The potential of UVC decontamination to prolong shelf-life of par-baked bread

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ABSTRACT

The effect of UVC (254 nm) treatment on the mould-free shelf-life of par-baked wholemeal, rye and six-grain bread was examined. Currently, these breads are par-baked, wrapped in HDPE-foil and transported or stored at room temperature for a couple of days before being full-baked and sold/consumed. Generally, after five days, these breads show signs of mould spoilage. A shelf-life increase of one or more days would already offer immense economical and logistic benefits for the baker or retailer. In this study, the parameters fluence rate (irradiation intensity), fluence (UV dose), distance to the UV-lamp (DTL) and number of layers of a common wrapping HDPE-foil (20 µm) were diversified. The breads were subjected to a UVC treatment (0 – 2502 mJ/cm²), packed and stored at room temperature for a period of 15 days (21.5 ± 0.8°C). Similar as for the breads, agar plates with mould spores of *Aspergillus niger*, *Aspergillus montevidensis* and *Penicillium roqueforti* were UVC treated (0 - 1664 mJ/cm²) and checked daily for visible mould growth during 15 days (25°C). *A. niger* showed the strongest resistance towards UVC, a fluence of 800 mJ/cm² was needed to inhibit growth during 15 days of storage, whereas for *P. roqueforti* and *A. montevidensis* respectively UV levels of 291 and 133 mJ/cm² were found sufficient. Furthermore, the shelf-life of wholemeal, rye and six-grain bread can be prolonged from 5 to respectively 6, 8 and 9 days using 2502 mJ/cm². The effect of higher UVC dosage and longer shelf-lives was strongly impacted by the wide variability on mould growth. Main factors influencing the potential of UV decontamination were the rough bread surface, differences in DTL, the possibility of post-contamination and UV permeability of packaging materials.

Keywords: UVC; par-baked bread; *Aspergillus niger*; *Penicillium roqueforti*; *Aspergillus montevidensis*

1. Introduction

Par-baking contributes to the extension of the microbiological and technological shelf-life of bread (Almeida et al., 2015; Debonne et al., 2018). One of the major benefits of par-baking is flexibility provided for bakers, restaurants and consumers who can easily bake off products according to demand (Decock & Cappelle, 2005; Lambert et al., 2009). Usually, par-baked (PB) bread products for business-to-business purposes are baked for 95%. However, this can vary from 50 up to 95% depending on the type of product and the offset market (Eveline Lopes Almeida & Chang, 2013; Fik & Surwka, 2002). PB breads can be stored under either frozen, ambient or chilled temperatures. The market share of frozen bread is large and is increasingly growing in Europe (Decock & Cappelle, 2005). Distribution of frozen PB bread is aiming at hotels and catering industries (eating outdoors), while for unfrozen PB breads, bake-off and consumption are mainly intended to take place indoors. The market share of unfrozen PB bread is smaller, nevertheless important. These breads are mostly stored at room temperature and are packaged under modified atmosphere (MAP). They often comprise packages of small amounts of products for individual use. On the contrary, bakers and restaurants have a higher demand of products which renders small packaging an expensive and inefficient strategy to store products. For small par-baked bread buns and rolls, frozen storage is currently the most important strategy. However, freezing can speed up retrogradation of bread after full-baking, thereby shortening the physico-chemical shelf-life of bread (Bárcenas & Rosell, 2006; Fik & Surwka, 2002). In larger breads which are not consumed immediately but over a period of time, freezing has a much more pronounced effect on the physico-chemical quality (Debonne et al., 2017) and is therefore to be avoided. PB breads are characterized by a high aw (≥ 0.94), depending on the degree of par-baking and the type of product (Debonne et al., 2018). Therefore, unfrozen PB bread products are highly sensitive to post-baking contamination. Mould growth is by far the most important shelf-life limiting factor of PB bread, with *Penicillium* spp., *Cladosporium* spp. and *Aspergillus* spp. being the most dominant species (Saranraj, 2012). The shelf-life of frozen PB bread can be up to 12 months (Vulicevic et al., 2004), whereas that of clean label MAP PB-bread is 3 weeks (Deschuyffeleer et al., 2011) and without MAP 4 to 6 days (Debonne et al., 2018). Main factors influencing microbiological and physico-chemical properties of bread are relative humidity (RH) of the packaging environment and storage temperature. RH plays an important role in moisture migration during storage. When the RH of the environment is lower than the a_w of bread, the environment will take up water from the moist bread. This can result in harder bread crumb properties after full-baking (Baik & Chinachoti, 2000), but also in a bread which is potentially more resistant towards microbiological spoilage due to the lower moisture content and reduced a_w. A similar trade-off exists for storage temperature.

Besides chilled and frozen storage, MAP and (chemical) preservatives, UVC decontamination (254 nm) of air and surfaces can also be a promising strategy to prolong mould-free shelf-life of par-baked bread. In a study of Debonne et al. (2020), the use of a Flexbaker-UV storage unit with built in UVC air decontamination was tested. Storage of PB-bread in a flexbaker-UV with 90% RH and 3°C extended mould free shelf-life to up to 3 weeks and showed similar antifungal effect as MAP. Begum et al. (2009) investigated the effectiveness of UVC surface treatment against *Aspergillus flavus*, *Aspergillus niger*, *Aspergillus ruber* (formerly known as *Eurotium rubrum*) and *Penicillium coryphilum* and found that UVC irradiation can effectively inactive spores, but the efficacy varies significantly according to methods of exposure and among genera. Spores of *A. niger* showed the strongest resistance compared to the other

moulds tested. Kawaguchi et al. (2019) found that 70 mJ/cm² is effective in delaying mould growth of *Penicillium* spp. from 4 to 6 days without having to compromise on taste. They also stated that to improve the use of UV irradiation in bread production lines, it is necessary to decrease the amount of mould on bread. By doing so, UV will be more effective. One of the limitations of UVC decontamination is the small penetration depth of UVC light. The presence of surface cracks or small particles on bread (e.g. flour, grains) reduces the effectiveness of UV as some fungal spores might not be exposed to UV light directly (Begum et al., 2009; Kawaguchi et al., 2019). The fact that this technology does not emit heat nor causes condensation on the packaging is a positive aspect. Moreover, it is considered a highly efficient green technology which reduces the need of any anti-microbial and comes with a lower operational cost compared to other food processing techniques. The data on the disinfection of surfaces of solid foods, meat, and fresh products are rather limited (Singh et al., 2021).

The aim of this study was to evaluate the effect of UVC surface decontamination on agar plates against three bread moulds and on three bread varieties of par-baked bread which were prone to natural contamination. In order to mimic a real situation in the bakery, the effect of a wrapping foil (HDPE-foil) was also studied. On the agar plates, fluence was varied between 0 and 1664 mJ/cm², whereas on bread the range was 0 to 2502 mJ/cm².

2. Materials and methods

2.1. Experimental design

This study consisted of three main research questions (Figure 1). First, what influence does the distance to the lamp (DTL) and layers of HDPE-foil have on the fluence? Second, how sensitive are bread moulds towards UVC? Third, can UVC decontamination be used as a tool to prolong mould-free shelf-life of par-baked bread? In the first part, the effect of DTL (12.5, 17.0 and 21.5 cm) and HDPE-foil (0 – 4 layers) on the UVC transmission was studied. In the second part, three moulds were selected. *A. niger* was selected based on its increased resistance towards UVC (Begum et al., 2009) and has been isolated from bread products (Dagnas et al., 2015; Valerio et al., 2009), *A. montevidensis* (formerly known as *Eurotium amstelodami*) is known for its growth on intermediate moisture foods and has been isolated from bakery products (Greco et al., 2021; Guynot et al., 2005; Vytřasová et al., 2002), and *P. roqueforti* based on its high tolerance against weak organic acid preservatives (Kalai et al., 2017) and its occurrence as early bread spoilage organism (Garcia et al., 2019; Moro et al., 2022). Their sensitivity against UVC was tested on agar plates to reduce all other factors influencing the outcome. In the third part, par-baked wholemeal, rye and six-grain breads were subjected to UVC decontamination and mould-free shelf-life was recorded during a period of 15 days.

2.2. Materials and methods

2.2.1. Fungal isolates and growth medium

Aspergillus niger van Tieghem (DTO 359-C5), *Aspergillus montevidensis* (formerly known as *Eurotium amstelodami* (Chen et al., 2017)) (MUCL 15640) and *Penicillium roqueforti* (MUCL 046746) were kept active on malt extract agar (MEA, Thermo Scientific™ Malt Extract Agar *(Dehydrated) - 500 g) or dichloran-glycerol agar (DG18, Thermo Scientific™ Dichloran-Glycerol 18%* (DG18) (ISO) Agar Base (Dehydrated) - 500 g) + chloramphenicol supplement; for *Eurotium* spp.) (Oxoid). They are maintained in the culture collection of the Laboratory of Applied Mycology MYCOLAB, Department of Food Technology, Safety and Health,

Ghent University (Ghent, Belgium). One week prior to use, fungal spores were transferred to fresh MEA/DG18 plates (3x) and incubated for 7 days at 26°C. Sterile Tween 80 (polyoxyethyleensorbitan mono oleaat, Merck) - water solution (1 g Tween 80 per liter distilled water) (5 mL) was added to a full-grown petridish. All the fungal material was scraped loose from the petridish. The Tween-solution was filtered in a sterile falcon tube using a sterile cotton filter (3x). The filter was removed and the falcon tube was centrifuged for 15 min at 8000 rpm (Relative centrifugal force (RCF) of 6654) and 4°C. After removal of the supernatant, the pellet was resuspended in 25 ml Tween-PBS (1 g Tween 80 and 10 tablets of PBS per liter of distilled water) (Phosphate buffered saline, Oxoid). The centrifugation step was repeated and the supernatant was removed. Furthermore, the pellet was resuspended in 25 ml of PBS and the latter centrifugation step was repeated a second time. The concentration of spores present was determined by a microscopic evaluation using a Thoma cell counting chamber (7 – 8 log spores/mL). Finally, a concentration of 100 spores per 20 µL volume was obtained and used to inoculate the agar plates. Three spots of the mould spore suspension (5 x 10^3 spores/mL) were applied on each Petri Dish. In total there were 12 replicate spots per condition.

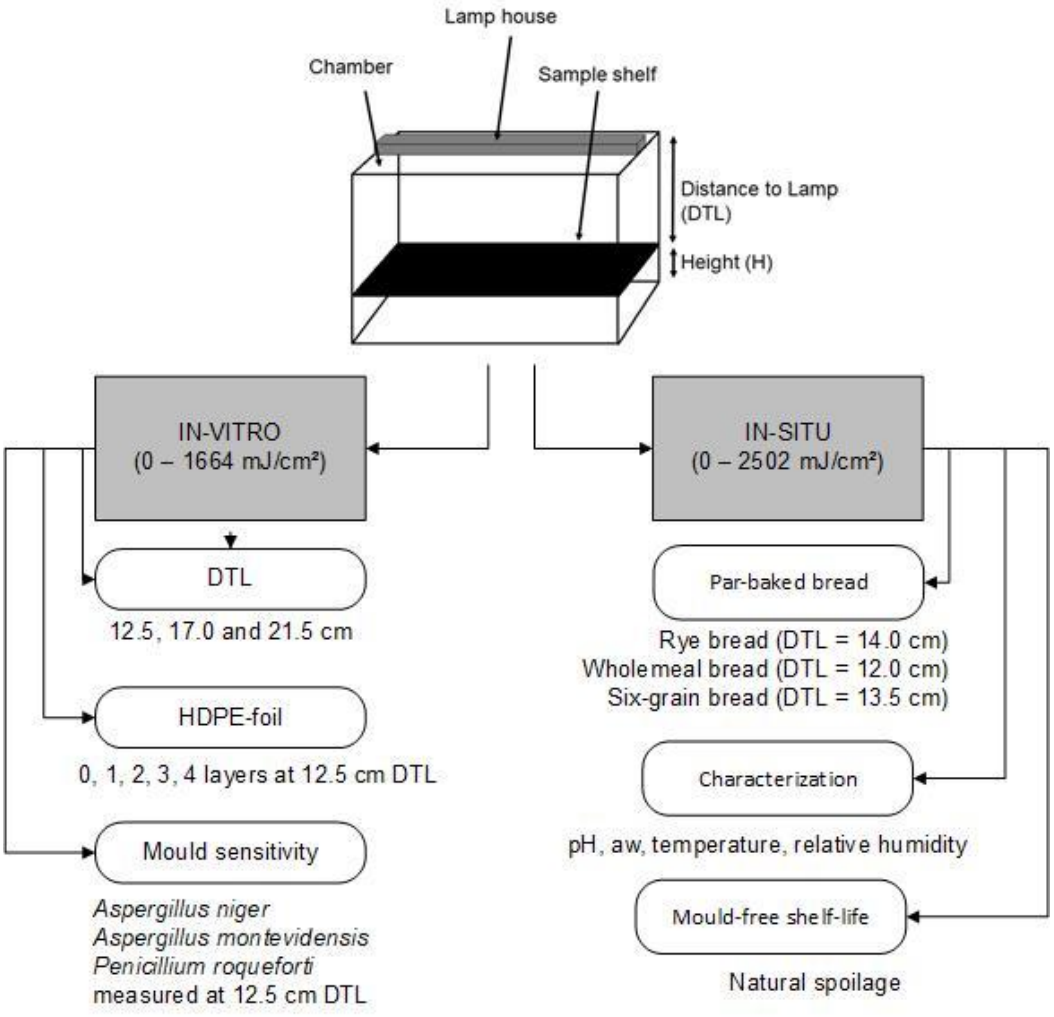

Figure 1. Schematic overview of the experimental design of the study.

2.2.2. Breads

Three bread varieties were supplied by Bakkerij BroodNodig (Hofstade, Belgium): rye bread, wholemeal bread and six-grain bread (Figure 2). All breads were par-baked at the bakery and transported in crates (per 12), wrapped in High-density polyethylene (HDPE)-foil (20 µm, Galoppin), to the University Campus (Ghent, Belgium) where the UVC treatments were conducted. Par-baking was stopped when the core temperature of the breads reached a certain temperature: e.g. 93°C for wheat bread and 97°C for rye bread. These breads are considered fully-baked after 10-11 min baking at 190-200°C (reheated until core temperature reaches 65°C). However, the breads were already consumable due to the advanced state of par-baking. Because of logistic reasons, the par-baked breads were frozen upon arrival (-18°C), and were collected from the freezer when needed for UVC treatment. UV treatment of all the breads was spread out over multiple days. All breads were thawed for 1 to 3h before the decontamination treatment. The intrinsic properties of the bread crust were measured max. 3h after thawing and 48h after thawing. The a_w was checked with a LabMaster-Aw (Novasina) whereas pH was measured with a portable pH meter (model HI 83141, Hanna Instruments) (Table 1). The pH of the crust was measured as follows: 10 g crust was dissolved in 100 mL distilled water. After 1h soaking, pH was measured of the suspension. The height of the breads is also given in Table 1, as the distance between the bread surface and the UVC lamp played an important role in the final fluence reaching the bread surface. The distance to the lamp (DTL) was respectively 14.0 (rye), 12.0 (wholemeal) and 13.5 (six-grain) cm. Height was measured at the highest point. Storage temperature and relative humidity in the bags were logged with four Testo 174H loggers. The data was retrieved using a Testo Interface 174T/174H and Software ComSoft Basic (Testo SE & Co. KGaA, Germany). The temperature was recorded throughout the whole storage period of the experiment. The temperature was 21.5 ± 0.8 °C and relative humidity was 77.0 ± 7.4%.

Figure 2. Side (left) and top (right) view of the three types of bread, from top to bottom: rye bread, wholemeal bread and six-grain bread.

Table 1: pH, a_w and height of the breads. pH and a_w measured at the start (max. 3h after thawing) and after 48h stored at 21.5°C (n = 3)

	At the start		48h after thawing		
	pH	a_w	pH	a_w	Height (cm)
Rye bread	5.47 ± 0.02	0.914 ± 0.011	5.50 ± 0.02	0.939 ± 0.001	7.5 ± 0.5
Wholemeal bread	5.74 ± 0.03	0.883 ± 0.015	5.78 ± 0.02	0.933 ± 0.002	9.5 ± 0.5
Six-grain bread	5.88 ± 0.06	0.870 ± 0.007	5.74 ± 0.04	0.925 ± 0.003	8.0 ± 0.5

2.2.3. UVC treatment (lamp and dosimetry)

The UVC lamp (254 nm, 230V, 50/60 Hz, 0.14A, 2x15W, produced by Thermo Electron Corporation (Massachusetts, USA) was placed in a closed box in which a measuring probe was added (XRD140T254, LOT Quantum Design GmbH, Darmstadt, Germany). The probe measured the fluence rate or intensity of the lamp (mJ/cm²) at a given DTL. Based on exposure time (s) and fluence rate, the UVC dose or fluence (mJ/cm²) was calculated. Additionally, an experiment with HDPE-foil was conducted in order to gain information on the UVC permeability of the wrapping foil, used in a bakery environment for transporting the par-baked breads in crates. After par-baking, the breads are packed per 12 in crates covered with HDPE-foil. On the bottom and the side of the crates, one layer of HDPE-foil is present, whereas on the top there are four layers of foil present (overlaying/wrapping technique). Currently, breads in the center of the crates are touching each other, no foil is present between them. The effect of 0, 1, 2, 3 and 4 layer of HDPE-foil covering the probe and DTL of 21.5, 17 and 12.5 cm was studied. The fluence rate was measured three times over a period of 180s. UV treatment on bread was performed without HDPE-foil.

The effect of UVC on spoilage moulds on agar (DTL = 12.5 cm) and the mould-free shelf-life of bread was studied with respectively maximal levels of 1664 mJ/cm² and 2502 mJ/cm². The exposure time of the agar plates was varied from 0 to 600 s which correlated with the following fluence (mJ/cm²): 0 (0s), 27 (15s), 60 (30s), 133 (60s), 291 (120s), 458 (180s), 626 (240s), 800 (300s) and 1664 (600s). The breads were subjected to longer exposure times and therefore also higher fluence: 0 (0s), 149 (60s), 481 (180s), 818 (300s), 1155 (420s), 1660 (600s) and 2502 mJ/cm² (900s). The fluence for the breads was calculated with the probe placed at 12.5 cm DTL (matches with a height of bread of 9 cm). After UVC treatment, the agar plates were sealed with parafilm and incubated at 25°C for 15 days, whereas the breads were packed in sealed plastic bags (PA/PE/20/70) (PA: polyamide; PE: polyethylene) to ensure no further post-contamination. The plates were checked daily for visual mould growth. The breads were treated similarly, but here we made a distinction between the top, sides and bottom of the bread. The static experimental set-up only allowed decontamination on the top of the breads.

2.6. Statistical analysis

To assess significant differences among samples, a multiple comparison analysis of samples was performed using SPSS. Where the results were normally distributed, either a Tukey test (homoscedasticity) or Dunnett T3 test was used to describe the means with 95% confidence (p = 0.05). A Dunn test for multiple comparisons was applied, preceded by a non-parametric Kruskal-Wallis one-way ANOVA, for non-normally distributed data. For the determination of the significant differences between the mould-free shelf-life, the Bonferroni correction was applied for multiple tests (p = 0.05).

3. Results & Discussion

3.1. UVC transmission of HDPE-foil

At a semi-industrial level, par-baked breads are often wrapped in plastic foil and placed in bread crates. HDPE is of high interest in flexible packaging due to its high moisture barrier and strength (Bauer et al., 2021). However, UVC cannot pass through most plastics or ordinary glass (Ha et al., 2016). In this study, the transmission of UVC irradiation through HDPE-film was studied in order to examine the potential of using this film for packaging of bread and consecutive UVC decontamination as to reduce the risk of post-contamination upon storage. Figure 3 shows the measured fluence rate in terms of the number of HDPE-layers (0 – 4; 20 µm) and at distance to lamp (DTL) 12.5, 17.0 and 21.5 cm. A certain time is needed to

reach an equilibrium fluence rate. In Table 2, the mean values between 150 and 180s of irradiation time are presented. The fluence rate strongly decreased with increasing DTL and is conversely proportional to the square of the distance from the source (Jin et al., 2005) or coincide with the power trend line (fluence rate x DTL) (Chadyšiene et al., 2009). These findings were validated and resulted in R^2 ranging from 0.995 (0 HDPE) to 1.000 (4 HDPE) for the power trend line; e.g. 0 layers HDPE-foil: y = fluence rate; x = DTL; eq. $y = 117.95x^{-1.314}$; 4 layers: eq. $y = 94.274x^{-1.315}$. Four layers of HDPE-foil reduced UV transmission by 19.3 – 22.1% compared to no layers of HDPE, whereas one layer reduced transmittance with 2.4 – 4.4%. Ha et al. (2016) found that PE-film of 70 µm thick transmits 60% of UVC light, whereas PP (polypropylene) of the same thickness 80%. The DTL plays a big role on fluence, but also the position of the lamp and the orientation of the light influences the decontamination potential (Oms-Oliu et al., 2010).

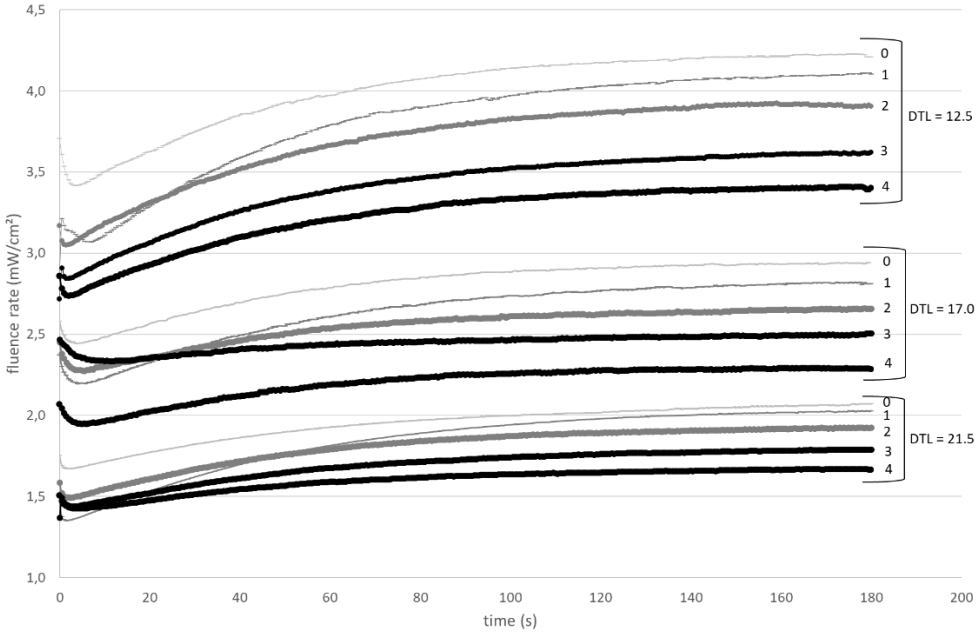

Figure 3. Fluence rate (mW/cm²) measured at 12.5, 17.0 and 21.5 cm Distance to Lamp (DTL) and influence of 0, 1, 2, 3 or 4 layers of HDPE-foil (n = 3).

Table 2: Fluence rate measured at different DTL (Distance to Lamp, cm) and influence of 0, 1, 2, 3 or 4 layers of HDPE-foil, mean fluence rate measured between 150 and 180s (n = 3). The last column represents the relative decrease of fluence rate compared to 0 layers of HDPE-foil (%) (n = 3).

DTL (cm)	HDPE	fluence rate (mW/cm²)	% decrease vs 0 HDPE
12.5	**0**	4.21 ± 0.03	-
	1	4.11 ± 0.01	2.4%
	2	3.90 ± 0.01	7.4%
	3	3.62 ± 0.04	14.1%
	4	3.40 ± 0.01	19.3%
17	**0**	2.94 ± 0.02	-
	1	2.81 ± 0.02	4.4%
	2	2.66 ± 0.02	9.3%
	3	2.51 ± 0.01	14.7%
	4	2.29 ± 0.01	22.1%

21.5	**0**	2.07 ± 0.01	
	1	2.02 ± 0.01	2.4%
	2	1.92 ± 0.00	7.2%
	3	1.79 ± 0.01	13.6%
	4	1.67 ± 0.01	19.4%

3.2. Susceptibility of moulds to UVC

Growth of all three moulds was inhibited for 15 days with the use of 800 mJ/cm² (Table 3). *A. niger* showed the highest resistance, compared to *A. montevidensis* and *P. roqueforti* for which respectively 133 and 291 mJ/cm² was sufficient for growth inhibition. *A. niger* spores contain the pigment melanin which can partially absorb UVC (Begum et al., 2009). This shows that spores with dark pigmentation are more resistant towards UV. Begum et al. (2009) found that 928 mJ/cm² was enough to completely destroy *A. niger* on agar plates which is in line with the results obtained in this study. In a study of Trivittayasil et al. (2015), UVC resistance of *Cladosporium cladosporoides* and *Penicillium digitatum* was compared. They concluded that *P. digitatum*, which is a non-melanized fungus, is significantly more sensitive to UVC radiation. In order to achieve 3 log reduction on PDA agar, 500 mJ/cm² was required for *C. cladosporoides* whereas for *P. digitatum* 60 mJ/cm² was sufficient (Trivittayasil et al., 2015).

Table 3: Percentage of UVC treated agar plates, containing spores of *A. niger*, *A. montevidensis* and *P. roqueforti*, showing no growth after 15 days of storage at 25°C (n = 9)

UV dose (mJ/cm²)	*A. niger*	*A. montevidensis*	*P. roqueforti*
0	0%	0%	0%
27	0%	22%	33%
60	0%	78%	56%
133	0%	100%	78%
291	0%	100%	100%
458	33%	100%	100%
626	78%	100%	100%
800	100%	100%	100%
1664	100%	100%	100%

3.3. Mould-free shelf-life of par-baked bread treated with UVC

Values for pH of crust, a_w of crust and height of par-baked bread after 1-3h after thawing and 48h after storage at room temperature are given in Table 1. The pH of rye bread (5.47 ± 0.02) was slightly lower compared to wholemeal (5.74 ± 0.03) and six-grain bread (5.88 ± 0.06). The pH did not change significantly over time. The a_w was the lowest for wholemeal and six-grain bread crust (resp. 0.883 ± 0.015 and 0.870 ± 0.007), compared to rye bread at the start (0.914 ± 0.011). However, after 48h of storage in closed plastic bags, a_w increased for all breads and ranged from 0.925 – 0.939. We assume that pH and a_w will not impact potential differences observed for mould-free shelf-life as the values are more or less similar for all three bread types. Initial microbiological load, presence of cracks (irregular surface) and small particles on the bread crust such as flour and grains will be more important. The effectiveness of UVC on natural spoilage on bread was studied (Figure 4). Mould-free shelf-life was recorded daily during a period of 15 days. Without UV treatment, (median) shelf-life of par-baked bread was 5 to 6 days. A significant increase in shelf-life was already observed for rye and six-grain bread at 149 mJ/cm². The median value increased with respectively 2.5 days and 1 day. At higher fluence, the median shelf-life showed an increase compared to

previous UV dosage for wholemeal bread at 481 mJ/cm² (+ 2 days), 1155 mJ/cm² (+ 3 days) and 2502 mJ/cm² (+ 3.5 days). However, due to the increase in interquartile range and the Bonferroni correction applied on the data, further increase in shelf-life was not proven significant. Similar trend was observed for rye bread (+ 5 days at 1155 mJ/cm²; + 7.5 days at 1660 mJ/cm²) and six-grain bread (+ 3 days at 481 mJ/cm²; + 4 days at 1660 mJ/cm²). These values which are referred to are median values. A wide interquartile range is often observed and is inherent to mould-free shelf-life. This is due to potential post-contamination after UVC treatment, the shadowing effect and the irregular surface of the bread crust (Kawaguchi et al., 2019; Raeiszadeh & Adeli, 2020). When considering the highest dosage tested (2502 mJ/cm²) and the minimum shelf-life, fungal spoilage on wholemeal bread can be prolonged from 5 to 6 days, for rye bread from 5 to 8 days and for six-grain bread from 5 to 9 days. The values for the coefficient of determination (R^2) between UV dosage and mould-free shelf-life were respectively $R^2 = 0.31$, $R^2 = 0.66$ and $R^2 = 0.53$ for wholemeal bread, rye bread and six-grain bread. This means that the shelf-life can be partly assigned to UV dosage, whereas the rest will be a results of post-contamination, shadowing effect and irregular bread crust.

Kawaguchi et al. (2019) found that within *Penicillium* spp. UVC resistance varies among species or strains. For example, *P. hispanicum* was far more resistant than *P. chrysogenum*, whereas *P. paneum* and *P. chermesinum* were the most sensitive. They also studied the effectiveness of UVC decontamination on white bread and concluded that the mould-free shelf-life could be prolonged with one day using 70 mJ/cm² UVC radiation. Higher fluence was not tested due to the concern of the risk of oxidized flavor in white bread. However, the formation of off-flavors and aromas is likely dependent on the wavelength and dose and will be different for different food products. Consequently, in order to determine the best way to use UV, it is necessary to test each product for its spectral response to UV (Koutchma, 2009). Sensory tests were not conducted in this study, because the UVC treatment was only applied on the crust of the par-baked bread, whereas the share of UVC treated bread crust is minimal upon consumption of a bread slice. Moreover, there are only few studies mentioning the sensory impact of UVC treatment of bread.

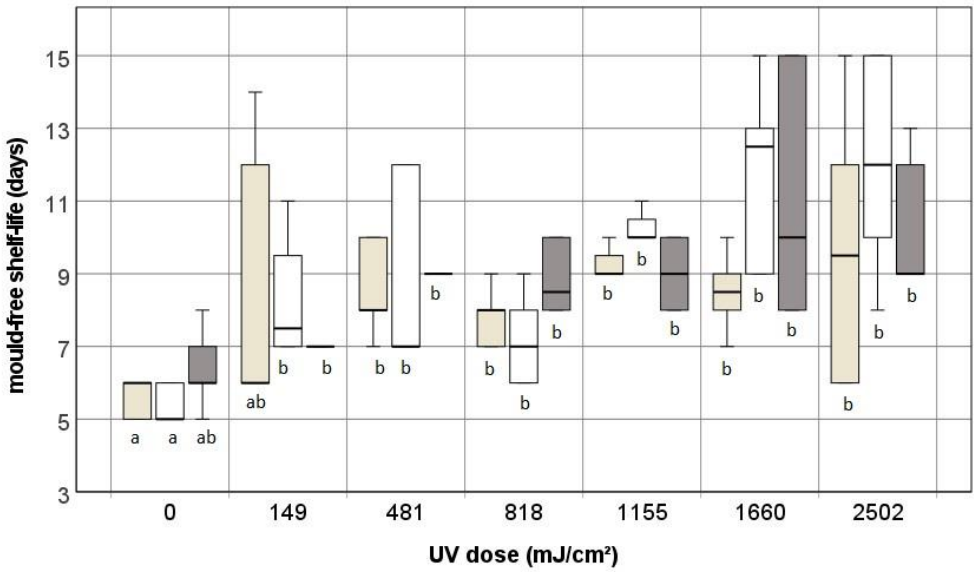

Figure 4. Mould-free shelf-life of wholemeal bread (off-white), rye bread (white) and six-grain bread (grey) in function of UV-dose (mJ/cm²), stored at 21.5 ± 0.8°C. Different letters indicate significant different values ($p < 0.05$) ($n > 6$)

3.4. Industrial application

Prolonging mould-free shelf-life of par-baked bread with a few days can provide various economical and logistic benefits for industrial bakers. In research papers, the use of static UVC systems for solid foods is often mentioned, either with lamps on one side, two sides, or lamps placed longitudinally around the chamber's inner surface (Lázaro et al., 2014; Manzocco et al., 2011; Manzocco & Nicoli, 2015; Rosario et al., 2021). In static systems with one side exposure, the food product must be turned to obtain an even level of decontamination. Whereas with two or more side exposure the food product must be placed on a food support in the form of a UV-permeable net or film. The static approach in this study showed the potential of UVC decontamination on the top of the breads, meaning in direct contact with UV-light. Moreover, the possibility of using HDPE-foil as an extra hurdle for preventing post-contamination was highlighted. The UVC permeability of the foil reduced with max. 22.1% using 4 layers of HDPE-foil. This showed that the combination of UVC treatment and wrapping of the breads in HDPE-foil can be a promising strategy to prolong shelf-life of par-baked bread with a couple of days. An engineering approach can further elucidate on how to implement mechanical rotating systems which can be used for UVC decontamination, preferably of par-baked breads packaged in UVC permeable foil and bread crates which enables easy storage and transport of these breads. However, stacking in bread crates introduces an extra problem for which a solution must be found: blind spots between two adjacent breads. There the bread crust has no direct contact with UVC radiation and is therefore not UVC treated. Further research is needed solving this problem as well, without having to increase the amount of packaging foil or excessive energy needs.

4. Conclusion

UVC treatment and HDPE-foil packaging can be promising alternatives to prolong mould-free shelf-life of par-baked bread. Shelf-life of wholemeal, rye and six-grain bread was extended with respectively one day (from 5 to 6), three days and four days. Moreover, the HDPE-foil showed promising UVC transmittance and can be used as an extra hurdle to prevent early mould spoilage on par-baked bread. This study encourages future studies approaching the mould-free shelf-life of bread using UVC decontamination.

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