Chicken fillets subjected to UV-C and pulsed UV light: reduction of pathogenic and spoilage bacteria, and changes in sensory quality

Anette McLeod | Kristian Hovde Liland | John-Erik Haugen | Oddvin Sørheim | Kristine S. Myhrer | Askild Holck

Nofima AS – Norwegian Institute of Food, Fisheries and Aquaculture Research. P.O. Box 210, N-1431 Ås, Norway

Correspondence: A. Holck, Nofima AS – Norwegian Institute of Food, Fisheries and Aquaculture Research. P.O. Box 210, N-1431 Ås, Norway. Email: askild.holck@nofima.no

Short title: UV light reducing bacteria on chicken fillets

Keywords: chicken, continuous UV-C light, pulsed UV light, ESBL, modified atmosphere packaging

17 ## Abstract

18 We have compared the efficacy of continuous UV-C (254 nm) and pulsed UV light in reducing
19 the viability of *Salmonella* Enteritidis, *Listeria monocytogenes*, *Staphylococcus aureus*,
20 enterohemorrhagic *Escherichia coli*, *Pseudomonas* spp., *Brochothrix thermospacta,*
21 *Carnobacterium divergens* and Extended-Spectrum β-Lactamase (ESBL) producing *E. coli*
22 inoculated on chicken fillet surface. Fluences from 0.05 to 3.0 J/cm^2 (10 mW/cm^2, from 5 to
23 300 s) used for UV-C light resulted in average reductions from 1.1 to 2.8 log CFU/cm^2. For
24 pulsed UV light, fluences from 1.25 to 18.0 J/cm^2 gave average reductions from 0.9 to 3.0 log
25 CFU/cm^2. A small change in the odour characterized as sunburnt and increased concentration
26 of volatile compounds associated with burnt odour posed restrictions on the upper limit of
27 treatment, however no changes were observed after cooking the meat. Treatments under
28 modified atmosphere conditions using a UV permeable top film gave similar or slightly lower
29 bacterial reductions.

30

31 ## Practical applications

32 UV light may be used for decontaminating the surface of food products and reduce viability of
33 pathogenic and spoilage bacteria. Exposure of raw chicken fillet surface to various doses of
34 continuous UV-C or pulsed UV light proposed in the present work represent alternatives for
35 microbiological improvement of this product. Chicken fillets can be treated in intact packages
36 covered with UV permeable top film, thus avoiding recontamination of the meat. UV-C light
37 treatment is a low cost strategy with low maintenance, whereas pulsed UV light involves more
38 elaborate equipment, but treatment times are short and less space is required. Both methods can
39 be helpful for producers to manage the safety and quality of chicken fillets.

40 **1 | INTRODUCTION**

41 The desired long shelf life in today's food industry has led to increasing demands in the
42 development of methods for improving microbial safety and quality. According to the Food and
43 Agriculture Organization of the United Nations (FAO), the average annual consumption of
44 chicken meat pro capita worldwide increased from 10.2 kg in 1999 to 13.8 kg in 2015 (FAO,
45 2015). The global meat consumption is projected to rise more than 4% per person over the next
46 10 years, and for poultry it is predicted to rise more than 10% (OECD/FAO, 2016). As live
47 poultry animals contain microorganisms on their skin, feathers, and in their digestive tract,
48 contamination of the carcasses during slaughtering procedures can not be completely avoided
49 when live animals are converted to meat for consumption.

50 Food contamination is a major global burden because of foodborne illnesses that can
51 result from it. Poultry may be the vector of *Salmonella* spp., *Campylobacter* spp.,
52 *Staphylococcus aureus, Listeria monocytogenes*, Shiga toxin-producing *Escherichia coli* and
53 other pathogens (Capita, Alonso-Calleja, Garcia-Fernandez, & Moreno, 2002; Hafez, 1999;
54 Zhao, Ge, De Villena, Studler, Yeh, Zhao, White, Wagner, & Meng, 2001). The first two
55 mentioned are the most common causes of human foodborne bacterial diseases linked to poultry
56 (EFSA, 2015; Hafez, 2005). According to the Community Summary Reports of the European
57 Food Safety Authority (EFSA) and the European Centre for Disease Prevention and Control
58 (ECDC), 2008, campylobacteriosis and salmonellosis accounted for 214,779 and 82,694,
59 respectively, confirmed human cases in the EU (EFSA, 2015). The number of confirmed
60 listeriosis cases in humans was 1,763, where a high fatality rate of 15.6% was reported among
61 the cases. Antibiotic-resistant bacteria, such as the Extended-Spectrum Beta-Lactamase
62 (ESBL)-producing *E. coli*, have become a growing public health threat (Briongos-Figuero,
63 Gomez-Traveso, Bachiller-Luque, Dominguez-Gil Gonzalez, Gomez-Nieto, Palacios-Martin,
64 Gonzalez-Sagrado, Duenas-Laita, & Perez-Castrillon, 2012; Lu, Liu, Toh, Lee, Liu, Ho, Huang,
65 Liu, Ko, Wang, Tang, Yu, Chen, Chuang, Xu, Ni, Chen, & Hsueh, 2012; Picozzi, Ricci, Gaeta,
66 Macchi, Dinang, Paola, Tejada, Costa, Bozzini, Casellato, & Carmignani, 2013; Pitout, 2010).
67 The ESBL-producing strains are feared as they produce the enzyme beta-lactamase that has the
68 ability to break down commonly used antibiotics like penicillins and cephalosporins, and render
69 them ineffective for treatment. In 2014, the World Health Organization (WHO) warned that the
70 antibiotic resistance crisis is becoming dire, with diseases that have been curable for decades
71 becoming increasingly difficult to treat (Michael, Dominey-Howes, & Labbate, 2014; WHO,

72 2014). The presence of ESBL genes has been clearly documented in *Enterobacteriaceae*
73 isolated from food-production animals, and especially from chickens (Machado, Coque,
74 Canton, Sousa, & Peixe, 2008; Overdevest, Willemsen, Rijnsburger, Eustace, Xu, Hawkey,
75 Heck, Savelkoul, Vandenbroucke-Grauls, van der Zwaluw, Huijsdens, & Kluytmans, 2011;
76 Smet, Martel, Persoons, Dewulf, Heyndrickx, Catry, Herman, Haesebrouck, & Butaye, 2008).
77 Occurrence of cephalosporin-resistant *E. coli* on poultry in Norway ranged from 8 to 43% (Mo,
78 Norstrom, Slettemeas, Lovland, Urdahl, & Sunde, 2014).

79 Food rendered unfit for human consumption because of product spoilage results in
80 significant economic losses when products must be removed from the market. The
81 accumulation of metabolic by-products or the action of extracellular enzymes produced by
82 spoilage bacteria multiplying on these foods, leads to deterioration like discoloration, texture
83 change, and formation of off-flavours, off-odours and slime. The meat acquires an offensive
84 odour when the bacterial flora reaches about 10^7 CFU/cm^2 of the surface, and when reaching
85 10^8 CFU/cm^2, the surface becomes slimy (Borch, Kant-Muermans, & Blixt, 1996; Holck,
86 Pettersen, Moen, & Sorheim, 2014; Molin, 2000). Common spoilage microorganisms on
87 poultry stored aerobically at 4°C are *Pseudomonas* spp., *Brochothrix* spp. and
88 *Enterobacteriaceae*. A widely used strategy for increasing shelf life of poultry meat is modified
89 atmosphere packaging (MAP) (Holck, Pettersen, Moen, & Sorheim, 2014; van Velzen &
90 Linnemann, 2008). Storage with high CO_2 (70% CO_2, 30% N_2) can lead to lactic acid bacteria
91 like carnobacteria dominating the flora (Holck, Pettersen, Moen, & Sorheim, 2014; Vihavainen,
92 Lundstrom, Susiluoto, Koort, Paulin, Auvinen, & Bjorkroth, 2007). Although some strains of
93 carnobacteria show little influence on the sensory properties of a product, others can spoil the
94 product (Laursen, Bay, Cleenwerck, Vancanneyt, Swings, Dalgaard, & Leisner, 2005; Leisner,
95 Laursen, Prevost, Drider, & Dalgaard, 2007).

96 Various physical and chemical methods to reduce microbes on poultry products have
97 been studied, such as water spraying, air chilling, ultrasound, irradiation, trisodium phosphate,
98 and lactic acid (Capita, Alonso-Calleja, Garcia-Fernandez, & Moreno, 2002; Loretz, Stephan,
99 & Zweifel, 2010). Potential disadvantages using these methods are sensory changes,
100 deterioration of product appearance and quality, and safety concerns. In recent years, there has
101 been a growing interest in using ultraviolet (UV) light for decontamination of poultry. UV light
102 is widely known for its germicidal effect by damaging nucleic acids (Kowalkski, 2009). The
103 high energy associated with short-wavelength UV energy (UV-C), primarily at 254 nm, is

104 absorbed by cellular RNA and DNA. This energy absorption initiates a reaction between
105 adjacent pyrimidine bases to form dimer lesions, which in turn inhibit replication and
106 transcription in cells (Harm, 1980; Weber, 2005).

107 As a means for controlling surface microorganisms on food products, regulations in
108 conjugation with using conventional continuous UV-C light (henceforth referred to as UV-C
109 light) in the US are given by the U.S. Food and Drug Administration (FDA) (FDA, 2010). UV-
110 C light can be employed in Europe, however in Germany the use is limited to water, fruit and
111 vegetable products and stored hard cheeses (Anon, 2000). Decontamination of raw boneless,
112 skinless chicken or broiler breast fillets by the use of UV-C light has been reported to reduce
113 bacterial counts of various pathogens by 0.6 to 1.7 log depending on the conditions used (Chun,
114 Kim, Lee, Yu, & Song, 2010; Haughton, Lyng, Morgan, Cronin, Fanning, & Whyte, 2011;
115 Isohanni & Lyhs, 2009; Sommers, Scullen, & Sheen, 2016). High intensity pulsed UV light has
116 been approved by the FDA up to 12 J/cm^2 (FDA, 2010). The UV energy spectrum of pulsed
117 UV light consists of a continual broadband spectrum from deep UV to infrared light, especially
118 rich in UV range below 400 nm, which is germicidal. In addition to creating dimer lesions,
119 pulsed UV light has been proposed to cause cell damage and cell death by inducing damage of
120 the cell membrane and to cause rupture of the bacteria by thermal stress (Krishnamurthy,
121 Tewari, Irudayaraj, & Demirci, 2010; Takeshita, Shibato, Sameshima, Fukunaga, Isobe,
122 Arihara, & Itoh, 2003; Wekhof, 2000). The use of this technology for food decontamination
123 has previously been reviewed (Demirci & Panico, 2008; Gomez-Lopez, Ragaert, Debevere, &
124 Devlieghere, 2007). Pathogen reduction on boneless skinless chicken breast has been reported
125 to vary from 1.2 to 2.4 log depending on the conditions used (N. M. Keklik, Demirci, & Puri,
126 2010; Paskeviciute, Buchovec, & Luksiene, 2011). Several investigations have demonstrated
127 the effectiveness of UV light on microbial reduction *in vitro*, and a wide range of bacterial
128 species were reduced by 5-7 log when treated on petri dishes under different conditions (Farrell,
129 Garvey, Cormican, Laffey, & Rowan, 2010; Gomez-Lopez, Devlieghere, Bonduelle, &
130 Debevere, 2005; Paskeviciute, Buchovec, & Luksiene, 2011; Rowan, MacGregor, Anderson,
131 Fouracre, McIlvaney, & Farish, 1999).

132 The objective of our investigation was to study and compare the efficacy of UV-C and
133 pulsed UV light against bacteria often found as natural contaminants on fresh chicken meat, of
134 which several of the species have not previously been investigated for UV light treatment on
135 food. To our knowledge, studies on UV light exposure of intact packages of MAP-chicken fillet

136 for bacterial reduction have not been reported, thus we aimed at undertaking this issue using a
137 UV permeable top film. We also aimed at determining whether the UV light treatments had
138 adverse effects on the sensory quality of chicken fillets.

139 ## 2 | MATERIALS AND METHODS

140

141 ### 2.1 | Bacterial strains, media and growth conditions

142 The bacterial strains used in this work are listed in Table 1. The strains were maintained at -
143 80°C in their respective media supplemented with 20% glycerol (v/v). Rifampicin resistant
144 (Rif^R) derivatives were prepared for all isolates by growing strains in liquid media containing
145 200 µg/ml rifampicin as described by Heir et al. (Heir, Holck, Omer, Alvseike, Hoy, Mage, &
146 Axelsson, 2010), except for the ESBL-producing *E. coli* strains already resistant to several types
147 of antibiotics. Growth experiments using a Bioscreen C instrument (Labsystems) where the
148 Optical Density (OD) at 600 nm was monitored, showed no significant difference in growth
149 between the original strains and their Rif^R mutants in their respective media and growth
150 conditions. The different bacterial strains of each species were cultured separately.
151 *Carnobacterium divergens* was grown in cystein-deMan Rogosa Sharpe broth (cMRS, Oxoid)
152 with 200 µg/ml rifampicin (Sigma-Aldrich; 48 h incubation, 30°C), ESBL-producing *E. coli* in
153 Brain Heart Infusion broth (BHI; Oxoid) with 50 µg/ml ampicillin (Sigma-Aldrich; 16 h
154 incubation, 37°C), and tryptic soy broth (TSB, Oxoid) with 200 µg/ml rifampicin was used for
155 *Pseudomonas* spp. (16 h incubation, 30°C), *Brochothrix thermospacta* (48 h incubation, 30°C),
156 *Salmonella* Enteritidis, *L. monocytogenes*, *S. aureus* and EHEC (16 h incubation, 37°C). Before
157 decontamination experiments, bacterial cultures of each of the different strains of the same
158 species were mixed in equal amounts, e.g. bacterial cultures of each of the four strains of *L.*
159 *monocytogenes* were mixed 1:1:1:1. An exception was *E. coli*, for which the ESBL-producing
160 *E. coli* strains and the EHEC strains were separated from each other.

161

162 ### 2.1 | UV illumination experiments of chicken and agar surface inoculated with bacterial
163 ### cells

164 Fresh skinless chicken breast fillets were purchased from local Norwegian supermarkets. The
165 meat was cut into pieces of 10 cm^2, and one side of the chicken was inoculated by spreading 15
166 µl suspension of a multi strain mix of one species (described above) to obtain bacterial levels
167 of 10^5-10^7 CFU/cm^2. The inoculated chicken samples were left at room temperature to dry for
168 1 h prior to UV light treatment. To assess the indigenous background flora of the chicken,

169 uninoculated samples were also analyzed. For *in vitro* illumination experiments, serial 10-fold
170 dilutions of each multi strain mix were made and plated onto the respective agar media
171 (described below). In the UV-C light experiments, samples were treated in a custom made
172 aluminium chamber (1.0x0.5x0.6) m^3 equipped with two UV-C lamps (UV-C Kompaktleuchte,
173 2x95 W, BÄRO GmbH, Leichlingen, Germany) in the ceiling. The UV-C light was emitted
174 essentially at 253.7 nm, measured using a UVX Radiometer (Ultra-Violet Products Ltd.,
175 Cambridge, UK) equipped with a UV-C sensor (model UVX-25, Ultra-Violet Products Ltd.,
176 Cambridge, UK). Both sample distance (6 cm) from the lamps and duration of the exposures
177 were chosen with aim to be relevant for industrial production lines. Exposures were thus at 10
178 mW/cm^2, which is close to a maximum when using commercial lamps, for 5, 10, 30, 60 or 300
179 s, giving fluences of 0.05, 0.1, 0.3, 0.6, 3.0 J/cm^2, respectively. For the pulsed UV light
180 experiments, a semi-automated intense pulsed UV system instrument XeMaticA-SA1L
181 (SteriBeam Systems GmbH, Kehl-Kork am Rhein, Germany) was used. Samples were placed
182 in the instrument chamber at a 6.5 cm distance from the xenon lamp (19 cm), which was water
183 cooled, had an aluminum reflector (10 cm x 20 cm), and the spectral distribution was 200-1100
184 nm, with up to 45% of the energy being in the UV-region (maximal emission at 260 nm). The
185 fluences were set according to the manufacturers specifications, and were adjusted to 1.25 J/cm^2
186 (low) or 3.6 J/cm^2 (high). The lowest level of exposure would result in limited bacterial
187 reductions, and fluences up to and above the limit value of 12 J/cm^2, which is the maximum
188 permitted dose by FDA (FDA, 2010), were tested. Samples were exposed either once to the low
189 pulse, or one, three or five times to the high pulse (3.6, 10.8 or 18.0 J/cm^2, respectively). Three
190 parallels of both treated samples and untreated controls were produced for each experiment,
191 and the experiments were repeated three times on different days.

192 For ESBL-producing *E. coli* and *C. divergens*, UV light treatments were also performed
193 under modified atmosphere conditions as follows: Chicken sample with inoculated bacteria
194 placed in a tray was packaged using a Polimoon 511VG tray sealing machine (RPC Promens
195 AS, Kristiansand, Norway) and UV permeable top film with 65 µm thickness and an ethylene
196 vinyl alcohol (EVOH) barrier layer (Opalen^{TM} 65, Bemis, Oshkosh, Wisconsion, USA). A gas
197 mixture of 60% CO_2 and 40% N_2 (AGA, Oslo, Norway) was used for the packages. The film
198 had an oxygen transmission rate (OTR) of 5 $ml/m^2/24$ h/atm at 23ºC/50% RH, and the trays of
199 dimension 208 x 146 x 32 mm had a barrier layer of high density polyethylene (HDPE; RPC
200 Promens 528) with an OTR of 3.5 $ml/m^2/24$ h/atm at 23ºC/50% RH. Intact packages (MAP-

201 chicken) were exposed to UV light doses similar to the chicken samples treated in air
202 (unpackaged chicken), allowing for comparison of bacterial reduction between the two. Three
203 parallels of both treated samples and untreated controls were produced for each experiment.
204 The experiments were repeated three times on different days.

205 Temperatures were measured using a Raynger MX infrared thermometer (Raytek
206 Corporation, Santa Cruz, USA). Samples were subjected to microbial and physiochemical
207 analyses as described below. The experiments with pathogens were performed in a Biosafety
208 level 3 pilot plant.

209

210 **2.2 | Microbial analyses**

211 Chicken samples were added 90 ml of peptone water and the samples were homogenized for 1
212 min in a stomacher (AES Smasher, AES Chemunex, Bruz, France). Serial 10-fold dilutions
213 from each sample were prepared. Quantification of *C. divergens* (CFU/cm^2) was performed
214 using a Whitley Automatic Spiral Plater (Don Whitley Scientific Ltd., West Yorkshire, UK) on
215 cMRS agar (Oxoid) with 200 µg/ml rifampicin (48 h incubation, 30°C), ESBL-producing *E.*
216 *coli* on BHI (Oxoid) with 50 µg/ml ampicillin (16 h incubation, 37°C), and tryptic soy agar
217 (TSA, Oxoid) with 200 µg/ml rifampicin was used for *Pseudomonas* spp. (16 h incubation,
218 30°C), *B. thermospacta* (48 h incubation, 30°C), *S.* Enteritidis, *L. monocytogenes*, *S. aureus* and
219 EHEC (16 h incubation, 37°C). The number of colonies were determined using an automatic
220 plate reader, and the detection limit was 20 CFU/cm^2. Since rifampicin resistant strains were
221 used, the indigenous background flora on the chicken was negligible.

222

223 **2.3 | Packaging film analyses**

224 The UV permeable top film Opalen^{TM} 65 was evaluated for its ability to transmit UV light by
225 measuring UV light at 254 nm (described above). The extended O_2 barrier properties of the top
226 film was evaluated by using empty packages with 100% N_2 that were initially exposed to four
227 different UV-C and pulsed UV light treatments up to 10.8 J/cm^2 in addition to an untreated
228 control, with five packages per treatment. The packages were analysed for concentrations of
229 residual oxygen at packaging and after 21 days of storage with a Dansensor Checkmate 3
230 (Dansensor, Ringsted, Denmark). The top films of the trays used for oxygen analysis were also

231 evaluated for structural damages by UV light by scanning electron microscopy, where the
232 samples were mounted on an aluminum stub using double-sided tape coated with carbon, before
233 being coated with gold/palladium using a SC7640 auto/manual high resolution sputter coater
234 (Quorum Technologies, Ashford, UK). An EVO-50-EP environmental scanning electron
235 microscope (Zeiss, Cambridge, UK) was used to study the samples at a magnification of x8000.

236

237 **2.4 | Preparation of chicken samples for sensory analyses**

238 Fresh skinless chicken breast fillets obtained from a local producer were mixed to achieve an
239 equal number of CFU per cm^2 on the surface. One set of chicken samples were exposed to UV
240 light in air (unpackaged chicken), and were thereafter packaged in modified atmosphere, while
241 a parallel set of chicken samples were exposed to UV light under modified atmosphere (MAP-
242 chicken), as described above. None of these chicken samples were inoculated with bacterial
243 culture, and both sample sets were then stored at 4°C for 6 days before being used for the
244 sensory analyses described below. The color stability of the chicken fillets were evaluated by
245 visual inspection of the chicken before and after UV light exposure, and after storage.

246

247 **2.5 | Sensory evaluations**

248 Descriptive sensory profiling was conducted by a trained sensory panel of ten assessors at
249 Nofima AS, Norway, according to Generic Descriptive Analysis (Lawless & Heymann, 2010).
250 All panellists were selected and trained in accordance with ISO 8586:2012 (International
251 Organisation for Standardisation, 2007). The following chicken samples treated in air and under
252 modified atmosphere were prepared: untreated control, chicken exposed to UV-C at fluence 0.1
253 J/cm^2 (10 s at 10 mW/cm^2), chicken exposed to UV-C at fluence 0.6 J/cm^2 (60 s at 10 mW/cm^2),
254 chicken exposed to pulsed UV light at low intensity at fluence 1.25 J/cm^2 and chicken exposed
255 to pulsed UV light three times at high intensity giving a fluence of 10.8 J/cm^2. Based on a pre-
256 trial performed by the panellists, a consensus list of attributes for the profiling was developed:
257 Smell of raw chicken (sour odour, sunburnt odour, burnt odour, metallic odour, sulphur odour,
258 off-odour, cloying odour and rancid odour) and odour/taste/flavour of cooked chicken
259 (sunburnt odour, burnt odour, sour flavour, burned flavour, metallic flavour, off-flavour,
260 cloying flavour and rancid flavour). Both raw and cooked chicken fillet samples were evaluated.
261 For the raw samples, the panellists were given 1/6 raw chicken fillet served at room temperature

262 on white plastic cups coded by random three-digit numbers. The cooked samples were heated
263 (100°C, 100% steam, 30 min) in an Electrolux Air-o-steam oven (Combi LW 6 GN 1/1 Gas) to
264 a core temperature of 78°C ± 3°C. After heating, the samples rested for five minutes before
265 each panellist were served ¼ cooked chicken fillet in a white porcelain bowl with lid marked
266 with a random three-digit number, that had been pre-heated at 65°C. Samples were kept at 65°C
267 for the evaluation. The panellists had unsalted crackers and lukewarm water for rinsing the
268 palate between samples. The coded samples were evaluated in duplicate and served randomized
269 according to sample, panellist and replicate. Each panellist recorded their results at individual
270 speed using an unstructured line scale with labelled endpoints ranging from no intensity (1), to
271 high intensity (9), using the EyeQuestion Software (Logic8 BV, the Netherlands) for direct
272 recording of data.

273 Changes in the quality or sensory properties of raw chicken as a result of UV light
274 exposure were also assessed by a smaller consumer test. Twenty randomly chosen test persons
275 were asked if they would want to use the chicken samples for dinner. In addition, they assessed
276 the quality of the chicken on a scale ranging from very bad (1), to very good (9).
277

278 **2.6 | Dynamic headspace gas chromatography mass spectrometry**

279 The same set of raw chicken samples used in the pre-trail sensory evaluation was subjected to
280 dynamic headspace gas chromatography mass spectrometry (GC/MS) analysis. Based on
281 variation found both in the sensory results and the GC/MS results of the pre-trial, chicken
282 samples that showed the greatest variation were further selected for analysis of volatile organic
283 compounds. These included: untreated control, chicken exposed to UV-C light at fluence 0.60
284 J/cm^2 (60 s at 10 mW/cm^2) and pulsed UV light three times at high intensity giving a fluence
285 of 10.8 J/cm^2 treated in air, and pulsed UV light at low intensity at fluence 1.25 J/cm^2 treated
286 under modified atmosphere. A gas chromatography analysis was carried out on chicken samples
287 as previously described (Olsen, Vogt, Veberg, Ekeberg, & Nilsson, 2005). Fifteen gram aliquots
288 of homogenized sample (the samples were analyzed in duplicate) were distributed evenly in
289 250 ml Erlenmeyer flasks. The samples were heated to 70°C in a water bath and purged with
290 100 ml/min nitrogen through a Drechsel-head for 30 min. Volatile compounds were adsorbed
291 on Tenax GR (mesh size 60/80). Water was removed from the tubes by nitrogen flushing (50
292 ml/min) for 5 min in the opposite direction of sampling. Trapped compounds were desorbed at
293 250°C for 5 min in a Perkin Elmer Automatic Thermal Desorption System ATD400 and

294 transferred to an Agilent 6890 GC System with an Agilent 5973 Mass selective detector, which
295 is a quadrupole, operated in electron impact (EI) mode at 70 eV. The scan range was from 33
296 to 300 amu. The compounds were separated on a DB-WAXetr column from J&W
297 Scientific/Agilent (0.25 mm i.d., 0.5 lm film, 30 m). Helium (99.9999%) was used as carrier
298 gas. The temperature program started at 30°C for 10 min, increased 1°C/min to 40°C, 3°C/min
299 to 70°C, 6.5°C/min to 160°C, 20°C/min to 230°C with a final hold time of 4 min. Integration
300 of peaks and tentative identification of compounds were performed with HP Chemstation
301 (G1701CA version C.00.00, Agilent Technologies), Wiley 130 KMass Spectral and NIST98
302 Mass Spectral. Comparison of retention times and mass spectra of the sample peaks with those
303 of pure standards confirmed identities of several of the components. Heptanoic acid ethyl ester
304 was used as internal standard. System performance was checked with blanks and standard
305 samples before, during and after the sample series, and the selected major compounds (80–
306 100%) on a peak area basis were included in the data analysis.

307

308 **2.7 | Statistical analysis**

309 Bacterial reductions log CFU/cm^2 between control and UV light treated samples were
310 calculated. Analysis of variance (ANOVA) and Tukey's multiple comparison test were used to
311 determine statistically significant effects on the reduction by the treatments (R 3.3.2; R Core
312 Team (2017)) using a significance level of 0.05. For sensory evaluation, the same analyses were
313 performed on the descriptive sensory data from the trained panel in order to identify sensory
314 attributes that discriminated between samples.

315

316 **2.8 | Weibull models**

317 For each species, a two-parameter Weibull distribution was fitted to the observed log reductions
318 to produce predictive models of the effects of UV exposure. The chosen Weibull model is
319 defined as:

320
$$\log_{10}\left(\frac{N}{N_0}\right) = \frac{-1}{\log_e(10)}\left(\frac{f}{\alpha}\right)^{\beta},$$

321 where N_0 and N denote the number of bacteria per square cm before and after UV exposure,
322 respectively, f is the UV dose (fluence), α is the scale parameter (describes how sharply the

323 curve drops in the beginning), and β is the shape parameter (describes the shape of the curve).

324 Common models were produced based on log reduction data for all the bacterial species.

325 ## 3 | RESULTS

326

327 ### 3.1 | Bacterial reductions on skinless chicken fillets

328 We investigated the effect of UV-C and pulsed UV light against microbial flora associated with
329 fresh, skinless chicken fillets. Resulting bacterial log reductions CFU/cm^2 of the food pathogens
330 *S.* Enteritidis, *L. monocytogenes*, *S. aureus* and EHEC, and chicken spoilage bacteria
331 *Pseudomonas* spp., *B. thermospacta, C. divergens*, and ESBL-producing *E. coli* applied to
332 chicken meat surface are shown in Figure 1, Figure 2 and Table S1.

333 UV-C light exposure with fluences from 0.05 to 3.0 J/cm^2 (10 mW/cm^2, from 5 to 300
334 s), gave the largest reduction of 2.8 log for *C. divergens* after the highest fluence treatment,
335 while only 1.7 log reduction was obtained for EHEC. The lowest fluence level gave up to 2.2
336 log reduction for *S. aureus*, and EHEC was reduced the least with 1.1 log. By comparing UV-
337 C light results using ANOVA within each species, some of the shorter treatments were
338 considered statistically different from the treatments of longer duration for *S.* Enteritidis (Figure
339 1a, range 1.6-2.4 log), *Pseudomonas* spp. (1e, 2.0-2.7 log), *C. divergens* (1g, 1.9-2.8 log), and
340 ESBL-producing *E. coli* (1h, 1.7-2.8 log), while none of the treatments were statistically
341 different from each other for *L. monocytogenes* (1b, 1.5-1.8 log), *S. aureus* (1c, 2.2-2.6 log),
342 EHEC (1d, 1.1-1.7 log) and *B. thermospacta* (1f, 1.7-2.7 log).

343 Sensitivities against pulsed UV light, where fluences from 1.25 to 18.0 J/cm^2 were used,
344 seemed to be more similar between the different species than for UV-C light. Reductions after
345 pulsed UV light exposure at the highest fluences (10.8 and 18.0 J/cm^2) ranged from 1.6 log for
346 *L. monocytogenes* and *C. divergens* to 3.0 log for *S. aureus, Pseudomonas* spp. and *B.*
347 *thermospacta*. For the low fluence exposure of 1.25 J/cm^2, reductions ranged from 0.9 log for
348 *S.* Enteritidis to 1.7 log for *Pseudomonas* spp. ANOVA on the pulsed UV light results within
349 each species defined the treatment at low fluence statistically different from some or all of the
350 higher intensity treatments, thus increased reduction was obtained by increasing the UV dose.
351 The range of reduction was 0.9-2.4 log for *S.* Enteritidis (Figure 1a), 1.1-2.0 log for *L.*
352 *monocytogenes* (1b), 1.3-3.0 log for *S. aureus* (1c), 1.1-2.9 log for EHEC (1d), 1.7-3.0 log for
353 *Pseudomonas* spp. (1e), 1.3-3.0 log for *B. thermospacta* (1f) and 1.3-2.8 log for ESBL-
354 producing *E. coli* (1h). *C. divergens* deviated from this pattern, for which none of the treatments

355 were considered statistically different from each other and reductions ranged from 1.5 and 1.8
356 log (Figure 1g).

357 In the *in vitro* illumination experiments of petri dishes, the UV light treatments
358 inactivated all the bacterial species by 5-7 log, except from *L. monocytogenes* that was able to
359 withstand the low fluence 1.25 J/cm^2 treatment with pulsed UV light better than the other
360 species, showing approximately 4 log reduction (not shown).

361 Bacterial reductions after exposure with UV-C and pulsed UV light against *C. divergens*
362 and ESBL-producing *E. coli* on MAP-chicken, are shown in Figure 2 and Table S1. Samples
363 were stored under an anaerobic atmosphere with 60% CO_2 and 40% N_2, and the UV permeable
364 top film allowed for UV light exposure of intact packages. *C. divergens* reduction after UV-C
365 light treatments ranged from 1.3 to 1.8 log, and after pulsed UV light treatments from 0.5 to 1.5
366 log. The UV-C light treatments at the lowest fluences (0.05, 0.1, 0.3 J/cm^2) resulted in
367 approximately 0.7 log lower reduction on MAP-chicken compared with unpackaged chicken,
368 and 1.4 log lower reduction was seen for the highest fluence treatment (3.0 J/cm^2). ANOVA on
369 the UV-C light results confirmed the observed differences statistically (results not shown).
370 After pulsed UV light exposure, reductions were similar for MAP-chicken and unpackaged
371 chicken samples for the highest fluences (10.8 and 18.0 J/cm^2), while for fluences of 1.25 and
372 3.6 J/cm^2, 0.9 and 0.7 log lower reductions, respectively, were seen on MAP-chicken, which
373 were confirmed statistically by ANOVA (not shown). Reduction of ESBL-producing *E. coli*
374 after UV-C light treatments ranged from 1.5 to 2.5 log, and after pulsed UV light treatments
375 from 0.6 to 1.7 log. ANOVA on the UV-C light results confirmed statistically that reductions
376 on MAP-chicken and unpackaged chicken samples were similar (not shown). For pulsed UV
377 light, lower reductions were seen for the MAP-chicken samples regardless of UV dose, 0.7, 1.1,
378 0.9 and 1.3 log lower reductions for fluences of 1.25, 3.6, 10.8 and 18.0 J/cm^2, respectively,
379 confirmed statistically by ANOVA (not shown). The applied UV light up to 10.8 J/cm^2 did not
380 impair the oxygen barrier properties and structural integrity of the UV permeable top film, and
381 the O_2 concentrations of the trays increased from approximately 0.12+/- 0.03% at packaging to
382 0.69+/-0.02% after 21 days, and were similar for the different UV light treatments and the
383 untreated control. Scanning electron microscopy analysis showed no structural damages to the
384 UV treated films (not shown). The ability of the film to transmit UV light was measured as
385 80.5% at 254 nm, which was compensated for by increasing the UV doses accordingly in the
386 illumination experiments.

387 **3.2 | Weibull models describing bacterial reduction**

388 Weibull models created to predict the log reduction patterns for the different bacterial species
389 are shown in Figure 3 and parameters for the models are listed in Table 2. RMSE values
390 indicating the goodness of fit, were the lowest for *S. aureus* exposed to UV-C light (0.20) and
391 the highest for *Pseudomonas* spp. exposed to pulsed UV light (0.55). Determination coefficient
392 (R^2) values ranged from 0.41 to 0.80 for UV-C light and from 0.47 to 0.89 for pulsed UV light.
393 Since R^2 indicates the proportion of variation in log reduction explained by the fitted Weibull
394 model, a value approaching 1 would signify perfect predictability. Since all of the ß (shape
395 parameter) values were less than 1, the Weibull fits of the reduction data were concave upward.
396 The highest ß values were obtained for EHEC and *S.* Enteritidis (0.32 and 0.31, respectively)
397 for pulsed UV light. The α (scale parameter) values were very small, implying concentrated
398 distribution, as seen by how sharp the curve drops in the beginning. There was a noticeable
399 difference between the two UV methods, where higher α values were obtained for UV-C light
400 than for pulsed UV light, with *C. divergens* as an exception. Common models based on log
401 reduction values for all the species gave a good fit for the majority of the species, but for *L.*
402 *monocytogenes* exposed to both UV-C and pulsed UV light, reduction was overestimated. The
403 same was seen for EHEC exposed to UV-C light and *C. divergens* exposed to pulsed UV light.

404

405 **3.3 | Sensory evaluation of UV light treated chicken**

406 Changes in quality or sensory properties of chicken fillets as a result of UV light treatments
407 were assessed by ten trained assessors. Their evaluation results are shown in Figure 4, where
408 raw chicken samples were evaluated for odour and cooked chicken samples for
409 odour/taste/flavour. A statistically significant difference between the samples was only
410 registered for the odour characterized as sunburnt ($p<0.001$), which is associated with that of
411 sunburnt human skin. Most notably, treatment with the highest dose of pulsed UV light (10.8
412 J/cm^2) in air gave the highest intensity of the sunburnt odour (sensory intensity value score of
413 3.4). After cooking, this effect of the UV light treatment could not be detected. From the
414 consumer test, UV light exposed raw chicken fillet samples assessed by 20 random consumers
415 could not be differentiated from untreated control samples (data not shown). By visual
416 inspection, the color stability was not affected by the treatments at the doses used (data not
417 shown).

418 Denaturation of proteins in chicken has been considered to be initiated at temperatures
419 higher than 56°C (Murphy, Marks, & Marcy, 1998). Only minor elevation of the temperature
420 was observed, 2.5-4.0°C and 4.0-6.5°C for UV-C light treatments at fluences 0.6 J/cm^2 and 3.0
421 J/cm^2, respectively, and 0.5-2.5°C and 2.5-3.5°C for pulsed UV light treatments at fluences
422 10.8 J/cm^2 and 18.0 J/cm^2, respectively. The rise in surface temperature was only temporary
423 since the surface was rapidly cooled by the low temperature of the interior of the chicken fillet.

424

425 **3.4 | Volatile organic compounds**

426 Nearly 100 different volatile organic compounds were detected by dynamic headspace/GC-MS
427 in the raw chicken samples that were analyzed, of which approximately 70 compounds could
428 be identified. The major compounds were ketones (C2-C5, C7), alcohols (C2-C8), acids (C2-
429 C7), fatty and non-fatty aldehydes (C2-C9), hydrocarbons (C5-C7) and sulfides. Only a few
430 compounds were observed to increase in concentration as a result of exposure to UV light. This
431 included dimethyltrisulfide, pentane, heptane, propanoic acid, 2-pentanone, 1-pentanol and
432 hexanal (Figure 5). Linear correlation with the odour scores were calculated, and gave
433 correlations with the sunburnt odour scores as follows: dimethyltrisulfide $r=0.70$ ($p<0.01$), 2-
434 pentanone $r=0.95$ ($p<0.0025$), 1-pentanol $r=0.91$ ($p<0.005$), pentane ($r=0.92$, $p<0.005$), heptane
435 ($r=0.81$, $p<0.01$), propanoic acid ($r=0.98$, $p<0.001$), and hexanal ($r=0.81$, $p<0.01$). The sample
436 in which all the compounds increased the most, was chicken exposed to pulsed UV light at
437 fluence 10.8 J/cm^2 treated in air.

4 | DISCUSSION

4.1 | Effect of UV treatment on inoculated bacteria

There are large differences between the conventional continuous UV-C light and pulsed UV light with respect to wavelengths, intensities and exposure times. In this work, we have compared the efficacy of continuous UV-C light and pulsed UV light in reducing bacteria on chicken fillet. We used multi strain mixtures of the same species and bacterial cells that were in the same state during the different treatments. In earlier studies, single strains were often used which may not show reductions representative for the species. Differences in reduction within species have been reported, and state of the cells can influence the sensitivity to UV light (Farrell, Garvey, Cormican, Laffey, & Rowan, 2010; Haughton, Lyng, Morgan, Cronin, Fanning, & Whyte, 2011). To avoid possible changes in sensory perception, it is desirable to maximize bacterial reduction without treating the surface of a product more than necessary. Treatment levels employed for both UV methods were practical and relevant within industrial production, from weak exposures resulting in limited bacterial reduction, up to levels exceeding the maximum permitted dose by the FDA for pulsed UV light (FDA, 2010). The fluences are not directly comparable between the two methods, since the different wavelengths in the UV spectrum have different germicidal effectiveness (Bintsis, Litopoulou-Tzanetaki, & Robinson, 2000). For UV-C exposure at 0.05 J/cm^2, the germicidal effect was comparable to a fluence of 1.25 J/cm^2 for the pulsed UV light. UV-C light showed a higher germicidal effect when the same fluence was employed for the two methods, which can be explained by most of the energy being emitted at 254 nm, where the germicidal effect is close to the maximum (Bintsis, Litopoulou-Tzanetaki, & Robinson, 2000).

In the range tested, a limited dose-response effect was observed, likely caused by shading effects of the irregular surface structure of the chicken fillet. The increase in reduction with increasing dose was though more apparent for the pulsed UV light. Any substance between the light source and the bacterium that absorbs light will impair the decontamination process (Gomez-Lopez, Ragaert, Debevere, & Devlieghere, 2007). Even when a surface appears smooth to the naked eye, it may harbour crevices and cracks where bacteria are shielded against direct exposure, and bacteria may also be covered by protein or other organic matrices. Moreover, the average size of a bacterium is approximately 1 µm x 2 µm, and although its

469 spreading was carried out carefully, it is practically impossible to avoid some overlapping. A
470 shielding effect for colonies of *L. monocytogenes* growing on petri dishes where the upper cells
471 of a colony appeared to protect the lower cells has previously been described (Gomez-Lopez,
472 Devlieghere, Bonduelle, & Debevere, 2005). At high fluence rates, the light should be able to
473 penetrate deeper, but still, the efficiency of using UV light for decontamination of foods is
474 lower than when tested on smooth surfaces. Reductions of 5-7 log achieved on agar in petri
475 dishes was in accordance with previous reports (Farrell, Garvey, Cormican, Laffey, & Rowan,
476 2010; Gomez-Lopez, Devlieghere, Bonduelle, & Debevere, 2005; Paskeviciute, Buchovec, &
477 Luksiene, 2011; Rowan, MacGregor, Anderson, Fouracre, McIlvaney, & Farish, 1999), and the
478 observed higher resistance of *L. monocytogenes* to pulsed UV light, reduced only 4 log after
479 treatment at low fluence of 1.25 J/cm^2, has also been reported previously (Gomez-Lopez,
480 Devlieghere, Bonduelle, & Debevere, 2005; Lasagabaster & de Maranon, 2012). In general, the
481 reductions of inoculated bacteria on chicken fillet surface observed in this study correlated well
482 with previous findings, both for UV-C (Chun, Kim, Lee, Yu, & Song, 2010; Haughton, Lyng,
483 Cronin, Morgan, Fanning, & Whyte, 2011; Isohanni & Lyhs, 2009; Sommers, Scullen, &
484 Sheen, 2016) and for pulsed UV light (N. M. Keklik, Demirci, & Puri, 2010; Paskeviciute,
485 Buchovec, & Luksiene, 2011), including for *C. divergens*, *Pseudomonas* spp. and *B.*
486 *thermospacta*, for which previous reports on UV light inactivation on food surfaces does not
487 exist or are scarce. EHEC seemed to resist the UV-C light treatments better than ESBL-
488 producing *E. coli*, and better than the other species tested as well.

489 The Weibull distribution is suitable for the analysis of bacterial reduction (Chen, 2007;
490 N. M. Keklik, Demirci, Puri, & Heinemann, 2012; Martin, Sepulveda, Altunakar, Gongora-
491 Nieto, Swanson, & Barbosa-Canovas, 2007; Ugarte-Romero, Feng, Martin, Cadwallader, &
492 Robinson, 2006; van Boekel, 2002), and was previously demonstrated to be more successful
493 than models such as the log-linear model and first-order kinetic model (Chen, 2007; N. M.
494 Keklik, Demirci, Puri, & Heinemann, 2012; Martin, Sepulveda, Altunakar, Gongora-Nieto,
495 Swanson, & Barbosa-Canovas, 2007). The model seemed to be a useful tool to describe the
496 reduction patterns and give clues to how pathogens and spoilage bacteria on chicken fillet
497 surfaces are likely to respond to UV light treatments. The Weibull fits of the reduction data
498 were concave upward, indicating that exposed cells were destroyed and that the more resistant
499 cells or those shaded from exposure were left undamaged.

500 To our knowledge, studies on UV light treatment of intact packages of MAP-chicken
501 fillet for reducing bacteria on the chicken surface have previously not been reported. UV light
502 reduction of bacteria on various packaging materials have, however, been studied (Haughton,
503 Lyng, Morgan, Cronin, Fanning, & Whyte, 2011), and vacuum-packaged chicken breast
504 inoculated with *Salmonella* Typhimurium treated with pulsed UV light were shown to give
505 about 2 log reduction, but with double the exposure time (30 s) in comparison with unpackaged
506 samples (15 s) (N. M. Keklik, Demirci, & Puri, 2010). The additional bacterial reduction
507 obtained on ready packaged chicken fillet product would increase shelf life and safety.
508 Treatment after packaging should be simple to implement at industrial packaging lines without
509 reductions in production efficiency.

510

511 **4.2 | Sensory quality of the chicken fillets**

512 Meat exposed to UV light can develop off-flavours caused by the absorption of ozone and
513 oxides of nitrogen, or because of photochemical effects on the lipid fractions of the meat
514 (Bintsis, Litopoulou-Tzanetaki, & Robinson, 2000). Lipid oxidative rancidity is regarded as the
515 most important non-microbial factor responsible for meat deterioration, resulting in adverse
516 changes in appearance, texture, odour and flavour (Frankel, 1998). An increase in fatty
517 aldehydes due to lipid oxidation during irradiation of poultry meat has been documented (Du,
518 Ahn, Nam, & Sell, 2000, 2001; Du, Hur, Nam, Ismail, & Ahn, 2001; Kim, Nam, & Ahn, 2002).
519 The major fatty aldehyde hexanal is a typical volatile secondary lipid oxidation product
520 (Beltran, Pla, Yuste, & Mor-Mur, 2003; Jayasena, Ahn, Nam, & Jo, 2013; Shi & Ho, 1994).
521 Although we observed an increase in the concentration of hexanal, particularly for unpackaged
522 chicken exposed to UV light, no significant effect was found on the corresponding rancid
523 related sensory attributes in the proffesional sensory evaluation. This suggests that lipid
524 oxidation does not have a negative impact on the perceived odour and flavour of the chicken
525 meat at the applied UV doses. The higher intensity of the sunburnt odour for chicken exposed
526 to the most intense dose of pulsed UV light, does however seem to pose restrictions on the
527 upper limit of treatment of unpackaged chicken. The sensory intensity value was though only
528 3.4, which is considered relatively low, and for lower doses relevant in industrial application,
529 the odor should not be a problem. Detected changes in concentrations of volatile compounds
530 correlated well with the sensory observations. Increased levels were seen in unpackaged
531 chicken after UV light exposure. Hydrocarbons may be generated during irradiation of poultry

532 meat (Du, Ahn, Nam, & Sell, 2000, 2001; Du, Hur, Nam, Ismail, & Ahn, 2001; Kim, Nam, &
533 Ahn, 2002), where increased concentrations of propanol and butanol have been documented
534 (Du, Ahn, Nam, & Sell, 2000, 2001; Du, Hur, Nam, Ismail, & Ahn, 2001). In accordance, we
535 detected increased levels of pentane, heptane and 1-pentanol. Sulfur compounds with low odour
536 thresholds are important to odour associated with irradiation (Angelini, Merritt, Mendelsohn,
537 & King, 1975; Batzer & Doty, 1955; Patterson & Stevenson, 1995). Dimethyltrisulfide,
538 although only detected in small amounts in unpackaged chicken after UV light exposure, was
539 reported by Patterson and Stevenson (Patterson & Stevenson, 1995) to be the most potent off-
540 odour compound in irradiated raw chicken. Other compounds that showed an increase and
541 which character could be associated with sunburnt/irradiated odour and flavour, were 2-
542 pentanone (roasted sweet) and 1-pentanol (roasted meat) (Brewer, 2009). Together these three
543 compounds likely contribute to the sensory perceived sunburnt odour. Irradiation of poultry
544 meat is though based on irradiation by electrons using an accelerator, representing far higher
545 dose in terms of energy exposure per area compared to our applied UV doses, thus the results
546 may not be directly comparable. Paskeviciute et al. (Paskeviciute, Buchovec, & Luksiene,
547 2011) investigated chemical changes in pulsed UV light treated chicken breasts, and reported
548 that the intensity of lipid peroxidation in control and treated chicken samples differed in 0.16
549 mg malondialdehyde per kilogram of chicken meat. However, taste panellists did not observe
550 any changes in organoleptic properties of treated raw chicken, chicken broth or cooked chicken
551 meat in comparison with control. Although treated raw chicken samples could not be
552 differentiated from an untreated control sample by the 20 random chosen consumers in the
553 present study, more extensive consumer studies could aid in determining whether such UV light
554 treatments are acceptable.

555 The color of raw or cooked poultry meat is by origin pale with a low content of the
556 muscle pigment myoglobin. Furthermore, the color of raw meat is dependent on the oxidation
557 state of myoglobin (Mugler & Cunningham, 1972; USDA, 2013). Chicken breasts exposed to
558 high doses of UV light was previously reported to turn darker, show more redness and a slight
559 increasing amount of yellow coloration (Park & Ha, 2015). The color of the chicken fillets was
560 not affected by the treatments at the doses used in our experiments, as in agreement with other
561 reports (Chun, Kim, Lee, Yu, & Song, 2010; Haughton, Lyng, Cronin, Morgan, Fanning, &
562 Whyte, 2011). Together these results indicate that sensory and quality changes are small or
563 negligible both after UV-C and pulsed UV light treatments.

564 **4.3 | Advantages and disadvantages of continuous UV-C and pulsed UV treatments**

565 Both UV-C and pulsed UV light treatments provide effective tools for reduction of
566 microorganisms. They are rapid and efficient non-chemical, non-ionizing, and non-thermal
567 surface decontamination treatments and can be used in continuous processing. The methods
568 have been shown as effective technologies for decontamination of stainless steel conveyors and
569 surfaces in the production environment (Haughton, Lyng, Morgan, Cronin, Fanning, & Whyte,
570 2011; Sommers, Sites, & Musgrove, 2010). They can be used on foods and synergistically with
571 other treatments (Mukhopadhyay & Ramaswamy, 2012). The methods require little energy use,
572 are easy to implement and require no increase in work load. UV light is safe to apply, but some
573 precautions have to be taken to avoid exposure of workers to light and to evacuate any ozone
574 generated by the shorter UV wavelengths (Gomez-Lopez, Ragaert, Debevere, & Devlieghere,
575 2007). The effect of both UV-C and pulsed UV light is impaired in opaque matter, where
576 bacteria are shielded from direct exposure such as by food surface topography, organic matter
577 or by other bacteria. The UV light treatments of this study did not alter the properties of the
578 EVOH film used, as was also the case with polyethylene, polypropylene and
579 polyvinyldichloride films (Tarek, Rasco, & Sablani, 2015). The top film used transmitted
580 approximately 80% of the UV light, while in previous studies, films with polypropylene and
581 polyethylene barrier layers transmitted 75% (N. M. Keklik, Demirci, & Puri, 2009) and 72%
582 (N. M. Keklik, Demirci, & Puri, 2010), respectively, of pulsed UV light at 1.27 J/cm^2. By using
583 a packaging film with a high UV transmission, the chicken fillets could be packaged before the
584 UV light treatment, therefore avoiding the risk of recontamination. Both methods would be
585 beneficial for large scale industrial UV decontamination operations. UV-C light treatment is a
586 low cost strategy with low maintenance (N.M. Keklik, Krishnamurthy, & Demirci, 2012). The
587 treatment time is somewhat longer in comparison with pulsed UV light treatment, and therefore
588 the equipment may require more space if installed over for example a conveyor belt. Pulsed UV
589 light provides rapid decontamination, but involves equipment that is more elaborate. The xenon
590 flash lamps used for pulsed UV light are also more environment friendly than the mercury-
591 vapor lamps typically used in UV-C light treatment (Gomez-Lopez, Ragaert, Debevere, &
592 Devlieghere, 2007).

593 ## 5 | CONCLUSION

594 Despite good hygiene practices during production of fresh meat, contamination of carcasses
595 with pathogens and spoilage bacteria cannot be completely prevented. There is pressure on the
596 food industry for nutritious, fresh and healthy food products, to maximize the shelf life of the
597 products, and for reducing costs and waste. Antimicrobial interventions that effectively reduce
598 the bacterial load are feasible in slaughter and product processing. They should be safe,
599 economic, and easy to handle. Also, interventions should not change the organoleptic quality
600 of the food and should be widely accepted by consumers. The exposure of raw chicken fillet
601 surface to various doses of UV-C or pulsed UV light proposed in this work represents useful
602 alternatives for reducing the viability of pathogenic and spoilage bacteria on this product.

603 **ACKNOWLEDGEMENT**

604 We thank the trained sensory panel at Nofima for carrying out the sensory evaluation, Signe
605 Marie Drømtorp, Aud Espedal, Vibeke Høst, Elin-Merete Nicolaisen and Birgitte Vikrem for
606 excellent technical assistance. We are grateful to Bemis, Valkeakoski, Finland, for the supply
607 of packaging film. The work was funded by grants to the projects 221663 and 262306 financed
608 by the Research Council of Norway and the Research Levy on Agricultural Products,
609 respectively.

610 **COMPETING INTERESTS**

611 The authors declare that there is no conflict of interest regarding publication of this paper.

612 **FIGURE LEGENDS**

613

614 **FIGURE 1** Reductions of (a) *S.* Enteritidis, (b) *L. monocytogenes,* (c) *S. aureus,* (d)
615 enterohemorrhagic *E. coli* (EHEC), (e) *Pseudomonas* spp., (f) *B. thermospacta,* (g) *C. divergens*
616 and (h) ESBL-producing *E. coli* on chicken fillet meat after continuous UV-C (white bars) and
617 pulsed UV light (grey bars) exposures at different fluences (J/cm^2). Three separate ANOVA
618 were performed for each species, represented by upper case letters (comparing UV-C and
619 pulsed UV light treatments), numbers (comparing UV-C light treatments) and lower case letters
620 (comparing pulsed UV light treatments). Samples containing the same letter/number were not
621 considered different.

622

623 **FIGURE 2** Reductions of (a) *C. divergens* and (b) ESBL-producing *E. coli* on MAP-chicken
624 exposed to continuous UV-C (white bars) and pulsed UV light (grey bars) at different fluences
625 (J/cm^2). A gas mixture of 60% CO_2 and 40% N_2 and a UV permeable top film was used for the
626 packages. Three separate ANOVA were performed for each species, represented by upper case
627 letters (comparing UV-C and pulsed UV light treatments), numbers (comparing UV-C light
628 treatments) and lower case letters (comparing pulsed UV light treatments). Samples containing
629 the same letter/number were not considered different.

630

631 **FIGURE 3** Weibull models for bacterial log reduction as a function of UV exposure. Models
632 for each species (black continuous line) and common models (red dotted line) are shown for
633 bacterial reduction on chicken fillet meat after (a) continuous UV-C and (b) pulsed UV light
634 exposures at different fluences (J/cm^2).

635 **FIGURE 4** Sensory analysis of (a) raw chicken fillet samples and (b) cooked chicken fillet
636 samples. Chicken samples were exposed to continuous UV-C light at 10 mW/cm^2 for 10 s
637 (UVC-10) and 60 s (UVC-60), giving fluences of 0.1 J/cm^2 and 0.60 J/cm^2, respectively, and
638 pulsed UV light to a low pulse with fluence of 1.25 J/cm^2 (PUV-L) and three times to a high
639 pulse giving a fluence of 10.8 J/cm^2 (PUV-Hx3), both in air (O_2) and anaerobic (CO_2:N_2)
640 atmospheres, representing unpackaged chicken and MAP-chicken, respectively. The intensities
641 of different odours of raw samples and odour/taste/flavour of cooked samples were registered,
642 1 = no intensity and 9 = high intensity. The letters above the columns indicate grouping
643 according to ANOVA and Tukey multiple comparison test. Samples with the same letter are
644 considered being equal for the specific property.

645

646 **FIGURE 5** Volatile organic compounds from chicken which showed an increase in
647 concentration (pg/g) as a result of exposure to UV light. The samples included were chicken
648 exposed to pulsed UV light at low intensity at fluence 1.25 J/cm^2 (PUV-L) treated under
649 anaerobic (CO_2:N_2) atmosphere (MAP-chicken), an untreated control (Untreated), chicken
650 exposed to UV-C light at 10 mW/cm^2 for 60 s (UVC-60) giving a fluence of 0.60 J/cm^2 and
651 pulsed UV light three times at high intensity (PUV-Hx3) giving a fluence of 10.8 J/cm^2 treated
652 in air (O_2). The precision of replicate measurements were within 15%.

REFERENCES

Angelini, P., Merritt, C., Mendelsohn, J. M., & King, F. J. (1975). Effect of irradiation on volatile constituents of stored haddock flesh. *Journal of Food Science, 40*(1), 197-199. doi: 10.1111/j.1365-2621.1975.tb03770.x

Anon. (2000). *Lebensmittelbestrahlungsverordnung vom 14. Dezember 2000 (BGBl. I S. 1730), die zuletzt durch Artikel 62 der Verordnung vom 31. August 2015 (BGBl. I S. 1474) geändert worden ist.* Germany.

Batzer, O. F., & Doty, D. M. (1955). Nature of undesirable odors formed by gamma irradiation of beef. *Journal of Agricultural and Food Chemistry, 3*(1), 64-67. doi: 10.1021/Jf60047a009

Beltran, E., Pla, R., Yuste, J., & Mor-Mur, M. (2003). Lipid oxidation of pressurized and cooked chicken: role of sodium chloride and mechanical processing on TBARS and hexanal values. *Meat Science, 64*(1), 19-25. doi: 10.1016/S0309-1740(02)00132-8

Bintsis, T., Litopoulou-Tzanetaki, E., & Robinson, R. K. (2000). Existing and potential applications of ultraviolet light in the food industry - a critical review. *Journal of the Science of Food and Agriculture, 80*(6), 637-645. doi: 10.1002/(Sici)1097-0010(20000501)80:6<637::Aid-Jsfa603>3.0.Co;2-1

Blom, H., Nerbrink, E., Dainty, R., Hagtvedt, T., Borch, E., Nissen, H., & Nesbakken, T. (1997). Addition of 2.5% lactate and 0.25% acetate controls growth of *Listeria monocytogenes* in vacuum-packed, sensory-acceptable servelat sausage and cooked ham stored at 4 degrees C. *International Journal of Food Microbiology 38*(1), 71-76. doi: 10.1016/S0168-1605(97)00088-3

Borch, E., Kant-Muermans, M. L., & Blixt, Y. (1996). Bacterial spoilage of meat and cured meat products. *International Journal of Food Microbiology, 33*(1), 103-120.

Brewer, M. S. (2009). Irradiation effects on meat flavor: A review. *Meat Science, 81*(1), 1-14. doi: 10.1016/j.meatsci.2008.07.011

Briongos-Figuero, L. S., Gomez-Traveso, T., Bachiller-Luque, P., Dominguez-Gil Gonzalez, M., Gomez-Nieto, A., Palacios-Martin, T., . . . Perez-Castrillon, J. L. (2012). Epidemiology, risk factors and comorbidity for urinary tract infections caused by extended-spectrum beta-lactamase (ESBL)-producing enterobacteria. *International Journal of Clinical Practice, 66*(9), 891-896. doi: 10.1111/j.1742-1241.2012.02991.x

684 Capita, R., Alonso-Calleja, C., Garcia-Fernandez, M. C., & Moreno, B. (2002). Review:
685 Trisodium phosphate (TSP) treatment for decontamination of poultry. *Food Science and*
686 *Technology International, 8*(1), 11-24. doi: 10.1106/108201302023118
687 Chen, H. Q. (2007). Temperature-assisted pressure inactivation of *Listeria monocytogenes* in
688 Turkey breast meat. *International Journal of Food Microbiology, 117*(1), 55-60. doi:
689 10.1016/j.ijfoodmicro.2007.02.025
690 Chun, H. H., Kim, J. Y., Lee, B. D., Yu, D. J., & Song, K. B. (2010). Effect of UV-C irradiation
691 on the inactivation of inoculated pathogens and quality of chicken breasts during
692 storage. *Food Control, 21*(3), 276-280. doi: 10.1016/j.foodcont.2009.06.006
693 Demirci, A., & Panico, L. (2008). Pulsed ultraviolet light. *Food Science and Technology*
694 *International, 14*(5), 443-446. doi: 10.1177/1082013208098816
695 Du, M., Ahn, D. U., Nam, K. C., & Sell, J. L. (2000). Influence of dietary conjugated linoleic
696 acid on volatile profiles, color and lipid oxidation of irradiated raw chicken meat. *Meat*
697 *Science, 56*(4), 387-395. doi: 10.1016/S0309-1740(00)00067-X
698 Du, M., Ahn, D. U., Nam, K. C., & Sell, J. L. (2001). Volatile profiles and lipid oxidation of
699 irradiated cooked chicken meat from laying hens fed diets containing conjugated
700 linoleic acid. *Poultry Science, 80*(2), 235-241.
701 Du, M., Hur, S. J., Nam, K. C., Ismail, H., & Ahn, D. U. (2001). Volatiles, color, and lipid
702 oxidation of broiler breast fillets irradiated before and after cooking. *Poultry Science,*
703 *80*(12), 1748-1753.
704 European Food Safety Authority (EFSA). (2015). The European Union summary report on
705 trends and sources of zoonoses, zoonotic agents and food-borne outbreaks in 2013.
706 *EFSA Journal, 13*(1), 3991.
707 Farrell, H. P., Garvey, M., Cormican, M., Laffey, J. G., & Rowan, N. J. (2010). Investigation
708 of critical inter-related factors affecting the efficacy of pulsed light for inactivating
709 clinically relevant bacterial pathogens. *Journal of Applied Microbiology, 108*(5), 1494-
710 1508. doi: 10.1111/j.1365-2672.2009.04545.x
711 Food and Agriculture Organization of the United Nations (FAO). (2015). *World Agriculture:*
712 *Towards 2015/2030. An FAO perspective. Economic and Social Development*
713 *Department*. Retrieved from http://www.fao.org/docrep/005/y4252e/y4252e05b.htm
714 Frankel, E. N. (1998). *Lipid oxidation*. Dundee, Scotland: The Oily Press Ltd.

715 Glaser, P., Frangeul, L., Buchrieser, C., Rusniok, C., Amend, A., Baquero, F., . . . Cossart, P.
716 (2001). Comparative genomics of *Listeria* species. *Science, 294*(5543), 849-852. doi:
717 10.1126/science.1063447
718 Gomez-Lopez, V. M., Devlieghere, F., Bonduelle, V., & Debevere, J. (2005). Factors affecting
719 the inactivation of micro-organisms by intense light pulses. *Journal of Applied*
720 *Microbiology, 99*(3), 460-470. doi: 10.1111/j.1365-2672.2005.02641.x
721 Gomez-Lopez, V. M., Ragaert, P., Debevere, J., & Devlieghere, F. (2007). Pulsed light for food
722 decontamination: a review. *Trends in Food Science & Technology, 18*(9), 464-473. doi:
723 10.1016/j.tifs.2007.03.010
724 Hafez, H. M. (1999). Poultry meat and food safety: pre- and post-harvest approaches to reduce
725 foodborne pathogens. *Worlds Poultry Science Journal, 55*(3), 269-280. doi:
726 10.1079/Wps19990020
727 Hafez, H. M. (2005). Governmental regulations and concept behind eradication and control of
728 some important poultry diseases. *Worlds Poultry Science Journal, 61*(4), 569-581. doi:
729 10.1079/Wps200571
730 Harm, W. (1980). *Biological effects of ultraviolet radiation*. New York, USA: Cambridge
731 University Press.
732 Haughton, P. N., Lyng, J. G., Cronin, D. A., Morgan, D. J., Fanning, S., & Whyte, P. (2011).
733 Efficacy of UV light treatment for the microbiological decontamination of chicken,
734 associated packaging, and contact surfaces. *Journal of Food Protection, 74*(4), 565-572.
735 doi: 10.4315/0362-028X.JFP-10-356
736 Haughton, P. N., Lyng, J. G., Morgan, D. J., Cronin, D. A., Fanning, S., & Whyte, P. (2011).
737 Efficacy of high-intensity pulsed light for the microbiological decontamination of
738 chicken, associated packaging, and contact surfaces. *Foodborne Pathogens and*
739 *Disease, 8*(1), 109-117. doi: 10.1089/fpd.2010.0640
740 Heir, E., Holck, A. L., Omer, M. K., Alvseike, O., Hoy, M., Mage, I., & Axelsson, L. (2010).
741 Reduction of verotoxigenic *Escherichia coli* by process and recipe optimisation in dry-
742 fermented sausages. *International Journal of Food Microbiology, 141*, 195-202. doi:
743 10.1016/j.ijfoodmicro.2010.05.017
744 Holck, A. L., Pettersen, M. K., Moen, M. H., & Sorheim, O. (2014). Prolonged shelf life and
745 reduced drip loss of chicken filets by the use of carbon dioxide emitters and modified
746 atmosphere packaging. *Journal of Food Protection, 77*(7), 1133-1141. doi:
747 10.4315/0362-028X.JFP-13-428

748 International Organisation for Standardisation. (2007). *International Standard 8589. Sensory*
749 *analysis - Methodology - Sensory analysis - General guidance for the design of rooms*
750 *(Ref. No. ISO 8589:2007E)*. Genève, Switzerland.
751 Isohanni, P. M., & Lyhs, U. (2009). Use of ultraviolet irradiation to reduce *Campylobacter*
752 *jejuni* on broiler meat. *Poultry Science, 88*(3), 661-668. doi: 10.3382/ps.2008-00259
753 Jayasena, D. D., Ahn, D. U., Nam, K. C., & Jo, C. (2013). Flavour chemistry of chicken meat:
754 a review. *Asian-Australasian Journal of Animal Sciences, 26*(5), 732-742. doi:
755 10.5713/ajas.2012.12619
756 Keklik, N. M., Demirci, A., & Puri, V. M. (2009). Inactivation of *Listeria monocytogenes* on
757 unpackaged and vacuum-packaged chicken frankfurters using pulsed UV-light. *Journal*
758 *of Food Science, 74*(8), M431-M439. doi: 10.1111/j.1750-3841.2009.01319.x
759 Keklik, N. M., Demirci, A., & Puri, V. M. (2010). Decontamination of unpackaged and
760 vacuum-packaged boneless chicken breast with pulsed ultraviolet light. *Poultry Science,*
761 *89*(3), 570-581. doi: 10.3382/ps.2008-00476
762 Keklik, N. M., Demirci, A., Puri, V. M., & Heinemann, P. H. (2012). Modeling the inactivation
763 of *Salmonella* Typhimurium, *Listeria monocytogenes*, and *Salmonella* Enteritidis on
764 poultry products exposed to pulsed UV light. *Journal of Food Protection, 75*(2), 281-
765 288. doi: 10.4315/0362-028X.JFP-11-298
766 Keklik, N. M., Krishnamurthy, K., & Demirci, A. (2012). Microbial decontamination of food
767 by ultraviolet (UV) and pulsed UV light. In A. Demirci & M. O. Ngadi (Eds.), *Microbial*
768 *decontamination in the food industry: novel methods and applications*, 344-369.
769 Cambridge, United Kingdom Woodhead Publishing Limited.
770 Kim, Y. H., Nam, K. C., & Ahn, D. U. (2002). Volatile profiles, lipid oxidation and sensory
771 characteristics of irradiated meat from different animal species. *Meat Science, 61*(3),
772 257-265. doi: 10.1016/S0309-1740(01)00191-7
773 Kowalkski, W. (2009). *Ultraviolet germicidal irradiation handbook*: Springer.
774 Krishnamurthy, K., Tewari, J. C., Irudayaraj, J., & Demirci, A. (2010). Microscopic and
775 spectroscopic evaluation of inactivation of *Staphylococcus aureus* by pulsed UV light
776 and infrared heating. *Food and Bioprocess Technology, 3*(1), 93-104. doi:
777 10.1007/s11947-008-0084-8
778 Lasagabaster, A., & de Maranon, I. M. (2012). Sensitivity to pulsed light technology of several
779 spoilage and pathogenic bacteria isolated from fish products. *Journal of Food*
780 *Protection, 75*(11), 2039-2044. doi: 10.4315/0362-028X.JFP-12-071

781 Laursen, B. G., Bay, L., Cleenwerck, I., Vancanneyt, M., Swings, J., Dalgaard, P., & Leisner,
782 J. J. (2005). *Carnobacterium divergens* and *Carnobacterium maltaromaticum* as
783 spoilers or protective cultures in meat and seafood: phenotypic and genotypic
784 characterization. *Systematic and Applied Microbiology, 28*(2), 151-164. doi:
785 10.1016/j.syapm.2004.12.001

786 Lawless, H., & Heymann, H. (2010). *Sensory Evaluation of Food: Principles and Practices*
787 (2nd ed.). New York: Springer.

788 Leisner, J. J., Laursen, B. G., Prevost, H., Drider, D., & Dalgaard, P. (2007). *Carnobacterium*:
789 positive and negative effects in the environment and in foods. *FEMS Microbiology*
790 *Reviews, 31*(5), 592-613. doi: 10.1111/j.1574-6976.2007.00080.x

791 Loretz, M., Stephan, R., & Zweifel, C. (2010). Antimicrobial activity of decontamination
792 treatments for poultry carcasses: A literature survey. *Food Control, 21*(6), 791-804. doi:
793 10.1016/j.foodcont.2009.11.007

794 Lu, P. L., Liu, Y. C., Toh, H. S., Lee, Y. L., Liu, Y. M., Ho, C. M., . . . Hsueh, P. R. (2012).
795 Epidemiology and antimicrobial susceptibility profiles of Gram-negative bacteria
796 causing urinary tract infections in the Asia-Pacific region: 2009-2010 results from the
797 Study for Monitoring Antimicrobial Resistance Trends (SMART). *International*
798 *Journal of Antimicrobial Agents, 40*, 37-43. doi: 10.1016/S0924-8579(12)70008-0

799 Machado, E., Coque, T. M., Canton, R., Sousa, J. C., & Peixe, L. (2008). Antibiotic resistance
800 integrons and extended-spectrum β-lactamases among Enterobacteriaceae isolates
801 recovered from chickens and swine in Portugal. *Journal of Antimicrobial*
802 *Chemotherapy, 62*(2), 296-302. doi: 10.1093/jac/dkn179

803 Martin, M. F. S., Sepulveda, D. R., Altunakar, B., Gongora-Nieto, M. M., Swanson, B. G., &
804 Barbosa-Canovas, G. V. (2007). Evaluation of selected mathematical models to predict
805 the inactivation of *Listeria innocua* by pulsed electric fields. *LTW Food Science and*
806 *Technology, 40*(7), 1271-1279. doi: 10.1016/j.lwt.2006.08.011

807 McLeod, A., Mage, I., Heir, E., Axelsson, L., & Holck, A. L. (2016). Effect of relevant
808 environmental stresses on survival of enterohemorrhagic *Escherichia coli* in dry-
809 fermented sausage. *International Journal of Food Microbiology, 229*, 15-23. doi:
810 10.1016/j.ijfoodmicro.2016.04.005

811 Michael, C. A., Dominey-Howes, D., & Labbate, M. (2014). The antimicrobial resistance crisis:
812 causes, consequences, and management. *Frontiers in Public Health, 2*, 145. doi:
813 10.3389/fpubh.2014.00145

814 Mo, S. S., Norstrom, M., Slettemeas, J. S., Lovland, A., Urdahl, A. M., & Sunde, M. (2014).
815 Emergence of AmpC-producing *Escherichia coli* in the broiler production chain in a
816 country with a low antimicrobial usage profile. *Veterinary Microbiology, 171*(3-4), 315-
817 320. doi: 10.1016/j.vetmic.2014.02.002
818 Molin, G. (2000). Modified atmospheres. In B. M. Lund, T. C. Baird-Parker & G. W. Gould
819 (Eds.), *The microbial safety and quality of food, 1*, 214-234. Gaithersburg, MD: Aspen
820 Publishers.
821 Mugler, D. J., & Cunningham, F. E. (1972). Factors affecting poultry meat color - review.
822 *Worlds Poultry Science Journal, 28*(4), 400-406. doi: 10.1079/Wps19720017
823 Mukhopadhyay, S., & Ramaswamy, R. (2012). Application of emerging technologies to control
824 Salmonella in foods: A review. *Food Research International, 45*(2), 666-677. doi:
825 10.1016/j.foodres.2011.05.016
826 Murphy, R. Y., Marks, B. P., & Marcy, J. A. (1998). Apparent specific heat of chicken breast
827 patties and their constituent proteins by differential scanning calorimetry. *Journal of
828 Food Science, 63*(1), 88-91. doi: DOI 10.1111/j.1365-2621.1998.tb15682.x
829 Nesbakken, T. (1995). *Listeria monocytogenes* in the food chain - a foodborne infection
830 problem common to the Nordic countries. *Tema Nord 635*. Copenhagen, Denmark:
831 Nordic Council of Ministers.
832 Olsen, E., Vogt, G., Veberg, A., Ekeberg, D., & Nilsson, A. (2005). Analysis of early lipid
833 oxidation in smoked, comminuted pork or poultry sausages with spices. *Journal of
834 Agricultural and Food Chemistry, 53*(19), 7448-7457. doi: 10.1021/jf050886w
835 Organisation for Economic Co-operation and Development (OECD)/Food and Agriculture
836 Organization of the United Nations (FAO). (2016). *OECD-FAO Agricultural Outlook
837 2016-2025*. Paris, France: OECD Publishing. Retrieved from
838 http://dx.doi.org/10.1787/agr_outlook-2016-en
839 Overdevest, I., Willemsen, I., Rijnsburger, M., Eustace, A., Xu, L., Hawkey, P., . . . Kluytmans,
840 J. (2011). Extended-spectrum beta-lactamase genes of *Escherichia coli* in chicken meat
841 and humans, the Netherlands. *Emerging Infectious Diseases, 17*(7), 1216-1222. doi:
842 10.3201/eid1707.110209
843 Park, S. Y., & Ha, S. D. (2015). Ultraviolet-C radiation on the fresh chicken breast: inactivation
844 of major foodborne viruses and changes in physicochemical and sensory qualities of
845 product. *Food and Bioprocess Technology, 8*(4), 895-906. doi: 10.1007/s11947-014-
846 1452-1

847 Paskeviciute, E., Buchovec, I., & Luksiene, Z. (2011). High-power pulsed light for
848 decontamination of chicken from food pathogens: a study on antimicrobial efficiency
849 and organoleptic properties. *Journal of Food Safety, 31*(1), 61-68. doi: 10.1111/j.1745-
850 4565.2010.00267.x
851 Paton, A. W., Ratcliff, R. M., Doyle, R. M., Seymour-Murray, J., Davos, D., Lanser, J. A., &
852 Paton, J. C. (1996). Molecular microbiological investigation of an outbreak of
853 hemolytic-uremic syndrome caused by dry fermented sausage contaminated with Shiga-
854 like toxin-producing *Escherichia coli*. *Journal of Clinical Microbiology, 34*(7), 1622-
855 1627.
856 Patterson, R. L., & Stevenson, M. H. (1995). Irradiation-induced off-odour in chicken and its
857 possible control. *British Poultry Science, 36*(3), 425-441. doi:
858 10.1080/00071669508417789
859 Picozzi, S., Ricci, C., Gaeta, M., Macchi, A., Dinang, E., Paola, G., . . . Carmignani, L. (2013).
860 Do we really know the prevalence of multi-drug resistant *Escherichia coli* in the
861 territorial and nosocomial population? *Urology annals, 5*(1), 25-29. doi: 10.4103/0974-
862 7796.106962
863 Pitout, J. D. D. (2010). Infections with extended-spectrum beta-lactamase-producing
864 Enterobacteriaceae changing epidemiology and drug treatment choices. *Drugs, 70*(3),
865 313-333.
866 Rowan, N. J., MacGregor, S. J., Anderson, J. G., Fouracre, R. A., McIlvaney, L., & Farish, O.
867 (1999). Pulsed-light inactivation of food-related microorganisms. *Applied and*
868 *Environmental Microbiology, 65*(3), 1312-1315.
869 Schimmer, B., Nygard, K., Eriksen, H. M., Lassen, J., Lindstedt, B. A., Brandal, L. T., . . .
870 Aavitsland, P. (2008). Outbreak of haemolytic uraemic syndrome in Norway caused by
871 stx_2-positive *Escherichia coli* O103:H25 traced to cured mutton sausages. *BMC*
872 *Infectious Diseases, 8*. doi: 10.1186/1471-2334-8-41
873 Shi, H., & Ho, C. T. (1994). The flavour of poultry meat. In F. Shahidi (Ed.), *Flavor of meat*
874 *and meat products*, 52-70. London: Blackie Academic & Professional.
875 Smet, A., Martel, A., Persoons, D., Dewulf, J., Heyndrickx, M., Catry, B., . . . Butaye, P. (2008).
876 Diversity of extended-spectrum beta-lactamases and class C beta-lactamases among
877 cloacal *Escherichia coli* isolates in Belgian broiler farms. *Antimicrobial Agents and*
878 *Chemotherapy, 52*(4), 1238-1243. doi: 10.1128/AAC.01285-07

879 Sommers, C. H., Scullen, O. J., & Sheen, S. (2016). Inactivation of uropathogenic *Escherichia*
880 *coli* in ground chicken meat using high pressure processing and gamma radiation, and
881 in purge and chicken meat surfaces by ultraviolet light. *Frontiers in Microbiology, 7*.
882 doi: 10.3389/Fmicb.2016.00413
883 Sommers, C. H., Sites, J. E., & Musgrove, M. (2010). Ultraviolet light (254 nm) inactivation of
884 pathogens on foods and stainless steel surfaces. *Journal of Food Safety, 30*(2), 470-479.
885 doi: 10.1111/j.1745-4565.2010.00220.x
886 Takeshita, K., Shibato, J., Sameshima, T., Fukunaga, S., Isobe, S., Arihara, K., & Itoh, M.
887 (2003). Damage of yeast cells induced by pulsed light irradiation. *International Journal*
888 *of Food Microbiology, 85*(1-2), 151-158. doi: 10.1016/S0168-1605(02)00509-3
889 Tarek, A. R., Rasco, B. A., & Sablani, S. S. (2015). Ultraviolet-C light inactivation kinetics of
890 *E. coli* on bologna beef packaged in plastic films. *Food and Bioprocess Technology,*
891 *8*(6), 1267-1280. doi: 10.1007/s11947-015-1487-y
892 U.S. Food and Drug Administration (FDA). (2010). *Irradiation in the production, processing*
893 *and handling of food*. Retrieved from
894 http://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/CFRSearch.cfm?CFRPart=17
895 9&showFR=1
896 Ugarte-Romero, E., Feng, H., Martin, S. E., Cadwallader, K. R., & Robinson, S. J. (2006).
897 Inactivation of *Escherichia coli* with power ultrasound in apple cider. *Journal of Food*
898 *Science, 71*(2), 102-108.
899 United States Department of Agriculture (USDA). (2013). *Food safety information: the color*
900 *of meat and poultry*. Retrieved from
901 https://www.fsis.usda.gov/wps/portal/fsis/topics/food-safety-education/get-
902 answers/food-safety-fact-sheets/meat-preparation/the-color-of-meat-and-poultry/the-
903 color-of-meat-and-poultry/CT_Index
904 van Boekel, M. A. (2002). On the use of the Weibull model to describe thermal inactivation of
905 microbial vegetative cells. *International Journal of Food Microbiology, 74*(1-2), 139-
906 159. doi: 10.1016/S0168-1605(01)00742-5
907 van Velzen, E. U. T., & Linnemann, A. R. (2008). Modified atmosphere packaging of fresh
908 meats - sudden partial adaptation caused an increase in sustainability of dutch supply
909 chains of fresh meats. *Packaging Technology and Science, 21*(1), 37-46. doi:
910 10.1002/pts.776

911 Vihavainen, E., Lundstrom, H. S., Susiluoto, T., Koort, J., Paulin, L., Auvinen, P., & Bjorkroth,
912 K. J. (2007). Role of broiler carcasses and processing plant air in contamination of
913 modified-atmosphere-packaged broiler products with psychrotrophic lactic acid
914 bacteria. *Applied and Environmental Microbiology, 73*(4), 1136-1145. doi:
915 10.1128/Aem.01644-06
916 Weber, S. (2005). Light-driven enzymatic catalysis of DNA repair: a review of recent
917 biophysical studies on photolyase. *Biochimica Et Biophysica Acta-Bioenergetics,*
918 *1707*(1), 1-23. doi: 10.1016/j.bbabio.2004.02.010
919 Wekhof, A. (2000). Disinfection with flash lamps. *PDA Journal of Pharmaceutical Science*
920 *and Technology, 54*(3), 264-276.
921 World Health Organization (WHO). (2014). *Antimicrobial resistance: global report on*
922 *surveillance*. Geneva, Switzerland. Retrieved from
923 http://www.who.int/drugresistance/documents/surveillancereport/en/
924 Zhao, C. W., Ge, B. L., De Villena, J., Studler, R., Yeh, E., Zhao, S. H., . . . Meng, J. H. (2001).
925 Prevalence of *Campylobacter spp*., *Escherichia coli*, and *Salmonella* serovars in retail
926 chicken, turkey, pork, and beef from the Greater Washington, DC, area. *Applied and*
927 *Environmental Microbiology, 67*(12), 5431-5436. doi: 10.1128/Aem.67.12.5431-
928 5436.2001

929 **TABLE 1** Strains used in this study

Bacterial species	Strain name[a]	Reference/source/strain/other
Pseudomonas spp.	MF6041	Chicken fillet
	MF6042	Chicken fillet
	MF6043	Chicken fillet
	MF6044	Chicken fillet
B. thermospacta	MF6045	Chicken
	MF6047	Chicken
	MF6049	ATCC11509[b]
C. divergens	MF3036	DSM20623[c]
	MF6031	Chicken fillet
	MF6032	Chicken fillet
	MF6034	Chicken fillet
	MF6038	Chicken fillet
ESBL-producing *E. coli*	MF5658	Chicken[d]
	MF5660	Chicken[d]
	MF5664	Chicken[d]
	MF5670	Broiler[d]
	MF5674	Broiler[d]
***S.* Enteritidis**	MF3817	1049-1-99[d]
	MF3818	Poultry, 61-358-1[e]
	MF3824	ATCC13076[b]
L. monocytogenes	MF3508	2230/92 (Nesbakken, 1995)
	MF3509	167 (Blom, Nerbrink, Dainty, Hagtvedt, Borch, Nissen, & Nesbakken, 1997)
	MF3510	187 (Blom, Nerbrink, Dainty, Hagtvedt, Borch, Nissen, & Nesbakken, 1997)
	MF3571	EGD-e (Glaser, Frangeul, Buchrieser, Rusniok, Amend, Baquero, Berche, Bloecker, Brandt, Chakraborty, Charbit, Chetouani, Couve, de Daruvar, Dehoux, Domann, Dominguez-Bernal, Duchaud, Durant, Dussurget, Entian, Fsihi, Garcia-del Portillo, Garrido, Gautier, Goebel, Gomez-Lopez, Hain, Hauf, Jackson, Jones, Kaerst, Kreft, Kuhn, Kunst, Kurapkat, Madueno, Maitournam, Vicente, Ng, Nedjari, Nordsiek, Novella, de Pablos, Perez-Diaz, Purcell, Remmel, Rose, Schlueter, Simoes, Tierrez, Vazquez-Boland, Voss, Wehland, & Cossart, 2001)
S. aureus	MF2123	ATCC25923[b]
	MF2124	ATCC12600[b]
	MF2125	ATCC6538[b]
Enterohemorrhagic *E. coli* (EHEC)	MF3572	O103, fermented sausage, linked to outbreak in Norway 2006 (Schimmer, Nygard, Eriksen, Lassen, Lindstedt, Brandal, Kapperud, & Aavitsland, 2008)[f]
	MF3574	ATCC43895[b], 0157:H7
	MF3576	O111:H^{-}, semi-dry fermented sausage, outbreak Australia 1995 (Paton, Ratcliff, Doyle, Seymour-Murray, Davos, Lanser, & Paton, 1996)[g]
	MF5554	O145 (McLeod, Mage, Heir, Axelsson, & Holck, 2016)

[a]Antibiotic resistant strains. All strains were grown in their respective medium with 200 µg/ml rifampicin, except ESBL-producing *E. coli* grown in medium with 50 µg/ml ampicillin.

[b]ATCC, American Type Culture Collection, Manassas, VA, USA.

[c]DSM, Deutsche Sammlung von Microorganismen und Zellkulturen, Braunschweig, Germany.

[d]Kindly received from the Norwegian Veterinary Institute, Oslo, Norway.

[e]Kindly received from the Technical University of Denmark, the National Veterinary Institute, Denmark.

[f]Kindly received from the Norwegian School of Veterinary Science, Oslo, Norway.

[g]Kindly received from Statens Serum Institut, Copenhagen, Denmark.

930

931

932 **TABLE 2** Parameters for Weibull models predicting bacterial
933 reduction on chicken fillet meat after continuous UV-C and
934 pulsed UV light exposures, and goodness-of-fit parameters of
935 the models

	Bacterial species	α	β	RMSE	R^2
Continuous UV-C light	***E. coli* EHEC**	2.03E-06	0.09	0.31	0.75
	L. monocytogenes	2.02E-09	0.07	0.47	0.41
	***S.* Enteritidis**	2.35E-05	0.14	0.41	0.64
	S. aureus	2.22E-15	0.05	0.20	0.76
	***Pseudomonas* spp.**	2.86E-09	0.09	0.39	0.68
	C. divergens	1.45E-08	0.10	0.37	0.74
	B. thermospacta	1.66E-07	0.11	0.31	0.80
	***E. coli* ESBL**	1.65E-08	0.10	0.38	0.74
	All	9.89E-09	0.09	0.53	0.25

	Bacterial species	α	β	RMSE	R^2
Pulsed UV light	***C. divergens***	3.79E-10	0.06	0.29	0.86
	L. monocytogenes	2.27E-04	0.13	0.37	0.63
	***S.* Enteritidis**	6.32E-02	0.31	0.42	0.79
	***E. coli* EHEC**	5.29E-02	0.32	0.41	0.79
	***E. coli* ESBL**	7.58E-03	0.24	0.28	0.89
	***Pseudomonas* spp.**	1.31E-03	0.20	0.55	0.71
	S. aureus	6.61E-03	0.24	0.47	0.47
	B. thermospacta	9.21E-03	0.26	0.37	0.82
	All	6.23E-03	0.22	0.54	0.46

936

937 **SUPPORTING INFORMATION**

938

939 **TABLE S1** Bacterial reductions log CFU/cm^2 on chicken fillet meat after continuous UV-C
940 and pulsed UV light treatments at different fluences (J/cm^2)

941

	Continuous UV-C light treatment[a], J/cm^2					Pulsed UV light treatment[a], J/cm^2			
Bacterial species	**0.05**	**0.1**	**0.3**	**0.6**	**3.0**	**1.25**	**3.6**	**10.8**	**18.0**
***S.* Enteritidis**	1.56 (0.15)	1.21 (0.13)	1.81 (0.16)	1.53 (0.23)	2.44 (0.17)	0.90 (0.05)	1.58 (0.09)	2.44 (0.20)	2.23 (0.19)
L. monocytogenes	1.49 (0.13)	1.13 (0.14)	1.82 (0.22)	1.36 (0.16)	1.81 (0.27)	1.08 (0.12)	1.83 (0.13)	2.01 (0.25)	1.63 (0.21)
S. aureus	2.22 (0.18)	2.23 (0.22)	2.56 (0.20)	2.05 (0.26)	2.41 (0.16)	1.25 (0.09)	2.21 (0.16)	2.95 (0.33)	2.61 (0.25)
***E. coli* EHEC**	1.08 (0.18)	1.34 (0.19)	1.10 (0.12)	1.30 (0.18)	1.65 (0.17)	1.06 (0.11)	1.96 (0.22)	1.98 (0.29)	2.93 (0.21)
***Pseudomonas* spp.**	2.01 (0.10)	1.85 (0.20)	1.95 (0.15)	2.23 (0.21)	2.66 (0.24)	1.67 (0.06)	2.25 (0.18)	2.45 (0.18)	3.01 (0.14)
B. thermospacta	1.70 (0.17)	1.74 (0.24)	2.41 (0.22)	2.33 (0.32)	2.68 (0.37)	1.30 (0.13)	2.28 (0.20)	3.00 (0.37)	2.88 (0.30)
C. divergens	1.90 (0.16)	1.95 (0.25)	2.32 (0.14)	2.04 (0.14)	2.82 (0.14)	1.46 (0.17)	1.59 (0.17)	1.84 (0.21)	1.61 (0.35)
***E. coli* ESBL**	1.65 (0.11)	1.91 (0.11)	2.43 (0.20)	2.79 (0.15)	2.56 (0.22)	1.34 (0.09)	2.17 (0.17)	2.58 (0.17)	2.83 (0.25)
***C. divergens* MAP[b]**	1.26 (0.15)	1.30 (0.11)	1.52 (0.21)	1.80 (0.24)	1.38 (0.14)	0.54 (0.21)	0.90 (0.22)	1.35 (0.29)	1.53 (0.08)
***E. coli ESBL* MAP[b]**	1.46 (0.11)	1.69 (0.22)	2.12 (0.27)	2.49 (0.25)	2.33 (0.18)	0.61 (0.14)	1.09 (0.12)	1.70 (0.18)	1.56 (0.16)

[a]Standard error values are shown in brackets

[b]MAP refers to modified atmosphere packaging