants is based on the inactivation of reference microorganisms, *Candida albicans* (ATCC 10231) and *Aspergillus brasiliensis* (ATCC 16404), either by the suspension test, the carrier test or the airborne room disinfection procedure (Table 1). The European Standard 1275 (2006) entitled "*Quantitative suspension test for the evaluation of the basic fungicidal activity of antiseptics and chemical disinfectants*" consists in demonstrating a basic activity of the test product in optimal conditions of use. A suspension test is described to establish whether the test product has a fungicidal activity based on reducing by at least 4 log the reference microorganisms. The European Standard 1650 (2019) entitled "*Quantitative suspension test for the evaluation of the fungicidal or yeasticidal activity of antiseptics and chemical disinfectants used in the food industry, in industry, in domestic and community areas*", assesses the activity of the disinfectant under practical conditions of use. A suspension is tested in the presence of an interfering substance simulating clean or dirty conditions. The European Standard EN 13697/+A1 (2019) entitled "*Chemical antiseptics and disinfectants - Quantitative test of a non-porous surface for the evaluation of the bactericidal and/or fungicidal activity of chemical disinfectants used in the food industry, in industry, in domestic and community sectors. Test method without mechanical action and requirements*" describes a test on a non-porous surface intended to assess the efficacy of the disinfectant molecule diluted in hard water. The ability of the latter to reduce, by at least 3 log, the reference microorganisms after 15 min or less exposure, at a temperature between 18°C and 20°C is also evaluated in the presence of an interfering substance simulating clean or dirty conditions.

The surface test is by far the most important, challenging and representative of the tests of disinfectant efficacy. With the exception of drinking water, the surface test is more relevant than the suspension test because it is truer to practical conditions and theoretically, microorganisms attached to a surface will be more resistant than those in a suspension, therefore this presents the greatest challenge. The quantitative surface test evaluates test suspensions of bacteria and fungi in a solution of interfering substances, designed to simulate clean and dirty conditions, which are inoculated onto a test surface and dried (Sandle, 2017). More recently, the European Standard 17272 (2020), described a test to disinfect by an automated process the surfaces of the overall area including the external surfaces of the equipment contained in rooms. This standard aims at simulating practical conditions of airborne disinfection in a laboratory situation.

There are several sanitizing chemical compounds approved for use on food contact surfaces, such as hypochlorites, chlorine dioxide, iodophors, peroxides, ethanol, quaternary ammonium. Regardless of the chemical, the stock solution must be diluted to a specific concentration to ensure maximum efficacy. The list of authorized compounds may vary with time and according to countries. Final concentrations in use for some sanitizing compounds approved in the Canada and in the US are listed Table 2. Some compounds, such as ethanol, do not require any rinsing. For the other compounds, the maximum residue levels that remain in the food product should be evaluated as acceptable by the safety authorities in Canada. In Europe, disinfectants (biocides) used in the food industry are controlled by a range of legislation, but two are key in determining the level of disinfectant that can be taken up by foodstuffs after the disinfectant's legitimate use. Regulation (EC) No 396/2005 (2005) on maximum residue levels of pesticides in or on food and feed of plant and animal origin governs the use of pesticide residues. Regulation (EU) No 528/2012 (2012), concerning the

114 making available on the market and use of biocidal products, governs the use of biocides for
115 the purpose of disinfection in the food hygiene sector.

116 Despite the importance of fungal contamination in the food industry, in the medical
117 environment, and in domestic and community areas, to the best of our knowledge, the effect
118 of disinfectants on molds spores was not reviewed. With the notable exception of *Aspergillus*
119 *fumigatus*, and *Trichophyton mentagrophytes*, this review was concerned with mold species
120 relevant to the food industry. *A. fumigatus* is the most common species implicated in all
121 pulmonary syndromes and some contaminated food could be a potential source of exposition
122 in immunosuppressed patients (Bouakline *et al.*, 2000). In Canada, *T. mentagrophytes* is the
123 reference organism for assessing the fungicidal efficacy of a disinfectant in the medical area
124 (Gaulin et al., 2011). In this context, this review reported the effects of various biocides
125 against the inactivation of more than sixty different mold species. This work synthesized for
126 the main disinfectants used, their chemical nature, mode of action, efficacy on mold spores
127 through studies published over the past twenty years.

128 In the context of this review, disinfectant efficacy was usually assessed by means of
129 the log reduction in viable spores, $\log(N/N_0)$, where N was the number of survivors after
130 treatment, and N_0 the initial load of spores which, according to the European standards,
131 should be in the range 1.5-5 10^7 CFU/ml. When the N_0 value was not stated in a study, the
132 effect of the disinfectant could not be evaluated and the publication was not used, as for
133 example Roberts and Reymond's (1994) study.

134 In many studies, disinfection treatments were applied to fruits, vegetables, or grains
135 artificially contaminated by sprayed spore suspensions. The efficacy of treatments were not
136 assessed by enumerating the number of survivors but by determining a decay number
137 (Karabulut et al., 2004, 2005) or a contamination percentage (Andrews, 1996). None of these
138 responses could be correlated to the number of survivors after treatment. Accordingly, this

139 kind of studies was also discarded. In water applications, the disinfectant effectiveness was
140 often expressed in terms of the Ct (concentration x $time_{reaction}$) value needed to inactivate a
141 certain percentage of the population (Pereira et al., 2013). Therefore, in all studies reported in
142 Table 3, the impact of the treatments was always expressed in terms of log reduction. When
143 no survivors were detected after treatment, the log reduction was indicated as greater than log
144 N. Most studies assessed the fungicide effect of disinfectants for a given exposure duration,
145 but studies examining inactivation kinetics were scarce.
146

147 **2. Chlorine compounds**

148 *2. 1. Generalities*

149 Chlorine compounds are a family of biocides consisting of a chlorine atom responsible
150 for oxidative activity. The main disinfectants in this chemical group are hypochlorous acid,
151 hypochlorite ion, chlorine and chlorine dioxide. Hypochlorous acid, hypochlorite ion, and
152 chlorine are referred to as free (Fukuzaki, 2006; Leidholdt, 2000) or active (EU regulation
153 N°528/2012, 2017) chlorine. Formation of the latter compounds results from the
154 decomposition of sodium hypochlorite in water, 1% w/w sodium hypochlorite being
155 equivalent to 0.96% w/w active chlorine (EU regulation N°528/2012, 2017). Other chlorine
156 sources correspond, for example, to sodium dichloroisocyanuric acid or calcium hypochlorite
157 after dissolution in water. The first solution of sodium hypochlorite was produced by the
158 French chemist Claude Berthollet in the 18th century under the name "Eau de Javel" and its
159 antimicrobial properties were discovered in the 19th century by the French chemist Antoine
160 Germain Labarraque (Mupparapu and Kothari, 2019). Chlorine compounds are widely used in
161 the food industry to disinfect surfaces or in hospitals to disinfect material, but also in the
162 treatment of drinking water and some ready to eat food such as salads (Beuchat and Ryu,
163 1997; Gómez-López et al., 2009; Jeffrey, 1995; Okull et al., 2006; Rossman et al., 1994). The

main factor that influences the antimicrobial activity of chlorine compounds is the presence of soiling/organic load which will have a negative impact by reacting with chlorine (Boothe, 1998; Kotula et al., 1997). Neutral pH has a positive impact on antifungal activity of sodium hypochlorite solution by promoting the formation of hypochlorous acid (pKa 7.54) which is more active than the hypochlorite ion predominant in alkaline solution (pH 9-11) (Boothe, 1998; Leidholdt, 2000; McDonnell and Russell, 1999). Chlorine concentrations are usually expressed in ppm (mg/l) for disinfecting water and in percentage for sanitization of food industry surfaces.

2. 2. Mode of action

Antimicrobial activity of a sodium hypochlorite solution is due to the oxidative action of hypochlorous acid and hypochlorite ion on cellular components. These compounds are able to react with multiple biomolecules such as lipids, amino acids, proteins, peptides and nucleic acids. Therefore, chlorine compounds are able to target many cellular structures and compounds such as cell wall, cell and mitochondrial membrane, enzymes as well as DNA (Fukuzaki, 2006). Available chlorine inhibits the metabolism by oxidation of thiol functions or oxidation and chloramination of amino groups present in the membrane and cytoplasmic enzymes (Denyer and Stewart, 1998). In addition to disrupting the metabolism, hypochlorous acid has been shown to induce the production of Reactive Oxygen Species (ROS) with a lethal effect on cells (Dukan et al., 1999). Sodium hypochlorite and chlorine dioxide have also been shown to exert a genotoxic effect as observed on the *Saccharomyces cerevisiae* yeast (Buschini, 2004). Electron microscopic examination showed that *A. fumigatus* conidia exposed to sodium hypochlorite solution were smaller and smoother than the untreated conidia, with loss of surface structures and some surface padding compared to untreated conidia (Martyny et al., 2005).

189

190 *2. 3. Antifungal activity of sodium hypochlorite*

191 Bundgaard-Nielsen and Nielsen (1996) tested the fungicidal efficacy of 3% sodium
192 hypochlorite on twenty-five fungal contaminants. After 10 minutes exposure, inactivation
193 values ranged from 1.7 to more than 5.2 log. Twenty-one isolates exhibited more than 4 log
194 inactivation. Ascospores, except those of *Eurotium repens* (=*Aspergillus pseudoglaucus*)
195 showed a greater resistance than conidia to sodium hypochlorite. For example, *Monascus*
196 *ruber* and *Neosartorya pseudofischeri* (=*Aspergillus thermomutatus*) ascospores showed
197 inactivation of 2.9 and 4.0 log, respectively. In contrast to these ascospores, all conidia, with
198 the exception of one *Penicillium commune* isolate (1.7 log inactivation), exhibited more than
199 4 log reduction. However, the fungicidal activity of sodium hypochlorite can vary within the
200 same species. At a concentration of 0.3 % for a 10 min exposure, the inactivation of
201 *Penicillium roqueforti* ranged from 0.5 to 4.5 log depending on the considered strain (n=2).

202 A low sodium hypochlorite concentration at relatively short exposure times was
203 sufficient to ensure effective inactivation of *Aspergillus niger* and *P. roqueforti*, both widely
204 distributed contaminants in the food industry. Indeed, three minutes exposure to 0.5% sodium
205 hypochlorite solution were sufficient to completely inactivate (about 6 log inactivation) all *A.*
206 *niger* isolates (*n*=5) and less than 1 minute was sufficient for all tested *P. roqueforti* isolates
207 (*n*=5) (Korukluoglu et al., 2006).

208 A lower pH, and the presence of certain non-ionic surfactants, may increase the
209 antifungal activity of sodium hypochlorite. Okull et al. (2006) showed that a *Penicillium*
210 *expansum* suspension exposed for 5 min to sodium hypochlorite at 50 ppm, induced 1.9 log
211 and 0.5 log decrease in viable conidia at pH 6.3 ± 0.2 and pH 8.5 ± 0.2, respectively. At the
212 lower pH, the addition of nonionic surfactant such as Span 20, Tween 20 or Tween 80 at

213 0.01% (v/v) led to the absence of viable spores. At the higher pH, only Span 20 and Tween 20
214 at 0.1% gave a significant reduction of 2.4 log.

215 Furthermore, it has been observed that, at concentrations lower than 0.1%, the
216 fungicidal activity of sodium hypochlorite decreases sharply. The contact times required for
217 the complete inactivation of *Penicillium brevicompactum* conidia at sodium hypochlorite
218 concentrations of 0.053% was 30 min as compared to 4 and 2 min for 0.299 and 0.525 %
219 concentrations, respectively (Ebling, 2008). A contact time of 15 min to 1% chlorine allowed
220 total inactivation of *Aspergillus ochraceus* (Gupta et al., 2002). The fungicidal efficacy of
221 sodium hypochlorite on *Aspergillus flavus*, *A. fumigatus* and *A. niger* isolates was further
222 evaluated by Mattei et al. (2013). The recommended concentration of 0.4% sodium
223 hypochlorite for 72h was sufficient to inactivate one third of the *Aspergilli* (n=18). Another
224 third required 0.8 and 1.6%, while the remaining third exhibited survivors for 1.6%. These
225 authors concluded that sodium hypochlorite was the least effective disinfectant against
226 *Aspergillus* spp. as compared to chlorhexidine-cetrimide, benzalkonium chloride and a
227 chlorophenol derivative. It should be underlined that 72h exposure time exceeds the
228 maximum time that can be allowed in the food industries, even for a complete disinfection.

229 Frison et al. (2015) showed that a decrease in pH from 9 to 6.3 reduced the contact
230 time required to achieve 4 log inactivation for five isolates of *Aspergillus* section Nigri. For a
231 700 mg/l (0.07%) sodium hypochlorite solution, according to the considered strain, the
232 contact time required to reach 4 log at pH 9 and at pH 6.3, ranged from 16.2 to 28.8 min, and
233 from 9.5 to 14.7 min, respectively. However, at higher sodium hypochlorite concentrations,
234 the effect of pH on the contact time required to reach 4 log inactivation was less noticeable.
235 For 1300 mg/l (0.13%) sodium hypochlorite, the contact time associated with 4 log
236 inactivation ranged from 1.1 to 1.2 min at pH 6.3 and 1.4 to 2 min at pH 9.

237 Pereira et al. (2013) investigated the impact of pH and temperature on the efficacy of
238 two free chlorine concentrations (1 and 3 mg/l) to inactivate *A. fumigatus*, *Aspergillus terreus*,
239 *Cladosporium cladosporioides*, *Cladosporium tenuissimum*, *Penicillium citrinum*, *Penicillium*
240 *griseofulvum* and *Phoma glomerata*, molds which are found in different source waters.
241 Efficacy was evaluated by means of an inactivation rate constant expressed in min^{-1}, the
242 greater the inactivation rate, the more efficient the inactivation was. At 21°C, a pH decrease
243 from 7 to 6 increased the inactivation rate about 8-fold for *P. glomerata*. This was explained
244 by the higher proportion of hypochlorous acid (HOCl), a more powerful disinfectant, than
245 hypochloride ion (OCl^-) at pH 6. An increase from 1 mg/l to 3 mg/l increased also the
246 inactivation rates about 3 fold for *Aspergilli*, *C. cladosporioides*, and *P. citrinum*. A lower
247 impact was observed for *C. tenuissimum*, *P. griseofulvum* and *P. glomerata*. Eventually, at 1
248 mg/l, the impact of the type of water on inactivation was highlighted. Inactivation rates were
249 about 2-8 fold greater in laboratory grade water than in settled water (i.e. obtained for
250 decantation of treated wastewater). At pH 7, a temperature decrease from 21°C to 4°C led to a
251 decrease in inactivation rate of about 2-4 fold only depending on the considered species. In
252 contrast to this study, less than one log reduction difference was observed between *A.*
253 *brasiliensis* conidia submitted to sodium hypochlorite (0.5 and 1% for 5-15 min) at 10 and
254 40°C (Stefanello et al., 2021).

255 Drinking water contaminated with *A. fumigatus*, *Aspergillus versicolor* and
256 *Penicillium purpurogenum* was also tested using sodium hypochlorite and monochloramine
257 solutions (Ma and Bibby, 2017). Disinfectant concentrations and contact times were in the
258 range 1-4 mg/l, and 0-60 min respectively. The Ct values needed to obtain 3 log inactivation
259 ranged from 48.99 to 194.7 $mg.min.l^{-1}$ and from 90.33 to 531.3 $mg.min.l^{-1}$, for sodium
260 hypochlorite and monochloramine, respectively. *A. versicolor* and *P. purpurogenum* isolated

261 from a drinking water system were more resistant than an *A. fumigatus* clinical isolate to both
262 disinfectants.

263 The efficacy of sodium hypochlorite solution (0.1%, 0.5% and 1% of active chlorine)
264 on *A. brasiliensis* as well as on fungal food spoilers, namely *C. cladosporioides*, *P. commune*,
265 *Penicillium polonicum* and *P. roqueforti*, was tested by Bernardi et al. (2018) according to the
266 EN 13697 standard (2001). Mold conidia were fixed on stainless steel coupons in the
267 presence of an interfering solution, then sodium hypochlorite solutions were applied for 15
268 minutes. Under these conditions, sodium hypochlorite was the most effective disinfectant
269 against all tested species compared to the other disinfectants tested in the study (i.e.
270 benzalkonium chloride, biguanide, peracetic acid, and quaternary ammonia). Active chlorine
271 0.1% was very effective against *C. cladosporioides* with more than 4 log inactivation and
272 effective against *A. brasiliensis* with 3 log inactivation. However, the same concentration
273 showed insufficient fungicidal activity against the three tested *Penicillium* species (2 log
274 reduction). On the contrary, 0.5% active chlorine was very effective against all species with
275 more than 4 log inactivation. The greatest sodium hypochlorite concentration tested in this
276 study, 1%, was above the concentrations usually allowed for use in food industries.

277 Potential intraspecific response heterogeneity to sodium hypochlorite exposure was
278 evaluated on several strains of *Aspergillus pseudoglaucus* (n=2), *Hyphopichia burtonii* (n=3),
279 *Penicillium paneum* (n=3) and *P. roqueforti* (n=3), (Bernardi *et al.*, 2019). Exposure to 0.2%
280 active chlorine for 15 min had very limited effect against all tested strains with a mean
281 inactivation value of 1.37 log for *A. pseudoglaucus* and 2.30 log for *P. paneum*. At 0.2%
282 active chlorine, the greatest difference in inactivation within the same species was observed
283 for *P. roqueforti* with a 0.54 log inactivation difference between the most resistant strain (1.74
284 log) and the most sensitive one (2.28 log). However, amongst all the concentrations tested
285 (0.01%, 0.1% and 0.2%), the greatest difference in inactivation was obtained at 0.1% active

286 chlorine on *P. paneum* with a 1.03 log difference between the most resistant strain (0.04 log
287 reduction) and the most sensitive strain (1.07 log reduction). Although sodium hypochlorite is
288 used in a relatively wide concentration range from 0.01 to 2% depending on the target mold,
289 cleanliness conditions and desired level of hygiene, active chlorine concentrations lower than
290 or equal to 0.2% do not guarantee an inactivation greater than 3 log on treated surfaces.
291 Sodium hypochlorite and biguanide were the least effective, reducing less than 3 log from
292 initial control, not being the most suitable agents for the control of toxigenic fungi (*Aspergilli*)
293 in food industries (Gonçalves Lemos *et al.*, 2020).

294 On the other hand, disinfectant treatments of three *Penicillium* species isolated from
295 fruit juices were evaluated according to the EN 13697 standard (2015) on stainless steel, in
296 the absence or presence of sucrose as interfering substance (Nierop Groot et al., 2019).
297 Remarkably, for *Penicillium buchwaldii* conidia, chlorine from hypochlorite inactivation was
298 enhanced in the presence of sucrose (1.8 log reduction with sucrose compared to 0.9 log in the
299 absence without).

300 Evaluation of sodium hypochlorite fungicidal activity has been extended to other types
301 of material than the traditional steel coupon. The spores of *Alternaria alternata*, *A. niger*,
302 *Cladosporium herbarum*, *Mucor bainieri*, *Penicillium chrysogenum*, *Stachybotrys chartarum*
303 and *T. mentagrophytes* were inactivated by 2.4% sodium hypochlorite to undetectable levels
304 in glazed and unglazed ceramic carriers. Test organisms were non-culturable in 10/10 trials,
305 after 5-min contact times in glazed ceramic carriers, and after 10 min in unglazed ceramic
306 carriers, representing a >3-log10 to >5-log10 reduction, depending on the mold type (Reynolds
307 et al., 2012).

308

309 *2. 4. Antifungal activity of chlorine dioxide*

310 In their study, Bundgaard-Nielsen and Nielsen (1996) found that 5% chlorine dioxide
311 had a fungicidal efficacy similar to 3% sodium hypochlorite on their selection of target fungi
312 (see §2.3). For 10 minutes exposure, inactivation values ranged from 2.7 log to more than 5.2
313 log. Eleven out of 20 isolates exhibited more than 4 log inactivation. All isolates exhibited
314 more than 3 log reduction except *Penicillium caseifulvum* (2.7 log).

315 The impact of pH, temperature and humic acid concentration on the fungicidal activity
316 of chlorine dioxide (ClO_2) in the range 0.5-3.0 mg/l was assessed on *Cladosporium* sp.,
317 *Penicillium* sp., and *Trichoderma* sp. (Wen et al., 2017). The inactivation rate constants for
318 chlorine dioxide, 2 mg/l, were 5, 26 and 17 fold those obtained for chlorine, 2 mg/l, for
319 *Cladosporium* sp., *Penicillium* sp., and *Trichoderma* sp., respectively. Inactivation rate
320 constants were not significantly affected by pH 6 and 7. In contrast to pH, inactivation rate
321 constants decreased significantly by lowering temperature from 27 to 10°C (by 25% for
322 *Penicillium* sp. and 50% for *Cladoporium* sp. and *Trichoderma* sp.). While the inactivation
323 rate constants did not vary significantly in the 0-2 mg/l humic acid range, inactivation rates at
324 0.4 mg/l were half those obtained at 0.2 mg/l. Overall, by increasing susceptibility order, the
325 species were ranked *Penicillium*<*Trichoderma*<*Cladosporium*.

326 As shown in the study of Nierop Groot et al. (2019), chlorine dioxide remained
327 effective against *Penicillium* spp. at low temperatures. At 7°C, for 5 min contact time to 500
328 ppm chlorine dioxide an inactivation greater than 5 log was shown for *Penicillium*
329 *bialowiezense*, *P. buchwaldii* and *P. expansum*. In comparison, the inactivation obtained by
330 chlorine was 2.5 log in the case of *P. bialowiezense* and less than 1 log for the two other
331 species. In another study (Okull et al. 2006), *P. expansum* exposed to chlorine dioxide at 3
332 ppm for 5 min exposure exhibited 3.7 log inactivation.

333 Regarding the effect of chlorine dioxide on ascospore-producing species, 10 min
334 exposure to 5% chlorine dioxide led to more than 4.5, more than 4 and 3.3 log inactivation for

335 *E. repens* (=*A. pseudoglaucus*), *M. ruber* and *N. pseudofischeri* (=*A. thermomutatus*),
336 respectively (Bundgaard-Nielsen and Nielsen, 1996). Dijksterhuis et al., (2018) also evaluated
337 the fungicidal effect of this biocide on heat-resistant ascospores of *Aspergillus fischeri*,
338 *Paecilomyces variotii*, *Paecilomyces niveus* and *Talaromyces macrosporus* (=*Penicillium*
339 *macrosporum*) which were either dormant or activated by 80°C heat treatment for 5 min. For
340 the first three mentioned species, the two kind of ascospores were inactivated after 500 and
341 1000 ppm treatments for 5 min. Only *T. macrosporus* (=*P. macrosporum*) ascospores
342 survived up to 500 ppm, but full eradication of this species (i.e. inactivation ≥ 5 log) was
343 observed after 30 min. During viability assessment experiments, heat activated ascospores of
344 this species showed larger colonies than dormant ascospores, thus suggesting an increased
345 resistance of heat activated ascospores to the disinfectant.
346
347 *2. 5. Antifungal activity of sodium dichloroisocyanuric acid*
348 In their 1996 study, Bundgaard-Nielsen and Nielsen also tested the fungicidal efficacy
349 of sodium dichloroisocyanuric acid at 0.37 g/l. After 10 minutes exposure, inactivation values
350 ranged from 1.3 log to more than 5.2 log according to the considered target fungi (see §2.3),
351 seven isolates exhibiting more than 4 log inactivation. Eight strains were particularly resistant,
352 namely two *P. commune* isolates (1.7 and 3.7 log reduction), *P. caseifulvum* (1.9 log
353 reduction), *Penicillium discolor* (1.9 log reduction), *Penicillium nalgiovense* (1.7 log
354 reduction), *P. roqueforti* (0.9 log reduction) and *Penicillium carneum* (1.7 log reduction) as
355 well as *E. repens* (= *A. pseudoglaucus*) ascospores (0.3 log reduction).
356
357 **3. Alcohols**
358 *3. 1. Generalities*

359 Alcohols used as disinfectants correspond to ethyl alcohol (or ethanol), isopropyl
360 alcohol (or isopropanol) and n-propanol. However, ethanol is the most commonly used
361 molecule in this family. Alcohols are water soluble molecules consisting of a polar hydroxyl
362 function and a hydrocarbon tail. Alcohols have long been used for their antimicrobial activity
363 and the first evaluations of their efficacy can be traced back to 1881 with the work of Robert
364 Kock (Price, 1939). In the food industry, the use of alcohols as disinfectant has the advantage
365 of being safe for the user (food-grade) and of not leaving any residue on the treated surface
366 due to their rapid evaporation. Alcohols can be sprayed, fumigated or applied through
367 impregnated wipes. Alcohols, like ethanol, are formulated in relatively strong concentrations.
368 Their antimicrobial activity is optimal in the range 60-90% (Boyce, 2018a; Jeffrey, 1995;
369 McDonnell and Russell, 1999).
370
371 *3. 2. Mode of action*
372 Alcohols act on the cell membrane and cytoplasmic proteins. These molecule toxicity
373 depends on their aliphatic chain and hydrophobicity. This is why small chain alcohols, like
374 ethanol, are toxic at high concentrations. The mode of action of ethanol on fungal cells was
375 reviewed by Dao and Dantigny (2011). Ethanol molecules will interact with cell membrane
376 lipids at the lipid-water interface leading to increased polarity and decreased cell permeability
377 to polar compounds. Cell death at high ethanol concentrations is believed to be associated
378 with an increase of the fluidity and then the disruption of their cell membrane followed by
379 leakage of cellular compounds (Ingram and Buttke, 1985; Jones and Greenfield, 1987;
380 Tesnière, 2019, Russell, 2003). Ethanol has several deleterious effects on the integrity of the
381 cell membrane. At high concentrations, ethanol dissolves membrane lipids and denature
382 proteins on the membrane leading to destruction of the cell membrane (Bacílková, 2006;
383 Ingram and Buttke, 1985). However, it seems that thinning of the membranes also takes place

384 at low concentrations of ethanol. At higher ethanol concentrations (> 20%), ethanol would
385 transform the phospholipid bilayer into an interdigitated phospholipid phase (Henderson and
386 Block, 2014; Simon and McIntosh, 1984). In the interdigitated phospholipid phase, the
387 membrane lipids of the phospholipid bilayer are distributed over a single layer leaving the
388 terminal methyl group of the acyl chains exposed. This configuration is a consequence of the
389 interactions between the hydroxyl group of the short alcohol chains (C <3) with the polar
390 heads of the phospholipids and their non-polar half with the acyl chains of the phospholipids.
391 Since the nonpolar part of these alcohols is smaller than the acyl part of phospholipids, empty
392 spaces are created in the inner part of the membrane. These spaces will be filled by lipids
393 from the opposite side leading to the formation of an interdigital phase (Simon and McIntosh,
394 1984; Weber and de Bont, 1996). Interdigital phase membranes have a lower thickness and
395 greater permeability than the natural state of the membrane.

396 The modification of the biophysical properties of membranes also disrupts the
397 function of membrane proteins. In addition, alcohols can interact directly with proteins and
398 denature them. Due to their ability to diffuse across the plasma membrane, alcohols are
399 responsible for the denaturation of cytoplasmic proteins. Protein denaturation is believed to be
400 an important factor in the fungicidal activity of alcohols (Boyce, 2018). Given the role of
401 proteins in the proper functioning of cells, their denaturation affects the metabolism and
402 absorption of nutrients in the cell (Ingram and Buttke, 1985). Moreover, ethanol has been
403 reported to damage mitochondrial membranes (Dao and Dantigny, 2011) and DNA (Ibeas and
404 Jimenez, 1997). Mitochondria are thought to have a close role in ethanol-induced death in S.
405 cerevisiae (Carmona-Gutierrez et al., 2012).

406

407 *3. 3. Antifungal activity of ethanol*

408 Bundgaard-Nielsen and Nielsen (1996) tested the fungicidal efficacy of 70% ethanol
409 on target species (see §2.3.). For 10 minutes exposure, inactivation values ranged from 1.3 to
410 more than 5.2 log and eleven isolates exhibited more than 4 log inactivation. *M. ruber*
411 ascospores were the most resistant spores (1.3 log reduction) thus suggesting that ascospores
412 had a greater resistance than conidia to ethanol. The age of ascospores seems to have an
413 influence on the fungicidal activity of ethanol as 110-day *M. ruber* ascospores were more
414 resistant to 70% ethanol than 21-day ascospores (3.5 log difference). An important difference
415 in inactivation of approximately 4 log was observed between the most sensitive isolate and
416 the most resistant *P. roqueforti* isolate, indicating intraspecific susceptibility heterogeneity.

417 Concentration and contact time are important factors that explain the antifungal
418 activity of ethanol. However, other factors can affect the efficacy of ethanol. Dao et al. (2008)
419 showed that temperature, water activity and the mode of application impacted *P.*
420 *chrysogenum*, *Penicillium digitatum* and *Penicillium italicum* inactivation by ethanol. In this
421 study, *P. digitatum* was the most sensitive to ethanol, while *P. chrysogenum* was the most
422 resistant mold. Increasing the ethanol preparation water activity from 0.7 to 0.9 a_w resulted in
423 a greater inactivation of *P. chrysogenum*. For this species, ethanol solutions were more
424 effective than ethanol vapors. For the more sensitive species, namely *P. digitatum* and *P.*
425 *italicum*, vapor ethanol was more effective at 30°C than at 10°C. The experimental condition
426 "0.7 a_w, 30°C, liquid application for 4 days, 10% w/w ethanol" was the most drastic tested
427 condition and ensured total inactivation of the three tested species with inactivation values
428 ranging from 3.19 log to 5.78 log.

429 Biological factors of the target mold had also a great effect on the fungicidal activity
430 of ethanol. Dao and Dantigny, (2009) tested the effect of ethanol vapors at 0.30 and 0.45 kPa
431 on hydrated and dry-harvested conidia of *P. chrysogenum*, *P. digitatum* and *P. italicum*. After
432 24 hours exposure, all dry-harvested conidia remained viable, while the hydrated conidia had

433 mean inactivation values of approximately 1, 3.5 and 2.5 log for *P. chrysogenum*, *P.*
434 *digitatum* and *P. italicum*, respectively. The fungicidal efficacy of ethanol vapors on dry-
435 harvested conidia of *P. chrysogenum*, *P. digitatum* and *P. italicum* was further evaluated by
436 Dao et al. (2010). For a 24-hour exposure, 0.7 kPa ethanol vapor pressure inactivated 4 log *P.*
437 *digitatum* and *P. italicum* conidia, but only 3.2 log *P. chrysogenum* conidia. While an ethanol
438 vapor pressure of 1.5 kPa achieved an inactivation of about 4.5 log and more than 5 log for *P.*
439 *chrysogenum* and the two other species, respectively. Fungicidal activity of ethanol was also
440 impacted by the water activity of the spore production medium (Dao and Dantigny, 2009).
441 Conidia produced from mycelium grown at 0.85 a_w were more resistant to 0.67 kPa ethanol
442 vapors than conidia produced at 0.99 a_w. After 48 h exposure, 6.5, 5.1 and 5.9 log inactivation
443 were obtained for conidia produced at 0.99 a_w for *P. chrysogenum*, *P. digitatum* and *P.*
444 *italicum*, respectively. Conidia produced at reduced a_w (0.90-0.95) required 120 h contact
445 time to reach 4.5 log inactivation for *P. chrysogenum* and *P. digitatum*, a 6 log reduction was
446 observed at 98 h and 120 h exposure for *P. italicum* conidia produced at 0.95 and 0.90 a_w,
447 respectively. The greatest resistance of dry-harvested conidia produced at a reduced water
448 activity was also observed on four isolates of *P. commune* exposed to a 70% ethanol (Visconti
449 et al., 2020). For 1 min exposure, regardless of the isolates, only dry-harvested conidia
450 produced at a_w 0.950 exhibited survivors. Survival after 2 min exposure (and even 3 min) for
451 this physiological state was only observed for *P. commune* UBOCC-A-116003. For this
452 strain, the impact of the physiological state was greater than 1.54 log reduction between dry-
453 harvested conidia produced at 0.950 a_w, that exhibited survivors after 1 min treatment, and the
454 3 other kinds of conidia that were all inactivated.
455
456 *3. 4. Antifungal activity of isopropanol*

457 According to Bundgaard-Nielsen and Nielsen (1996), 70% isopropanol was less
458 effective than 70% ethanol to ensure the total inactivation of the great majority of the target
459 species (see §2.3.). After 10 minutes exposure, inactivation values ranged from 0.9 to more
460 than 5.2 log, and eleven isolates exhibited inactivation values greater than or equal to 4 log. *E.*
461 *repens* (=*A. pseudoglaucus*) and *M. ruber* ascospores, but also *P. roqueforti* conidia, were
462 more resistant to 70% isopropanol than the other selected isolates with inactivation values of
463 2.3, 0.9 and 3.5 log, respectively.

464 Korukluoglu et al. (2006) reported a significant intraspecific variability in the
465 resistance of *P. roqueforti* conidia to an isopropanol-based disinfectant. While, three isolates
466 were completely inactivated (approximately 6 log reduction) after 2 to 8 minute treatments,
467 two others could survive for more than 60 min exposure. In contrast to *P. roqueforti*, lower
468 intraspecific heterogeneity was noticed for *A. niger,* 6 log reduction being obtained for
469 treatments ranging from 10 to 25 min depending on the considered isolates.

470

471 **4. Peroxides**

472 *4. 1. Generalities*

473 Peroxides are chemical species characterized by the presence of two covalently bond
474 oxygen atoms (R-O-O-R'). In disinfection, the most widely used peroxides are hydrogen
475 peroxide (H_2O_2), peracetic acid (CH_3COOOH) and ozone (O_3). These disinfectants, which are
476 powerful oxidizers, can be used in liquid or gaseous form by misting, nebulization or
477 vaporization. Hydrogen peroxide and peracetic acid are both sensitive to soils, such as organic
478 matter, and more effective at temperatures greater than 25°C. Unlike peracetic acid, hydrogen
479 peroxide is more effective at alkaline pH albeit more unstable (Stanga, 2010). Due to its lower
480 sensitivity to organic load and peroxidases, peracetic acid is considered more effective than
481 hydrogen peroxide (McDonnell and Russell, 1999). Peracetic acid has a limited impact on the

482 environment and human health due to its decomposition into water and acetic acid (Alvaro et
483 al., 2009; Lee and Huang, 2019; Taverner et al., 2018), thus making peracetic acid an
484 alternative of interest to chlorine compounds that can form chloramines.
485
486 *4. 2. Mode of action*
487 Hydrogen peroxide and peracetic acid produce ROS which are powerful oxidizing
488 agents of proteins by acting on their thiol groups (Denyer, 1995). Hydrogen peroxide can act
489 on other cellular components such as ribosomes, cell and mitochondrial membranes as well as
490 DNA (McDonnell and Russell, 1999; Qin et al., 2011; Russell, 2003). In *P. expansum*, Qin et
491 al., (2011) showed that the accumulation of ROS following exposure to hydrogen peroxide
492 was responsible for oxidative damage on the proteins of the mitochondrial membrane leading
493 to the collapse of the membrane potential.
494
495 *4. 3. Antifungal activity of hydrogen peroxide*
496 Bundgaard-Nielsen and Nielsen (1996) reported that 10 min exposure to 3% hydrogen
497 peroxide had almost no effect on *P. roqueforti* conidia and *E. repens* (=*A. pseudoglaucus*)
498 ascospores (0.3 and 0 log reduction, respectively). As shown by Martin and Maris (2012),
499 *Absidia corymbifera*, *A. versicolor*, *Geotrichum candidum*, *Penicillium cyclopium* and
500 *Scopulariopsis brevicaulis* exhibited 3 log inactivation at 12.5, 1.71, 0.50, 2.34, 5.51% for 15
501 min exposure. Formic, propionic, acetic, oxalic, lactic and sulfuric acids had synergistic
502 activity with hydrogen peroxide. In most cases (92%), the addition of these organic acids
503 reduced the effective fungicide concentrations by more than 4 fold. Among these six acids,
504 only three retained this synergy when tested in the presence of an interfering agent. They were
505 corresponded to formic acid, against *A. corymbifera*, *G. candidum* and *S. brevicaulis*,

506 propionic acid against *A. corymbifera,* and *A. versicolor* and acetic acid against *A.*
507 *corymbifera.*
508
509 *4. 4. Antifungal activity of peracetic acid*
510 The effect of 0.3% peracetic acid was the same as 3% hydrogen peroxide on *P.*
511 *roqueforti* and *E. repens* (=*A. pseudoglaucus*) (Bundgaard-Nielsen and Nielsen, 1995). In
512 contrast to these authors who reported 0.3 log inactivation in *P. roqueforti*, 5 to 16 min
513 exposure to 0.3% peracetic acid inactivated 6 log of the latter species (Korukluoglu et al.,
514 2006). The same authors indicated a stronger resistance of *A. niger* than *P. roqueforti* to
515 peracetic acid as more than 55 min were necessary to obtain a 6 log reduction in *A. niger*
516 conidia. According to Frison et al. (2015), 6.2-13.8 min exposure to 0,6% peracetic acid
517 decreased viable *A. niger* conidia by 4 log.
518 The effect of paracetic acid was also evaluated on conidia inoculated on stainless steel
519 coupons (Bernardi et al, 2018). A 15 min treatment by 0.15% peracetic acid was not sufficient
520 to inactivate 4 log *P. roqueforti* conidia. These authors showed that 1.5% peracetic acid
521 succeeded in inactivating more than 4 log of *C. cladosporioides, P. commune*, *P. polonicum*
522 and *P. roqueforti* conidia but failed to inactivate 3 log of *A. brasiliensis* conidia. The same
523 authors extended their study on coupons to other molds i.e., *A. pseudoglaucus*, *P. paneum* and
524 *P. roqueforti,* and disinfectants (benzalkonium chloride, biguanide and quaternary
525 ammonium, all tested at 0.3, 2.5 and, 5%) (Bernardi et al., (2019). At 3%, peracetic acid was
526 more effective than the other disinfectants at their highest concentrations to inactivate all the
527 tested species. *P. paneum* and one *P. roqueforti* were the most sensitive species to 3%
528 peracetic acid, exhibiting more than 4 log reduction, while *A. pseudoglaucus* was the most
529 resistant. Eventually, it was shown that *A. brasiliensis* proved less resistant than ascospore-
530 forming molds tested, i.e., *Chaetomium globosum*, *Talaromyces bacillisporus* (=*Penicillium*

531 *bacillisporum*) and *Aspergillus hiratsukae* (Scaramuzza et al. 2020). In contrast to
532 benzalkonium chloride, a clearer higher antifungal efficacy of peracetic acid at higher
533 temperatures was demonstrated (Stefanello *et al.*, 2021). When studying the efficacy of
534 electrolyzed water and sanitizers against heat resistant molds, Stefanello *et al*. (2020) found
535 out that peracetic acid at the maximum concentration of 1% was the best antifungal agent
536 against *Paecilomyces variotii*, *Paecilomyces niveus*, *Paecilomyces fulvus*, *Paecilomyces* sp.
537 and *Aspergillus neoglaber*. Peracetic acid showed the best inactivation of *Aspergillus* from
538 Circumdati section spores (Gonçalves Lemos *et al.*, 2020).
539

540 **5. Quaternary ammonium compounds**

541 *5. 1. Generalities*

542 Quaternary ammonium compounds (QACs) are cationic surfactants. The cationic part
543 consists of a central positively charged nitrogen atom covalently bond with 4 alkyl or aryl
544 groups. The cationic part is most often linked to a chlorine or a bromide to form a QAC salt.
545 Among the most widely used QACs, one can mention benzalkonium chloride, twin-chained
546 QAC dimethyl dodecyl ammonium chloride or bromide (DDAC or DDAB, 12),
547 cetyltrimethylammonium bromide (CTAB) and cetylpyridinium chloride (CPC) (Jennings et
548 al., 2015). QACs are usually formulated with nonionic detergents to increase detergency
549 activity. The presence of a high concentration of calcium and magnesium ions in water,
550 soiling matter (Jeffrey, 1995) or lipids in organic matter (Boothe, 1998) has a negative impact
551 on QAC efficacy. (Jeffrey, 1995). QACs are not compatible with soaps or ordinary anionic
552 detergents; if the latter are used for cleaning, they must be rinsed off before applying QACs
553 otherwise the disinfectants will see its efficacy largely impacted. QACs are more effective in
554 alkaline conditions than in acid ones and a rise in temperature increases their activity. At the

usage dilutions, QACs are usually non-corrosive to surfaces but strong concentrations can corrode mild steel or iron (Jeffrey, 1995).

5. 2. Mode of action

QACs are membrane disruptors, membrane disorganization would be due to electrostatic interactions between the QACs and the cell membrane lipids (potentially the phospholipids) at the intramembrane region level. This leads to the leakage of low molecular weight content (potassium ions, inorganic phosphates, amino acids, etc.), destruction of proteins and nucleic acid as well as lysis of the cell wall following the action of autolytic enzymes (Jennings et al., 2015; McDonnell and Russell, 1999; Russell, 2003).

5. 3. Quaternary ammonium compounds antifungal activity

In their extensive disinfectant study, Bundgaard-Nielsen and Nielsen (1996) tested the fungicidal efficacy of four QAC-based disinfectants on the same previously mentioned 23 isolates (see § 2.3). For a 1.5% benzalkonium chloride-based disinfectant, after 10 minutes exposure, inactivation ranged from 1 to more than 5.2 log according to the considered isolate. Fourteen isolates exhibited inactivation greater than or equal to 4 log, namely *E. repens* (=*A. pseudoglaucus*) (> 4.5 log), *M. ruber* (> 4.1 log) and *N. pseudofischeri* (=*A. thermomutatus*) (> 4.5 log) ascospores. One out of two *A. versicolor*, *P. discolor*, *P. roqueforti* and *P. roqueforti* were characterized by log reduction greater than 4 log. Exposure to a 2% N-alkyl-dimethyl-ammonium chloride-based disinfectant for 10 minutes led to inactivation values ranging from 2.1 to more than 4.2 log (for *S. brevicaulis*). Overall *Penicillia* were less resistant than *Aspergilli*. Exposure to 2% dodecyl- + dodecyl-benzyldimethyl-ammonium chloride-based disinfectant (same exposure time), inactivated from 1.5 log (*A. versicolor*) to more than 5.2 log spores *(A. flavus*, *A. niger* and *Penicillium crustosum*). The latter species

were also resistant to 10 minutes exposure to a mixture of benzalkonium chloride, formaldehyde, glutaraldehyde and 2% cetalkonium chloride-based disinfectant.

Korukluoglu et al., (2006) tested the sensitivity of five *A. niger* isolates and five *P. roqueforti* isolates to three commercial QAC disinfectants based on alkyl-dimethyl-benzylammonium chloride (product A, 2%), on didecyl-dimethyl-ammonium chloride (product B, 0.5 and 1%), and on benzalkanium chloride (product C, 0.5, 1 and 1.5%). Product B was the less efficient, at 1%, 8-21 min and more than 45 min were necessary to completely inactivate *P. roqueforti* and *A. niger*, respectively. Product A and product C, at 1%, completely inactivated *P. roqueforti* and *A. niger* in maximum contact times of 3 and 5 min, respectively. Benzalkonium chloride concentrations required to inactivate 2.7 log conidia were 0.25-2% for *A. flavus*, less than 0.125-0.5% for *A. fumigatus* and 0.25% for *A. niger* (Mattei et al., 2013).

Benzalkonium chloride 2% demonstrated a poor efficacy (< 2 log reduction) when applied to *A. brasiliensis*, *C. cladosporioides*, *P. commune*, *P. polonicum* and *P. roqueforti* for 15 min (Bernardi et al., 2018). However, a maximum efficacy, more than 4 log reduction, was achieved for *C. cladosporioides* by increasing the concentration up to 3.5%, but a concentration of 5% failed to reach this maximum efficacy for all the other species. This observation was latter extended to *A. pseudoglaucus* (Bernardi et al., 2019). Another un-specified quaternary ammonium at 5% reached this maximum efficacy for *C. cladosporioides*, *P. commune* and *P. polonicum* (Bernardi et al., 2018), but not for *A. pseudoglaucus*, *P. paneum* and some *P. roqueforti* isolates (Bernardi et al., 2019). Benzalkonium chloride and iodine were the most effective sanitizers to eliminate *Aspergillus* from the Flavi and Nigri section (Gonçalves Lemos *et al.*, 2020).

6. Conclusions

605 In the agri-food-industry context, cleaning and sanitation are crucial steps to ensure
606 both microbial safety (absence of pathogens) and quality (absence of spoilers) in the final
607 product. As for the sanitation aspect, there is a wide variety of active substances that can be
608 used and that are characterized by different chemical structure, mode of action,
609 physicochemical properties and interactions with the environment. Moreover, each active
610 substance can be found in a variety of commercial disinfectants that differ in their
611 formulation. An effective disinfectant should be broad spectrum (i.e. eliminating Gram-
612 positive and –negative bacteria as well as yeast and molds), act quickly, active even in the
613 presence of organic load, non-aggressive on the treated surface, safe for the environment, the
614 operator, the consumer and should not form by-products (Stanga, 2010). On one hand, the
615 efficacy of a disinfectant can be improved by modifying the physico-chemical properties of
616 the disinfectant solution or by adding co-formulants that are not always disclosed by
617 manufacturers (Okull et al., 2006; Dao, 2008; Pereira et al., 2013; Wen et al., 2017). On the
618 other hand, presence of soiling substances significantly decreases the efficacy of disinfectants.
619 The effectiveness of disinfectants generally increases at higher concentrations. Stefanello et
620 *al.*, (2020) reported that the lowest concentration specified in various sanitizers label was
621 ineffective in most cases (94%), thus suggesting that the greatest concentrations should be
622 preferred. However, increasing disinfectant concentrations is synonymous for a greater
623 consumption of product at an increased cost and leads to more time and water are necessary to
624 rinse the disinfectant. Then, some biocides, such as chlorine compounds, release by-products
625 (e.g. chloramines) that can have impacts on the consumer health and the environment. In this
626 context, although efficient, potentially deleterious substances should be substituted for more
627 health and environmentally friendly products, provided that these disinfectants are fungicidal
628 enough.

629 Although *A. brasiliensis* (ATCC 10231) is the standard strain for assessing antifungal
630 efficiency of sanitizers, the European Standards suggested to extend these assessments to
631 other species. This review suggested not to use *C. cladosporioides* as an additional species
632 because this species was found to be very sensitive to many disinfectants. Disinfectants
633 should be tested against microorganisms present in each industry and veterinary/medicine
634 places, and selected according to their ability to inactivate the most resistant species. The
635 choice of the sanitizer is not easy, because disinfectant molecules perform differently not only
636 depending on the considered species but also on the considered isolate within the same
637 species; therefore, intraspecific resistance heterogeneity should also be taken into
638 consideration. Real contaminations are due to highly hydrophobic airborne conidia. For this
639 reason, liquid sanitizers contain non-ionic surfactant to speed-up the action of the fungicidal
640 molecules. However, airborne conidia remain dry, whereas conidia used in standard assays
641 are wet in spore suspensions. As demonstrated, hydration has a significant effect on the
642 physiological state of fungal spores and their susceptibility to disinfectant, therefore this
643 aspect should also be taken into consideration. Overall, the choice of a multi-target efficient
644 disinfectant is not an easy task as numerous abiotic and biotic factors can impact its efficacy.
645

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Table 1: European standards for fungicidal assessment of disinfectants

European Standard	Year	Areas	Method	Interfering substances	Experimental conditions	Required log reduction
EN 1275	2006	Not stated	Suspension test	none	20°C/15 min	≥ 4
EN 1650	2019	Food, industrial, domestic and institutional	Suspension test	Bovin serum albumin / skimmed milk	4-40°C/1-60 min	≥ 4
EN 13624	2019	Medical	Suspension test	Bovin serum albumin / sheep erythrocytes	4-30°C/5-60 min	≥ 4
EN 13697/+A1	2019	Food, industrial, domestic and institutional	Carrier test	Bovin serum albumin / skimmed milk	4-40°C/1-60 min	≥ 3
EN 17272	2020	Medical, veterinary, food, industrial, domestic and institutional	Airborne room disinfection by automated process	Bovin serum albumin / skimmed milk / erythrocytes/ yeast extract	20°C/≤ 15h /50-75% RH	≥ 4

Table 2: Concentrations of some sanitizers approved in the Canada and the US for use on food contact surfaces.

Compounds	Utilisation range	Recommended concentrations	Reference	Country
Hypochlorites	50-500 ppm	200 ppm (non porous) 800 ppm (porous)	Gaulin *et al.* 2011	Canada
		200 ppm	Rasin, 2021	US
Chlorine dioxide		100 ppm	Rasin, 2021	US
Iodophors	6.5-75 ppm		Gaulin *et al.* 2011	Canada
		25 ppm	Rasin, 2021	US
Peracetic acid	50-350 ppm	150-200 ppm	Gaulin *et al.* 2011	Canada
		100-200 ppm	Rasin, 2021	US
Hydrogen peroxide	Powder in 3 and 6%		Gaulin *et al.* 2011	Canada
		80-600 ppm	Rasin, 2021	US
Quaternary ammonium	200-1000 ppm	200 ppm	Gaulin *et al.* 2011	Canada
	100-400 ppm	200 ppm	Rasin, 2021	US

Table 3: Fungicidal effect of disinfectants on different mold species, concentration used and application conditions.

Organism	Disinfectant	Concentration	Application conditions	Fungicidal effect	Reference
Absidia corymbifera	Hydrogen peroxide	Up to 50% (m/v)	Liquid / 15 min 20°C	3 log (12.5%)	Martin and Maris, 2012
Alternaria alternata	Sodium hypochlorite	2.4%	Spray on surface / 5-10 min	3.5-3.6 log (5 min)	Reynolds *et al.*, 2012
Aspergillus australensis	Benzalkonium chloride	0.3-2%	Surface / 15 min	2.0-4.9 log	Stefanello *et al.*, 2020
	Biguanide	2-5%	Surface / 15 min	1.0-2.9 log	
	Iodine	0.2-1%	Surface / 15 min	1->5 log	
	Peracetic acid	0.3-1%	Surface / 15 min	3-3.9 log	
	Sodium hypochlorite	0.5-1%	Surface / 15 min	2-3.9 log	
	Ortho-phenylphenol	15% 1g/m^3	Fumigation / 7h	2-2.9 log	
Aspergillus aureoluteus	Benzalkonium chloride	0.3-2%	Surface / 15 min	2-2.9 log	Stefanello *et al.*, 2020
	Biguanide	2-5%	Surface / 15 min	1-1.9 log	
	Iodine	0.2-1%	Surface / 15 min	2-4.9 log	
	Peracetic acid	0.3-1%	Surface / 15 min	1-1.9 log	
	Sodium hypochlorite	0.5-1%	Surface / 15 min	1-1.9 log	
	Ortho-phenylphenol	15% 1g/m^3	Fumigation / 7h	3-3.9 log	
Aspergillus brasiliensis	Benzalkonium chloride	0.3-5% 0.3-2%	Liquid / 15 min Liquid / 5 – 15 min	1-3.9 log 1.58-4.67 log	Bernardi *et al.*, 2018 Stefanello *et al.* 2021
	Biguanide hexamethylene	2-5%	Liquid / 15 min	<1 log	Bernardi *et al.,* 2018
	Peracetic acid	0.15-3% 0.3-1%	Liquid 15 min Liquid 5 – 15 min	1-3.9 log 0.94-5.67 log	Bernardi *et al.,* 2018 Stefanello *et al.* 2021
	Quaternary ammonium	0.3-5%	Liquid 15 min	<1-2.9 log	Bernardi *et al.* 2018
	Sodium hypochlorite	0.1-1% 0.5-1%	Liquid 15 min Liquid 5 -15 min	3->4 log 1.10-2.67 log	Bernardi *et al.* 2018 Stefanello *et al.* 2021
	Iodine	0.2-1%	Liquid 5 – 15 min	1.17-3.50 log	Stefanello *et al.* 2021
	Peracetic acid	0.1%	Surface / 40°C	4 log (20-60 s)	Scaramuzza *et al.* 2020

Aspergillus carbonarius	Peracetic acid	0.3-1%	Surface / 15 min	2->5 log	Gonçalves Lemos *et al.*, 2020
	Biguanide	2-5%	Surface / 15 min	1-2.9 log	
	Benzalkonium chloride	0.3-2%	Surface / 15 min	2-3.9 log	
	Iodine	0.2-1%	Surface / 15 min	1- 4.9 log	
	Sodium hypochlorite	0.5-1%	Surface / 15 min	1-1.9 log	
Aspergillus fischeri	Chlorine dioxide	50-1000 ppm	Liquid / 5-60 min	>5 log (500 ppm/5 min)	Dijksterhuis *et al.*, 2018
Aspergillus flavus	Sodium hypochlorite	0.2-0.8%	Surface / 2-8 min	<4.2 log (0.2-0.8%/2 min and 0.4%/ 2-8 min)	Andrews, 1996
	Benzalkonium chloride	0.0125-0.4%	Liquid / 72h	>2.7 log (0.0125-0.2%)	Mattei *et al.*, 2013
	Sodium hypochlorite	0.1-1.6%		>2.7 log (0.4-1.6%)	
	Quaternary ammonium	1.5, 2%	Liquid / 10 min 20°C	2->5.2 log	Bundgaard and Nielsen, 1995
	Quaternary ammonium + aldehydes	2%	Liquid / 10 min 20°C	>5.2 log	
	Ethanol	70%	Liquid / 10 min 20°C	4 log	
	Isopropanol	70%	Liquid / 10 min 20°C	4 log	
	Sodium dichloroisocyanuric acid	0.37 $g.L^{-1}$	Liquid / 10 min 20°C	4.3 log	
	Chlorine dioxide	5%	Liquid / 10 min 20°C	4 log	
	Sodium hypochlorite	3%	Liquid / 10 min 20°C	4.3 log	
	Peracetic acid	0.3-1%	Surface / 15 min	1-2.9 log	Gonçalves Lemos *et al.*, 2020
	Biguanide	2-5%	Surface / 15 min	<1-1.9 log	
	Benzalkonium chloride	0.3-2%	Surface / 15 min	2-4.9 log	
	Iodine	0.2-1%	Surface / 15 min	1->5 log	
	Sodium hypochlorite	0.5-1%	Surface / 15 min	1-1.9 log	
Aspergillus fumigatus	Benzalconium chloride	0.0125-0.4%	Liquid / 72h	>2.7 log (0.0125-0.05%)	Mattei *et al.,* 2013

	Chlorophenol derivative	0.0175-0.6%		>2.7 log (0.075-0.3%)	
	Sodium hypochlorite	0.1-1.6%		>2.7 log (0.4-0.8%)	
	Free chlorine	48.99-194.7 mg.min.L^{-1}	Liquid pH 7; 22.5°C	4 log (60.43-77.33 mg.min.l^{-1})	Ma and Bibby, 2017
	Monochloramine	90.33-531.3 mg.min.L^{-1}	Liquid pH 8; 22.5°C	4 log (120-136.7 mg.min.l^{-1})	
	Sodium hypochlorite	1-3 mg.L^{-1} free chlorine	Liquid pH 7; 25°C	2 log (946 mg.min.l^{-1})	Pereira *et al.*, 2013
Aspergillus hiratsukae	Peracetic acid	0.1%	Surface / 40°C	4 log (175-300 s)	Scaramuzza *et al.* 2020
Aspergillus niger	Benzalconium chloride	0.0125-0.4%		>2.7 log (0.025%)	Mattei *et al.,*2013
	Chlorophenol derivative	0.0175-0.6%		>2.7 log (0.15-0.30%)	
	Sodium hypochlorite	0.1-1.6%		>2.7 log (0.4%)	
	Sodium hypochlorite	100-1300 mg.l^{-1}	Liquid / 1-30 min pH 6.3 ; 9, 20°C	4 log (700-1300 mg.l^{-1}/1.1-28.8 min)	Frison *et al.*, 2015a
	Peracetic acid	750-6000 mg.l^{-1}			
	Sodium hypochlorite	2.4%	Spray on surface / 5-10 min	4.1-5.3 log (5 min)	Reynolds *et al.*, 2012
	Isopropyl alcohol	Un-diluted	Liquid / 1-60 min	6 log (10-25 min)	Korukluoglu *et al.*, 2006
	Peracetic acid	0.1, 0.3%	Liquid / 1-60 min	6 log (0.3% / ≥ 55 min)	
	Iodine	0.5, 1%	Liquid / 1-60 min	6 log (1% / 12-49 min)	
	Formaldehyde	0.2 ; 0.5%	Liquid / 1-60 min	6 log (2-15 min)	
	Quaternary ammonium compounds	0.5-2%	Liquid / 1-60 min	6 log (1% / <2->51 min)	
	Chlorine	0.5-2%	Liquid / 1-60 min	6 log (0.5% / <1-3 min)	
	Quaternary ammonium	1.5, 2%	Liquid / 10 min 20°C	2.7->5.2 log	Bundgaard and Nielsen, 1995
	Quaternary ammonium + aldehydes	2%	Liquid / 10 min 20°C	>5.2 log	
	Ethanol	70%	Liquid / 10 min 20°C	>5.2 log	
	Isopropanol	70%	Liquid / 10 min	>5.2 log	

			20°C		
	Sodium dichloroisocyanuric acid	0.37 $g.l^{-1}$	Liquid / 10 min 20°C	2 log	
	Chlorine dioxide	5%	Liquid / 10 min 20°C	>5.2 log	
	Sodium hypochlorite	3%	Liquid / 10 min 20°C	>5.2 log	
	Peracetic acid	0.3-1%	Surface / 15 min	1-1.9 log	Gonçalves Lemos *et al.*, 2020
	Biguanide	2-5%	Surface / 15 min	1-1.9 log	
	Benzalkonium chloride	0.3-2%	Surface / 15 min	2-3.9 log	
	Iodine	0.2-1%	Surface / 15 min	1-3.9 log	
	Sodium hypochlorite	0.5-1%	Surface / 15 min	1-2.9 log	
Aspergillus nomius	Peracetic acid	0.3-1%	Surface / 15 min	1-1.9 log	Gonçalves Lemos *et al.*, 2020
	Biguanide	2-5%	Surface / 15 min	1-1.9 log	
	Benzalkonium chloride	0.3-2%	Surface / 15 min	2-3.9 log	
	Iodine	0.2-1%	Surface / 15 min	1-4.9 log	
	Sodium hypochlorite	0.5-1%	Surface / 15 min	1-2.9 log	
Aspergillus ochraceus	Chlorine	1%	Liquid / 0.25-24h	>6.5 log	Gupta *et al.*, 2002
	Peracetic acid	0.3-1%	Surface / 15 min	>5 log	Gonçalves Lemos *et al.*, 2020
	Biguanide	2-5%	Surface / 15 min	1-1.9 log	
	Benzalkonium chloride	0.3-2%	Surface / 15 min	2-3.9 log	
	Iodine	0.2-1%	Surface / 15 min	2->5 log	
	Sodium hypochlorite	0.5-1%	Surface / 15 min	1-2.9 log	
Aspergillus parasiticus	Sodium hypochlorite	0.2-0.8%	Surface / 2-8 min	<4.1 (0.2-0.8%/2 min and 0.4%/ 2-8 min)	Andrews, 1996
	Peracetic acid	0.3-1%	Surface / 15 min	>1-1.9 log	Gonçalves Lemos *et al.*, 2020
	Biguanide	2-5%	Surface / 15 min	>1-1.9 log	

	Benzalkonium chloride	0.3-2%	Surface / 15 min	1->5 log	
	Iodine	0.2-1%	Surface / 15 min	<1-3.9 log	
	Sodium hypochlorite	0.5-1%	Surface / 15 min	<1-1.9 log	
Aspergillus pseudoglaucus	Benzalkonium chloride	0.3-5%	Liquid / 15 min Surface / 15 min / 20°C	1.10-1.56 log 0.1-1.9 log	Bernardi *et al.*, 2019 Bernardi *et al.*, 2021
	Biguanide	2-5% 0.3-5%	Liquid / 15 min Surface / 15 min / 20°C	1.01-2.02 log 1-1.9 log	Bernardi *et al.*, 2019 Bernardi *et al.*, 2021
	Peracetic acid	0.15-3%	Liquid / 15 min Surface / 15 min / 20°C	0-3.36 log 1-2.9 log	Bernardi *et al.*, 2019 Bernardi *et al.*, 2021
	Quaternary ammonium	0.3-5%	Liquid / 15 min	1.12-1.79 log	Bernardi *et al.*, 2019
	Sodium hypochlorite	0.01-0.2% 0.01-1%	Liquid / 15 min Surface / 15 min / 20°C	0-1.50 log 0.9-1.9 log	Bernardi *et al.*, 2019 Bernardi *et al.*, 2021
	Ortho-phenylphenol	1g/m^3	Fumigation	0 log	Bernardi *et al.*, 2021
Aspergillus terreus	Sodium hypochlorite	1-3 mg.l^{-1} free chlorine	Liquid pH 7; 25°C	2 log (1404 mg.min.l^{-1})	Pereira *et al.*, 2013
Aspergillus versicolor	Free chlorine	48.99-194.7 mg.min.l^{-1}	Liquid pH 7; 22.5°C	4 log (112.1 mg.min.l^{-1})	Ma and Bibby, 2017
	Monochloramine	90.33-531.3 mg.min.l^{-1}	Liquid pH 8; 22.5°C	4 log (707.8 mg.min.l^{-1})	
	Quaternary ammonium	1.5, 2%	Liquid / 10 min 20°C	1.2-4 log	Bundgaard and Nielsen, 1995
	Quaternary ammonium + aldehydes	2%	Liquid / 10 min 20°C	2-3 log	
	Ethanol	70%	Liquid / 10 min 20°C	3.3->5.2 log	
	Isopropanol	70%	Liquid / 10 min 20°C	3.3->5.2 log	
	Sodium dichloroisocyanuric acid	0.37 g.l^{-1}	Liquid / 10 min 20°C	>4.5 log	
	Chlorine dioxide	5%	Liquid / 10 min 20°C	3-3.3 log	
	Sodium hypochlorite	3%	Liquid / 10 min	>4.5 log	

			20°C		
	Hydrogen peroxide	Up to 50% (m/v)	Liquid / 15 min 20°C	3 log (1.56%)	Martin and Maris, 2012
Aspergillus westerdijkiae	Benzalkonium chloride	0.3-5%	Surface / 15 min / 20°C	0.1-1.9 log	Bernardi et al., 2021
	Biguanide	0.3-5%	Surface / 15 min / 20°C	0.1-0.9 log	
	Peracetic acid	0.15-3%	Surface / 15 min / 20°C	0.1-2.9 log	
	Sodium hypochlorite	0.01-1%	Surface / 15 min / 20°C	0->5 log	
	Ortho-phenylphenol	$1g/m^3$	Fumigation	2-3.9 log	
	Peracetic acid	0.3-1%	Surface / 15 min	1->5 log	Gonçalves Lemos *et al.*, 2020
	Biguanide	2-5%	Surface / 15 min	1-1.9 log	
	Benzalkonium chloride	0.3-2%	Surface / 15 min	2-4.9 log	
	Iodine	0.2-1%	Surface / 15 min	1->5 log	
	Sodium hypochlorite	0.5-1%	Surface / 15 min	1-3.9 log	
Chaetomium globosum	Peracetic acid	0.1%	Surface / 40°C	4 log (1-3h)	Scaramuzza *et al.* 2020
Cladosporium cladosporioides	Benzalkonium chloride	2-5%	Liquid / 15 min	2->4 log	Bernardi *et al.*, 2018
	Biguanide hexamethylene	2-5%		<1 log	
	Peracetic acid	0.15-3%		1->4 log	
	Quaternary ammonium	0.3-5%		1->4 log	
	Sodium hypochlorite	0.1-1%		>4 log	
	Sodium hypochlorite	1-3 $mg.L^{-1}$ free chlorine	Liquid pH 7; 25°C	2 log (139 $mg.min.l^{-1}$)	Pereira *et al.*, 2013
Cladosporium herbarum	Sodium hypochlorite	2.4%	Spray on surface / 5-10 min	4.1 log (5 min)	Reynolds *et al.*, 2012
Cladosporium tenuissimum	Sodium hypochlorite	1-3 $mg.l^{-1}$ free chlorine	Liquid pH 7; 25°C	2 log (71 $mg.min.l^{-1}$)	Pereira *et al.*, 2013
Cladosporium sp.	Chlorine dioxide	0.5-3 $mg.l^{-1}$	Liquid	1 log (1 $mg.min.l^{-1}$)	Wen *et al.*, 2017

			pH 6, 7/10, 27°C		
	Quaternary ammonium	1.5, 2%	Liquid / 10 min 20°C	2.9->4.1 log	Bundgaard and Nielsen, 1995
	Quaternary ammonium + aldehydes	2%	Liquid / 10 min 20°C	>4.1 log	
	Ethanol	70%	Liquid / 10 min 20°C	>4.1 log	
	Isopropanol	70%	Liquid / 10 min 20°C	>4.1 log	
	Sodium dichloroisocyanuric acid	0.37 $g.l^{-1}$	Liquid / 10 min 20°C	2.9 log	
	Chlorine dioxide	5%	Liquid / 10 min 20°C	>4.1 log	
	Sodium hypochlorite	3%	Liquid / 10 min 20°C	>4.1 log	
Dothiorella gregaria	Chlorine dioxide	3-7 $mg.l^{-1}$	Surface / 1-15 min	1.5-5 log (15 min)	Chen and Zhu, 2011
Eurotium repens (=*A. pseudoglaucus*)	Quaternary ammonium	1.5, 2%	Liquid / 10 min 20°C	3.3->4.5 log	Bundgaard and Nielsen, 1995
	Quaternary ammonium + aldehydes	2%	Liquid / 10 min 20°C	3.3 log	
	Ethanol	70%	Liquid / 10 min 20°C	3 log	
	Isopropanol	70%	Liquid / 10 min 20°C	2.3 log	
	Sodium dichloroisocyanuric acid	0.37 $g.l^{-1}$	Liquid / 10 min 20°C	0.3 log	
	Chlorine dioxide	5%	Liquid / 10 min 20°C	>4.5 log	
	Sodium hypochlorite	3%	Liquid / 10 min 20°C	>4.5 log	
Fusarium tricinctum	Chlorine dioxide	3-7 $mg.l^{-1}$	Surface / 1-15 min	1.4-4.5 log (15 min)	Chen and Zhu, 2011

Geotrichum candidum	Hydrogen peroxide	Up to 50% (m/v)	Liquid / 15 min 20°C	3 log (0.39%)	Martin and Maris, 2012
Hyphopichia burtonii	Benzalkonium chloride	0.3-5%	Liquid / 15 min	0-3.19 log	Bernardi *et al.*, 2019
	Biguanide	2-5%	Liquid / 15 min	0.84-0.98 log	
	Peracetic acid	0.15-3%	Liquid / 15 min	0-5.67 log	
	Quaternary ammonium	0.3-5%	Liquid / 15 min	0-2.35 log	
	Sodium hypochlorite	0.01-0.2%	Liquid / 15 min	0-1.89 log	
Monascus ruber	Quaternary ammonium	1.5, 2%	Liquid / 10 min 20°C	2.9->4.1 log	Bundgaard and Nielsen, 1995
	Quaternary ammonium + aldehydes	2%	Liquid / 10 min 20°C	>4.1 log	
	Ethanol	70%	Liquid / 10 min 20°C	1.3 log	
	Isopropanol	70%	Liquid / 10 min 20°C	0.9 log	
	Sodium dichloroisocyanuric acid	0.37 $g.l^{-1}$	Liquid / 10 min 20°C	1.6 log	
	Chlorine dioxide	5%	Liquid / 10 min 20°C	>4.1 log	
	Sodium hypochlorite	3%	Liquid / 10 min 20°C	2.9 log	
Mucor bainieri	Sodium hypochlorite	2.4%	Spray on surface / 5-10 min	5.2-5.3 log (5 min)	Reynolds *et al.*, 2012
Neosartorya pseudofischeri	Quaternary ammonium	1.5, 2%	Liquid / 10 min 20°C	3.3->4.5 log	Bundgaard and Nielsen, 1995
	Quaternary ammonium + aldehydes	2%	Liquid / 10 min 20°C	3.3 log	
	Ethanol	70%	Liquid / 10 min 20°C	4 log	
	Isopropanol	70%	Liquid / 10 min 20°C	3.3 log	
	Sodium dichloroisocyanuric acid	0.37 $g.l^{-1}$	Liquid / 10 min 20°C	3.6 log	

	Chlorine dioxide	5%	Liquid / 10 min 20°C	3.3 log	
	Sodium hypochlorite	3%	Liquid / 10 min 20°C	4 log	
Paecilomyces fulvus	Benzalkonium chloride	0.3-2%	Surface / 15 min	2-3.9 log	Stefanello *et al.*, 2020
	Biguanide	2-5%	Surface / 15 min	2-2.9 log	
	Iodine	0.2-1%	Surface / 15 min	2-4.9 log	
	Peracetic acid	0.3-1%	Surface / 15 min	3->5 log	
	Sodium hypochlorite	0.5-1%	Surface / 15 min	2-3.9 log	
	Ortho-phenylphenol	15% 1g/m^3	Fumigation / 7h	>5 log	
Paecilomyces niveus	Chlorine dioxide	50-1000 ppm	Liquid / 5-60 min	>5 log (500 ppm/5 min)	Dijksterhuis *et al.*, 2018
	Benzalkonium chloride	0.3-2%	Surface / 15 min	2->5 log	Stefanello *et al.*, 2020
	Biguanide	2-5%	Surface / 15 min	2-3.9 log	
	Iodine	0.2-1%	Surface / 15 min	3-4.9 log	
	Peracetic acid	0.3-1%	Surface / 15 min	3->5 log	
	Sodium hypochlorite	0.5-1%	Surface / 15 min	2-3.9 log	
	Ortho-phenylphenol	15% 1g/m^3	Fumigation / 7h	>5 log	
Paecilomyces variotii	Chlorine dioxide	50-1000 ppm	Liquid / 5-60 min	>5 log (500 ppm/5 min)	Dijksterhuis *et al.*, 2018
	Benzalkonium chloride	0.3-2%	Surface / 15 min	1-3.9 log	Stefanello *et al.*, 2020
	Biguanide	2-5%	Surface / 15 min	1-1.9 log	
	Iodine	0.2-1%	Surface / 15 min	1->5 log	
	Peracetic acid	0.3-1%	Surface / 15 min	1->5 log	
	Sodium hypochlorite	0.5-1%	Surface / 15 min	1-1.9 log	
	Ortho-phenylphenol	15% 1g/m^3	Fumigation / 7h	>5 log	
Penicillium bialowiezense	Sodium hypochlorite	500 ppm free chlorine	Surface 7°C	2.6 log (5 min)	Nierop Groot *et al.*, 2019
	Chlorine dioxide	500 ppm free chlorine	Surface 7°C	>5 log (5 min)	
Penicillium buchwaldii	Sodium hypochlorite	500 ppm free chlorine	Surface 7°C	0.9 log (5 min)	Nierop Groot *et al.*, 2019
	Chlorine dioxide	500 ppm free	Surface	>5 log (5 min)	

		chlorine	7°C		
Penicillium brevicompactum	Sodium hypochlorite	1-10%	Surface / 1-30 min	>7.3 log (30 min)	Ebling, 2007
Penicillium caseifulvum	Quaternary ammonium	1.5, 2%	Liquid / 10 min 20°C	2.7->4.9 log	Bundgaard and Nielsen, 1995
	Quaternary ammonium + aldehydes	2%	Liquid / 10 min 20°C	2.7 log	
	Ethanol	70%	Liquid / 10 min 20°C	2.7 log	
	Isopropanol	70%	Liquid / 10 min 20°C	2.7 log	
	Sodium dichloroisocyanuric acid	0.37 $g.l^{-1}$	Liquid / 10 min 20°C	1.9 log	
	Chlorine dioxide	5%	Liquid / 10 min 20°C	2.7 log	
	Sodium hypochlorite	3%	Liquid / 10 min 20°C	>4.9 log	
Penicillium chrysogenum	Ethanol	5-10%	Liquid / 1-4 days 10-30°C 0.7-0.9 a_w	0.36-5.78 log	Dao *et al.*, 2008
	Ethanol	5-10%	Vapour / 1-4 days 10-30°C 0.7-0.9 a_w	0.13-2.47 log	
	Ethanol	0.67 kPa	Vapour/ 48-120 h	4-6.5 log	Dao and Dantigny, 2009
	Ethanol	0.7-7.5 kPa	Vapours / 24 h 25°C	3.1->5 log	Dao *et al.*, 2010
	Sodium hypochlorite	2.4%	Spray on surface / 5-10 min	4.6-5.4 log (5 min)	Reynolds *et al.*, 2012
	Quaternary ammonium	1.5, 2%	Liquid / 10 min 20°C	4->5.2 log	Bundgaard and Nielsen, 1995
	Quaternary ammonium	2%	Liquid / 10 min	4 log	

	+ aldehydes		20°C		
	Ethanol	70%	Liquid / 10 min 20°C	>5.2 log	
	Isopropanol	70%	Liquid / 10 min 20°C	>5.2 log	
	Sodium dichloroisocyanuric acid	0.37 $g.l^{-1}$	Liquid / 10 min 20°C	3.7 log	
	Chlorine dioxide	5%	Liquid / 10 min 20°C	>5.2 log	
	Sodium hypochlorite	3%	Liquid / 10 min 20°C	>5.2 log	
Penicillium citrinum	Sodium hypochlorite	1-3 $mg.l^{-1}$ free chlorine	Liquid pH 7; 25°C	2 log (959 $mg.min.l^{-1}$)	Pereira *et al.*, 2013
Penicillium cyclopium	Hydrogen peroxide	Up to 50% (m/v)	Liquid / 15 min 20°C	3 log (1.56%)	Martin and Maris, 2012
Penicillium commune	Benzalkonium chloride	0.3-5%	Liquid / 15 min	1-2.9 log	Bernardi *et al.*, 2018
	Biguanide hexamethylene	2-5%		1-1.9 log	
	Peracetic acid	0.15-3%		2->4 log	
	Quaternary ammonium	0.3-5%		2->4 log	
	Sodium hypochlorite	0.1-1%		2->4 log	
	Benzalkonium chloride	0.3-5%	Surface / 15 min / 20°C	0.1-4 log	Bernardi *et al.,* 2021
	Biguanide	0.3-5%	Surface / 15 min / 20°C	0-2 log	
	Peracetic acid	0.15-3%	Surface / 15 min / 20°C	0.1->5 log	
	Sodium hypochlorite	0.01-1%	Surface / 15 min / 20°C	0.1->5 log	
	Ortho-phenylphenol	$1g/m^3$	Fumigation	0-0.9 log	
	Quaternary ammonium	1.5, 2%	Liquid / 10 min 20°C	2.7-4.3 log	Bundgaard and Nielsen, 1995
	Quaternary ammonium + aldehydes	2%	Liquid / 10 min 20°C	2.7-4.3 log	
	Ethanol	70%	Liquid / 10 min	2.9-4 log	

			20°C		
	Isopropanol	70%	Liquid / 10 min 20°C	2.7-4 log	
	Sodium dichloroisocyanuric acid	0.37 $g.l^{-1}$	Liquid / 10 min 20°C	1.7-4 log	
	Chlorine dioxide	5%	Liquid / 10 min 20°C	4.3->5.2 log	
	Sodium hypochlorite	3%	Liquid / 10 min 20°C	1.7-4 log	
	Ethanol	70%	Liquid / 1-5 min	2.35-5.4 log	Visconti *et al.*, 2020
Penicillium coryphilum	Quaternary ammonium	1.5, 2%	Liquid / 10 min 20°C	3.7->4.8 log	Bundgaard and Nielsen, 1995
	Quaternary ammonium + aldehydes	2%	Liquid / 10 min 20°C	>4.8 log	
	Ethanol	70%	Liquid / 10 min 20°C	4.6 log	
	Isopropanol	70%	Liquid / 10 min 20°C	>4.8 log	
	Sodium dichloroisocyanuric acid	0.37 $g.l^{-1}$	Liquid / 10 min 20°C	4.4 log	
	Chlorine dioxide	5%	Liquid / 10 min 20°C	>4.8 log	
	Sodium hypochlorite	3%	Liquid / 10 min 20°C	>4.8 log	
Penicillium crustosum	Quaternary ammonium	1.5, 2%	Liquid / 10 min 20°C	4->5.2 log	Bundgaard and Nielsen, 1995
	Quaternary ammonium + aldehydes	2%	Liquid / 10 min 20°C	>4.2 log	
	Ethanol	70%	Liquid / 10 min 20°C	4 log	
	Isopropanol	70%	Liquid / 10 min 20°C	4 log	

	Sodium dichloroisocyanuric acid	0.37 $g.l^{-1}$	Liquid / 10 min 20°C	2.3 log	
	Chlorine dioxide	5%	Liquid / 10 min 20°C	4 log	
	Sodium hypochlorite	3%	Liquid / 10 min 20°C	>5.2 log	
Penicillium digitatum	Ethanol	5-10%	Liquid / 1-4 days 10-30°C 0.7-0.9 a_w	0.76-3.19 log	Dao *et al.*, 2008
	Ethanol	5-10%	Vapour / 1-4 days 10-30°C 0.7-0.9 a_w	2.15-3.95 log	
	Ethanol	0.67 kPa	Vapour/ 48-120 h	4-5 log	Dao and Dantigny, 2009
	Ethanol	0.7-7.5 kPa	Vapours / 24 h 25°C	4.2->5 log	Dao *et al.*, 2010
Penicillium discolor	Quaternary ammonium	1.5, 2%	Liquid / 10 min 20°C	3 log	Bundgaard and Nielsen, 1995
	Quaternary ammonium + aldehydes	2%	Liquid / 10 min 20°C	3 log	
	Ethanol	70%	Liquid / 10 min 20°C	3 log	
	Isopropanol	70%	Liquid / 10 min 20°C	3 log	
	Sodium dichloroisocyanuric acid	0.37 $g.l^{-1}$	Liquid / 10 min 20°C	1.9 log	
	Chlorine dioxide	5%	Liquid / 10 min 20°C	3 log	
	Sodium hypochlorite	3%	Liquid / 10 min 20°C	>4.2 log	
Penicillium	Sodium hypochlorite	50 ppm free	Liquid / 0.5-5 min	0.2-1.9 log	Okull *et al.*, 2006

expansum		chlorine	pH 6.3, 8.5		
	Chlorine dioxyde	3 ppm free chlorine	Liquid / 0.5-5 min pH 3.7	1.4-4 log	
	Sodium hypochlorite	500 ppm free chlorine	Surface 7°C	0.7 log (5 min)	Nierop Groot *et al.*, 2019
	Chlorine dioxide	500 ppm free chlorine	Surface 7°C	>5 log (5 min)	
	Sodium dichloroisocyanurate-based sanitizer	25-75 ppm free chlorine	Liquid / 1-6 min	3.5-6 log (2 min)	Salamão *et al.*, 2009
Penicillium griseofulvum	Sodium hypochlorite	1-3 $mg.l^{-1}$ free chlorine	Liquid pH 7; 25°C	2 log (107 $mg.min.l^{-1}$)	Pereira *et al.*, 2013
Penicillium italicum	Ethanol	5-10%	Liquid / 1-4 days 10-30°C 0.7-0.9 a_w	0.44-3.65 log	Dao *et al.*, 2008
	Ethanol	5-10%	Vapour / 1-4 days 10-30°C 0.7-0.9 a_w	1.66-4.38 log	
	Ethanol	0.67 kPa	Vapour/ 48-120 h	4-5 log	Dao and Dantigny, 2009
	Ethanol	0.7-7.5 kPa	Vapours / 24 h 25°C	4.1->5 log	Dao *et al.*, 2010
Penicillium nalgiovense	Quaternary ammonium	1.5, 2%	Liquid / 10 min 20°C	2->4.2 log	Bundgaard and Nielsen, 1995
	Quaternary ammonium + aldehydes	2%	Liquid / 10 min 20°C	2.3->4.2 log	
	Ethanol	70%	Liquid / 10 min 20°C	2.3-3 log	
	Isopropanol	70%	Liquid / 10 min 20°C	2.3-3 log	
	Sodium dichloroisocyanuric acid	0.37 $g.l^{-1}$	Liquid / 10 min 20°C	1.7->4.2 log	

	Chlorine dioxide	5%	Liquid / 10 min 20°C	3.3->4.2 log	
	Sodium hypochlorite	3%	Liquid / 10 min 20°C	>4.2 log	
Penicillium paneum	Benzalkonium chloride	0.3-5%	Liquid / 15 min	1.39-3.96 log	Bernardi *et al.*, 2019
	Biguanide	2-5%	Liquid / 15 min	0 log	
	Peracetic acid	0.15-3%	Liquid / 15 min	0-5.75 log	
	Quaternary ammonium	0.3-5%	Liquid / 15 min	0.96-3.19 log	
	Sodium hypochlorite	0.01-0.2%	Liquid / 15 min	0-2.30 log	
Penicillium polonicum	Benzalkonium chloride	0.3-5%	Liquid / 15 min	1-3.9 log	Bernardi *et al.*, 2018
	Biguanide hexamethylene	2-5%		1-1.9 log	
	Peracetic acid	0.15-3%		1->4 log	
	Quaternary ammonium	0.3-5%		1->4 log	
	Sodium hypochlorite	0.1-1.5%		2->4 log	
	Benzalkonium chloride	0.3-5%	Surface / 15 min / 20°C	0.1-1.9 log	Bernardi *et al.,* 2021
	Biguanide	0.3-5%	Surface / 15 min / 20°C	0-0.9 log	
	Peracetic acid	0.15-3%	Surface / 15 min / 20°C	0-1.9 log	
	Sodium hypochlorite	0.01-1%	Surface / 15 min / 20°C	0-3.9 log	
	Ortho-phenylphenol	$1g/m^3$	Fumigation	0.1-0.9 log	
Penicillium purpurogenum	Free chlorine	48.99-194.7 $mg.min.l^{-1}$	Liquid pH 7; 22.5°C	4 log (258.9 $mg.min.l^{-1}$)	Ma and Bibby, 2017
	Monochloramine	90.33-531.3 $mg.min.l^{-1}$	Liquid pH 8, 22.5°C	4 log (200.6 $mg.min.l^{-1}$)	
Penicillium roqueforti	Benzalkonium chloride	0.3-5%	Liquid / 15 min	1-3.9 log	Bernardi *et al.*, 2018
	Biguanide hexamethylene	2-5%		1-1.9 log	
	Peracetic acid	0.15-3%		1->4 log	

	Quaternary ammonium	0.3-5%		2-2.9 log	
	Sodium hypochlorite	0.1-1%		2->4 log	
	Benzalkonium chloride	0.3-5%	Liquid / 15 min	0.96-4.19 log	Bernardi *et al.*, 2019
	Biguanide	2-5%	Liquid / 15 min	0.91-1.04 log	
	Peracetic acid	0.15-3%	Liquid / 15 min	2.90-5.66 log	
	Quaternary ammonium	0.3-5%	Liquid / 15 min	1.22-3.83 log	
	Sodium hypochlorite	0.01-0.2%	Liquid / 15 min	0.06-2.28 log	
	Benzalkonium chloride	0.3-5%	Surface / 15 min / 20°C	0.1-1.9 log	Bernardi *et al.,* 2021
	Biguanide	0.3-5%	Surface / 15 min / 20°C	0.1-2.9 log	
	Peracetic acid	0.15-3%	Surface / 15 min / 20°C	0.1->5 log	
	Sodium hypochlorite	0.01-1%	Surface / 15 min / 20°C	0.1->5 log	
	Ortho-phenylphenol	$1g/m^3$	Fumigation	0.1-0.9 log	
	Isopropyl alcohol	Un-diluted	Liquid / 1-60 min	6 log (<2-8 min)	Korukluoglu *et al.*, 2006
	Peracetic acid	0.1, 0.3%	Liquid / 1-60 min	6 log (0.3% / ≥ 55 min)	
	Iodine	0.5, 1%	Liquid / 1-60 min	6 log (1% / 5-16 min)	
	Formaldehyde	0.2 ; 0.5%	Liquid / 1-60 min	6 log (1-25 min)	
	Quaternary ammonium compounds	0.5-2%	Liquid / 1-60 min	6 log (1% / <1-21 min)	
	Chlorine	0.5-2%	Liquid / 1-60 min	6 log (0.5% / <1- min)	
	Quaternary ammonium	1.5, 2%	Liquid / 10 min 20°C	1-4 log	Bundgaard and Nielsen, 1995
	Quaternary ammonium + aldehydes	2%	Liquid / 10 min 20°C	1.7-4 log	
	Ethanol	70%	Liquid / 10 min 20°C	3.4-3.6 log	
	Isopropanol	70%	Liquid / 10 min 20°C	3.5->5.2 log	
	Sodium dichloroisocyanuric acid	$0.37\ g.l^{-1}$	Liquid / 10 min 20°C	0.9-2.7 log	
	Chlorine dioxide	5%	Liquid / 10 min	3.5-4 log	

			20°C		
	Sodium hypochlorite	3%	Liquid / 10 min 20°C	>5.2 log	
	Peracetic acid	0.3%	Liquid / 10 min 20°C	0.3 log	
	Hydrogen peroxide	3%	Liquid / 10 min 20°C	0.3 log	
Penicillium solitum	Quaternary ammonium	1.5, 2%	Liquid / 10 min 20°C	3.7->4.8 log	Bundgaard and Nielsen, 1995
	Quaternary ammonium + aldehydes	2%	Liquid / 10 min 20°C	3.7 log	
	Ethanol	70%	Liquid / 10 min 20°C	3.2 log	
	Isopropanol	70%	Liquid / 10 min 20°C	3.7 log	
	Sodium dichloroisocyanuric acid	0.37 $g.l^{-1}$	Liquid / 10 min 20°C	3.7 log	
	Chlorine dioxide	5%	Liquid / 10 min 20°C	3.7 log	
	Sodium hypochlorite	3%	Liquid / 10 min 20°C	>4.8 log	
Penicillium verrucosum	Quaternary ammonium	1.5, 2%	Liquid / 10 min 20°C	2.1->4.2 log	Bundgaard and Nielsen, 1995
	Quaternary ammonium + aldehydes	2%	Liquid / 10 min 20°C	3.1 log	
	Ethanol	70%	Liquid / 10 min 20°C	3.1 log	
	Isopropanol	70%	Liquid / 10 min 20°C	3.1 log	
	Sodium dichloroisocyanuric acid	0.37 $g.l^{-1}$	Liquid / 10 min 20°C	2.4 log	
	Chlorine dioxide	5%	Liquid / 10 min	3.1 log	

			20°C		
	Sodium hypochlorite	3%	Liquid / 10 min 20°C	>4.2 log	
Penicillium sp	Chlorine dioxide	0.5-3 $mg.l^{-1}$	Liquid pH 6, 7/10, 27°C	5 log (1 $mg.min.l^{-1}$)	Wen *et al.*, 2017
Phoma glomerata	Sodium hypochlorite	1-3 $mg.l^{-1}$ free chlorine	Liquid pH 7; 25°C	2 log (152 $mg.min.l^{-1}$)	Pereira et *al.*, 2013
Scopulariopsis brevicaulis	Quaternary ammonium	1.5, 2%	Liquid / 10 min 20°C	>4.2 log	Bundgaard and Nielsen, 1995
	Quaternary ammonium + aldehydes	2%	Liquid / 10 min 20°C	>4.2 log	
	Ethanol	70%	Liquid / 10 min 20°C	>4.2 log	
	Isopropanol	70%	Liquid / 10 min 20°C	>4.2 log	
	Sodium dichloroisocyanuric acid	0.37 $g.l^{-1}$	Liquid / 10 min 20°C	>4.2 log	
	Chlorine dioxide	5%	Liquid / 10 min 20°C	3 log	
	Sodium hypochlorite	3%	Liquid / 10 min 20°C	>4.2 log	
Stachybotrys chartarum	Sodium hypochlorite	2.4%	Spray on surface / 5-10 min	4.1 log (5 min)	Reynolds *et al.*, 2012
Talaromyces bacillisporus	Peracetic acid	0.1%	Surface / 40°C	4 log (400-1200 s)	Scaramuzza *et al.* 2020
Talaromyces macrosporus	Chlorine dioxide	50-1000 ppm	Liquid / 5-60 min	>5 log (500 ppm/30 min)	Dijksterhuis *et al.*, 2018
Trichoderma sp	Chlorine dioxide	0.5-3 $mg.l^{-1}$	Liquid pH 6, 7/10, 27°C	3 log (1 $mg.min.l^{-1}$)	Wen *et al.*, 2017
Trichophyton mentagrophytes	Sodium hypochlorite	2.4%	Spray on surface / 5-10 min	6.6 log (5 min)	Reynolds *et al.*, 2012