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Effect of titanium dioxide film thickness on photocatalytic and bactericidal activities against *Listeria monocytogenes*

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ABSTRACT

Structural, microstructural and bactericidal surface properties of TiO₂-coated glass substrates elaborated by reactive RF-sputtering are investigated. As pathogenic bacteria in biofilms are a major concern in food industries due to their growing resistance to cleaning and sanitizing procedures, the development of photoactive surfaces exhibiting bactericidal properties is acknowledged as an

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effective approach to tackle bacterial contaminations. Our principal aim concerns the study of the photoactive top-layer thickness impact (from 80 nm to ~500 nm) on *Listeria monocytogenes*. Structural characterization of the TiO₂ layers demonstrates that anatase and rutile phases are both present, depending on the film thickness. Photocatalytic activity of the samples has been evaluated through the degradation of aqueous methylene blue (MB) solutions under UVA light illumination for various time periods. The results show an efficiency rating increase according to TiO₂ film thickness up to a threshold value close to 400 nm. Moreover a significant decrease of the adherent bacteria number is observed after 20 min of UVA illumination. The quantitative study of the bactericidal activity associated with scanning electron microscopy observations of the post-process bacteria damaged cells demonstrates the efficiency of the 240 nm-thick TiO₂ coating sample. The results are correlated with the production of hydroxyl radical during the process of photocatalysis.

INTRODUCTION

In food industry environments microbial, biofilms grown on work surfaces are the source of contamination, food-borne infections and also equipment damages (1, 2). Biofilms represent therefore a recurrent economic and food safety problem. It appears difficult to remove a biofilm once it is formed on food plant surfaces. Indeed the complex biofilm structure protects bacteria from classic disinfection and sanitizing procedures (3–7). Some bacteria, such as *Listeria monocytogenes*, can persist in various food plant environments from months to several years even when appropriate hygienic measures are applied (8, 9). Reis-Teixeira and coworkers have demonstrated that although *L. monocytogenes* is not able to form thick multilayer biofilms, the cells can persist on abiotic surfaces (10). This result confirms the need to focus on measures or techniques to avoid biofilm formation, instead of trying to fight against mature biofilms. Deposition of semiconductor materials in thin coatings is an efficient way of biologically active and self-sanitizing surface preparation. Antibacterial activity of such top-layers is photoinduced through the

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formation of reactive oxygen species (ROS) when irradiated by light energy higher than the band gap value (11). Among chemically stable, non-toxic and cost-effective materials, titanium dioxide (TiO_2) has been widely studied as semiconducting oxide for a large range of photocatalytic applications (12). TiO_2 material exhibits different polymorphic phases: anatase, rutile and brookite. Rutile is thermodynamically stable, while anatase and brookite phases are in metastable states (13). Among the three crystalline phases, anatase presents the highest photocatalytic and bactericidal activity (14, 15). When TiO_2 is irradiated by UV light, it produces pairs of electrons and holes. These either recombine, or migrate to the surface of the catalyst where they can participate in oxidation and reduction reactions by generating strong oxidative radicals (hydroxyl radicals, superoxide anions and hydrogen peroxide) that decompose organic compounds (16–18). Therefore, TiO_2 can be used as a photocatalytic antibacterial material: it combines chemical stability, biocompatibility and high potential for self-cleaning. That way, TiO_2 -assisted photocatalytic disinfection, purification or clean-up processes have been evaluated on a wide range of organisms, including viruses, bacteria, fungi and algae (19–22).

Photocatalysts are conventionally available in powder form which makes the catalyst particles removal very difficult and expensive once work has been completed. This drawback can be overcome by immobilizing the catalyst onto or as a surface, at the expense of its developed corrugated surface (16, 23). TiO_2 photocatalytic coatings can be elaborated by various techniques, such as sol-gel process (24), chemical vapor deposition (25) and sputtering deposition methods (26). Radiofrequency (RF) and direct current (DC) sputtering are ones of the most available methods, frequently used in mass production due to their high deposition rates, high reliability, moderate running costs and possibility of covering a large range of substrate types (27).

In this work, titanium dioxide thin films with various thicknesses were grown by RF magnetron sputtering technique on glass substrates to investigate the effect of the TiO₂ film thickness on the photocatalytic and bactericidal activities. Transparent substrates have been especially selected in the present study to extract the intrinsic optical characteristics of the photoactive coatings. The elaborated samples have been tested against the relevant food-born pathogen *L. monocytogenes*.

MATERIALS AND METHODS

Bacterial strain. Two strains of *L. monocytogenes* were considered in the present study: the *L. monocytogenes* ScottA reference strain (28) and the ECL 136 environmental strain sampled in a food plant (29). Each strain was stored at -70°C in Brain Heart Infusion (BHI) broth (Biokar, France) containing 40% (v/v) of glycerol. After the strain culture on Plate Count Agar (PCA) for 18 hours at 37°C, one colony was placed into BHI broth for 7 hours, as a pre-culture, at 37°C. Using the pre-culture, the appropriate broth was inoculated for an overnight sub-culture. After this, the bacterial suspension concentration was adjusted to 10⁸ CFU/mL by measuring its optical density at 600 nm, and confirmed by enumeration on BHI. Then 50 µL of these suspensions have been loaded onto TiO₂ thin film to assess the susceptibility of the strains to UVA (365 nm) and to measure the bactericidal activity.

TiO₂ film elaboration. TiO₂ thin films were deposited on (50 mm × 50 mm × 0.7 mm) soda-lime glass substrates by RF magnetron sputtering technique (30, 31). The deposition chamber (Plassys MP 450S) that contained a titanium metal target (100.4 mm diameter, 99.995% purity) was pumped down to 5×10⁻⁵ Pa by a turbomolecular rotary pump system. The distance between the target and the substrate was set at 80 mm. Glass substrates were first cleaned in an alkaline lye at 60°C for 15 min, rinsed copiously with deionized water (10 min) and dried under a steam of dry nitrogen. The

glass substrate, clamped on a sample holder, was then introduced in the deposition chamber via a loadlock chamber. The titanium target was supplied with RF power through an automatic matching network. Before each deposition step, the target was pre-sputtered in pure argon (Ar) atmosphere (2.75 Pa) under 50 W RF power for 10 min to remove any target surface contaminates. Then a mixture of argon (Ar) and oxygen (O₂) gas was bled into the sputtering chamber and adjusted by two mass flow controllers. The different parameters during TiO₂ deposition were set as follows: RF power: 200 W, substrate temperature: 440°C, O₂/Ar volume ratio: 3% and working pressure: 2.75 Pa. In order to obtain different film thicknesses, six deposition times: 60, 120, 180, 240, 300 and 360 min were used. The elaborated films are denoted in the present paper by TiO₂-film thickness, such as TiO₂-80nm (film thickness d = 80 nm and sputtering time = 60 min). After deposition, each sample was cleaved into coupons of 1cm×1cm each.

Physical characterizations of the TiO₂ thin films. A standard 4-point probe configuration, with a 225 Keithley current source and a 7050 Schlumberger microvoltmeter, provides the sheet resistance R_s at room temperature.

Optical transmittance was recorded by a UV–Visible spectrophotometer (Perkin Elmer Lambda 20 (Waltham, MA, USA), scanning speed 240 nm/min, 2 nm width slit) in the 200–1100 nm spectral range at normal incidence. The UV–Visible spectrophotometer was previously calibrated with air (blank). In region of strong absorption, the transmittance of the thin film T is expressed in terms of absorption coefficient α and film thickness d, as follows:

$$\ln(T) = -\alpha \times d$$

Taking into account the indirect-allowed transition of the TiO₂ band structure (32), the absorption coefficient is expressed by:

$$(\alpha h\nu)^{1/2} = A \times (h\nu - E_g)$$

where $h\nu$ is the photon energy, A is a constant independent of photon energy and E_g is the optical band gap of TiO_2 . By extrapolating the linear part of $(\alpha h\nu)^{1/2}$ versus energy, E_g value is determined for $(\alpha h\nu)^{1/2} = 0$ with an accuracy of 0.05eV (33).

X-Ray Diffraction (XRD) analyses were performed on a Seifert 3003 PTS diffractometer in θ - 2θ mode. A parallel beam configuration was used with a Ge (220) monochromator mounted on the primary beam ($\text{Cu } \lambda_{\text{K}\alpha 1} = 0.154056 \text{ nm}$). Data were recorded from 10° to 80° with a step angle of 0.01° and a scan rate of $0.15^\circ/\text{min}$. TiO_2 peak indexation has been performed in reference to the joint committee in powder diffraction standards files: 71-1167 for anatase phase and 77-0442 for TiO_2 rutile phase.

Surface and cross-section observations were conducted on a Jeol JSM-5600 Scanning Electron Microscope (SEM) operating at 10 kV. Thickness of the TiO_2 films was measured by SEM cross-sectional view on cleaved sections.

Photocatalytic activity of the TiO_2 coatings. Photocatalytic activity of the TiO_2 coated glass samples under UVA illumination was assessed by the methylene blue (MB) test (34) using a UVA lamp at 365 nm, $1350 \mu\text{W}/\text{cm}^2$ (Vilbert Lourmat, VWR), for 60 minutes at a distance of 2 cm. Bare glass coupons have been used as negative controls.

Each coupon (coated with or without TiO_2 thin film) was placed into a well of a 24-well microplate (Greiner Bio-one, Austria) and loaded with 50 μL of a MB solution at 0.002% (w/v). After UVA illumination, 950 μL of saline water (9 g/L NaCl) was added in each well. Absorbance was measured with a visible spectrophotometer (Thermospectronic, Biomate3, France) at 650 nm. The decrease of the optical density before and after UVA illumination evidences the photocatalytic activity of the

TiO₂ thin layers in comparison with negative controls. The photocatalytic activity PA is expressed as the ratio between the relative variation of the absorbance (A-A₀) and the initial absorbance A₀, as follows:

$$PA = 100 \times (A - A_0) / A_0$$

Bactericidal activity of the TiO₂ coatings. For bactericidal activity measurements, coupons of glass (negative controls) and coupons coated with TiO₂ thin layers (1 cm² in size) were placed into wells of a 24-well microplate. Then 50 μL of the prepared bacterial suspension were loaded onto the surface of each coupon to obtain an initial load of 5×10⁶ bacteria. All coupons were incubated at 20°C for 3 hours to provide bacterial adhesion. The incubation was done in a wet atmosphere to avoid any drying effect of the coupons. After the adhesion step, half of the coupons were exposed to UVA radiations (365 nm, 20 min, 2 cm distance between coupons and UVA lamp); the other coupons were placed in the dark.

The bactericidal activity of the TiO₂-coated samples was assessed by two different ways: by enumerating the surviving bacterial cells and by observing the morphology of the cells anchored on the coupon surface by SEM.

For the enumeration of the surviving bacterial cells, coupons with adherent cells were first washed twice with saline solution and placed in 2 mL of saline solution for sonication at 47 kHz for 20 min (Ultrasonic Bath 3210, Branson, USA) to take off adherent cells. Cultivable cells were then enumerated on BHI agar plates after 48 hours at 37°C.

The decadic logarithm of reduction, i.e. log (N/N₀) was computed, where N₀ is the number of bacteria deposited onto coupons expressed in CFU, and N is the number of cultivable bacteria after treatment expressed in CFU.

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For the morphology observation of the cells anchored on the coupon surface by SEM, coupons with adherent cells were immersed in a 3% glutaraldehyde solution prepared in 0.1M phosphate buffer for 1 hour to allow fixation of the cells. Then coupons were washed twice with saline water and immersed in successive ethanol baths with increasing percentage in vol.: 50%, 75% and 90% for 5 min each and ethanol at 100% for 30 min. Finally ethanol was replaced using a hexamethyldisilazane (HMDS) (Sigma-Aldrich, France) gradient at 50%, 75% in vol. for 10 min each and 100% for 30 min. HMDS is a drying agent and is used as a good alternative to Critical Point Drying for SEM sample preparation (35). At the end, the coupons were dried at room temperature for 24 hours for final SEM observation.

ROS detection. The detection of ROS was performed on coupons of bare glass (negative controls) and coupons coated with TiO₂ thin layers (1 cm² in size). The involvement of hydroxyl radicals •OH, has been underlined using the methylene blue degradation test adding mannitol, a scavenger of •OH. Coupons were placed into a 24-well microplate. 50µL of a solution of MB (0.002%) with a solution of 300 mM mannitol were added onto the surface of each coupon. After UVA illumination for 20 min, absorbance of the solution was determined in order to assess the involvement of •OH in the photocatalysis reaction.

Statistical analysis. Statistical tests were carried out by using a two sample Student t-test with the same variance (XL Stats, free version, Addinsoft) and “R” software. Significant differences were indicated for each treatment (p<0.05).

RESULTS

Characterization of the TiO₂ thin films

Six TiO₂ thin films have been elaborated by RF sputtering according to various deposition times (from 1 to 6 hours) with the same substrate temperature and partial pressure of oxygen in argon (Table 1). An average deposition rate of 1.33 nm/min was obtained with the sputtering parameters as reported in Table 1. The sheet resistance (R_s) of the samples, measured at room temperature, are beyond the measurement range of our setup ($R_s > 5 \times 10^9 \Omega/\text{sq}$). Indeed TiO₂ thin film resistivity (ρ) is extremely high, $\rho > 10^6 \Omega \cdot \text{cm}$ (36), leading for the highest thickness ($d = 480 \text{ nm}$) to expected sheet resistance values higher than $2 \times 10^{10} \Omega/\text{sq}$. Those values put TiO₂ on the borderline between semiconductors and insulators.

The TiO₂ phases were identified by XRD. Figure 1 presents the XRD patterns according to the TiO₂ films thickness. On the one hand, a permanent signature of the anatase phase (main peak at $2\theta = 25.271^\circ$ that corresponds to the (101) orientation) appears on all diffraction patterns. On the other hand, the rutile phase is observed on the thicker films (d higher than 240 nm). From a TiO₂ thickness of 400 nm, the contributions of the rutile and anatase phases on XRD patterns are qualitatively similar.

Figure 2 shows the surface morphology of the TiO₂ thin films observed by SEM according to the film thickness. SEM images exhibit uniform distribution of submicron-sized grains and are crack free.

To assess the optical properties of the TiO₂ films, optical transmission spectra of the samples have been recorded in air (data not shown) and the band gaps E_g have been computed. E_g values of the thinner films are slightly higher than that of the thicker films. On thin films, as the reported band-gap values of the pure anatase and rutile phases are in the range [3.3 - 3.2 eV] and [3.1 - 3.0 eV]

respectively (32, 37-41), the decrease of the optical band gap versus the thickness supports the phase variation from anatase to rutile, as observed on the XRD patterns (Figure 1).

Photocatalytic properties of the TiO₂ coatings

The decrease of the methylene blue absorbance at 650 nm according to illumination time is presented in Figure 3. The six TiO₂ thin films exhibit a significant MB discoloration rate after 60 min of UVA illumination (Student test; $p < 0.05$) compared with both samples without UVA activation and the bare glass substrate (Figure 3A). An exponential decrease is observed and suggests first-order kinetics. According to the $-\ln(A/A_0) = kt$ equation, a straight line is fitted to the data and the apparent first-order constant k is retrieved from the slope (Figure 3B). As the TiO₂ thin film thickness increases, the MB discoloration rate increases too. The degradation rate saturates above the 400 nm film thickness value.

Bactericidal properties of the TiO₂ coatings

The antibacterial tests were carried out on the two strains of *L. monocytogenes* to determine the inactivation performance of the six TiO₂ coatings grown on glass substrates. The results of bactericidal assays, with and without UVA illumination, and using the bare glass substrate as negative control, are presented in Figure 4. The measurements undertaken on the bare glass substrate exhibit no significant bactericidal effect on both strains of *L. monocytogenes* in the dark and under UVA illumination (Figure 4).

Without UVA radiation, the number of adherent cells is similar over all samples, on the bare glass coupons as well as on the TiO₂ coatings whatever their thickness. On both strains, the difference in the bacteria natural ability to survive on the bare glass substrate, with or without UVA illumination, is not significant (Student test, $p > 0.05$). The bacteria adhesion on the coupons is not any more affected by the TiO₂ coatings, as shown by the measurements in the dark (Figure 4).

After photoactivation with UVA radiations for 20 min, TiO₂ coatings as a whole provide a strong bactericidal effect on both strains. On *L. monocytogenes* ScottA (Figure 4 A), the number of adherent bacteria decreases gradually with the increase of the TiO₂ thickness. That way, a reduction in the number of surviving cells of 2.5 log is obtained with the 480 nm-thick TiO₂ coating. On *L. monocytogenes* ECL136 (Figure 4 B), the photocatalytic efficiency of the active coating increases from the first few tens of nanometer and reaches a saturation point with a TiO₂ thickness close to 240 nm, corresponding to a similar efficiency (2.5 log) measured on the previous reference strain with the thicker TiO₂ coating ($d \approx 500$ nm) (Figure 5).

The cells of both strains, environmental and reference strains adhering onto the TiO₂-240 nm coupon surface and onto the bare glass surface were exposed to UVA radiations for 20 min and were observed by SEM. Damaged cells occur on the functionalized surface after UVA activation, by contrast to those adhering on the bare glass coupons and showing no apparent morphological damages (Figure 6). Damaged cells appear empty without cytoplasmic content as “ghost cells”, with some membranes drilled. Indeed, UVA illumination could be responsible for DNA mutation and death cell if UV exposure is long. In our case, we used UVA wavelength, the less damaging UV rays ($\lambda = 365$ nm) for a maximum time of 20 min.

All these observations have been correlated with the results of ROS detection. The involvement of $\bullet\text{OH}$ in methylene blue degradation has been confirmed with the TiO₂-240 nm sample (Figure 7).

After UVA illumination, TiO₂ coupons exhibit a MB discoloration. When mannitol is added to the MB

solution, no MB discoloration has been observed. The absorbance spectra of the MB solution after UVA illumination was the same as the absorbance observed with the bare glass coupons, showing that $\bullet\text{OH}$ scavenger presence has enabled to achieve the absorbance of the negative control.

DISCUSSION

In the present study, glass substrates have been functionalized by RF sputtering deposition of TiO_2 thin films. Influence of the TiO_2 thickness on the photocatalytic and bactericidal activities has been investigated. Thin layers have been obtained from deposition time of 1 hour up to 6 hours, and thickness is linearly correlated to deposition time with TiO_2 thin layers varying from 80 nm to 480 nm respectively. The deposition rate of 80 nm per hour is currently observed when using RF magnetron sputtering deposition for TiO_2 thin films (42). As the film thickness increases, the surface morphology changes. Heikkilä and co-workers, in 2009, concluded that grains and surface roughness increase toward the TiO_2 film thickness (23).

Using our sputtering parameters, TiO_2 thin films exhibit an anatase structure at low thicknesses (d thinner than ~ 240 nm) whereas the crystalline phase evolves toward a combination of anatase and rutile structures with the thicker films. Such dual structure could help to achieve a better efficiency in bactericidal activity. Indeed many studies have previously underlined a higher photocatalytic performance in a wide range of applications (self-cleaning surfaces, air and water purification, H_2 production by water splitting...) when TiO_2 provides a mixture of anatase and rutile structures (43) at a specific [anatase : rutile] ratio in the range [70 : 30 – 80 : 20] respectively, as found in the commercially available titania photocatalyst Degussa P25 (14, 15, 44). In that case, the efficiency of the UV-driven organic pollutants photocatalytic oxidation is enhanced by the existence of nanoscale

heterojunctions between the anatase and the rutile phases (45-46). In this context, on powder or on mesoporous nanofibers, those multi-semiconductor/semiconductor junctions between the TiO₂ polymorphs modify the band-gap structure and consequently the photocatalytic activity of the material. Concerning the bactericidal performance under UV light, while anatase-type TiO₂ powders or thin films always exhibit an antibacterial activity on various types of bacteria (47–50), rutile-type titanium dioxide phase demonstrates no bactericidal activity (15, 16, 48, 51) unless the film is fully {111}-oriented (52). Conversely, under the visible light, while the detrimental effect of the anatase phase on the survival of the bacteria is non-existent (53) or limited (54), the rutile structure takes over the activity (53–55). As the rutile phase exhibits a lower band-gap value than that of the anatase, its ability to use the blue part of the visible spectrum explains in part this behaviour. Moreover, ROS types, natures and quantities depend on both titanium dioxide structure and radiation wavelengths. That way, it has been shown that under UV illumination, the activity of anatase materials is primarily related to the efficient production of •OH species (56) while visible light illumination largely enhances •O₂⁻ formation on rutile surfaces (51, 56). One must also keep in mind that the exact composition of the ROS mixture formed as well as its reactivity depends not only on the structure and texture of the photocatalyst, but also on the bacteria-type itself. In the present study, TiO₂ coatings thicker than 240 nm, composed of anatase and rutile phases, exhibit the best photocatalytic and bactericidal activities. The kinetic data retrieved from the photocatalytic degradation of MB can be correlated with the bactericidal performance. The photocatalytic activity of our TiO₂ coatings with thicknesses up to 400 nm, allowed more than 90% of MB discoloration in one hour. Commercial Degussa P25[®], tested by Barnes and co-workers in 2013, provided 76% of discoloration rate after one hour exposure under UVA radiations at 365 nm (57). Moreover Heikkilä and co-workers also grew TiO₂ thin films by Atomic Layer Deposition (ALD) technique (23). Their anatase-TiO₂ films with various thicknesses (from 50 to 520 nm) caused MB discoloration, around 10% after 1 hour-UVA irradiation. As we observed above, Heikkilä and co-workers showed an exponential decrease which suggests first-order kinetics. Initial MB concentration, temperature,

TiO₂ concentration and form, illumination wavelength have been shown to influence the photocatalytic activity and especially the kinetics rate (58). Comparison of kinetics rate is therefore difficult because of the spread in the initial settings.

TiO₂ photocatalysts as fine particles have already been studied to fight against bacteria in various environments such as medical environments (59-60), water disinfection field (61–64) or food plants (19, 20). However, the use of TiO₂ suspension presents a disadvantage in the postcatalytic catalyst removal (17, 65). In food plants, an alternative way concerns the development of stable coatings through thin film deposition. In the present work, RF magnetron sputtering technique has been used to grow TiO₂ thin films with different thicknesses. This type of functionalized materials aims to restrict the first step of biofilm formation by preventing the bacteria adhesion. For this purpose, the TiO₂ thin films have been tested against adherent *L. monocytogenes* bacteria and not against mature biofilms (19, 66). Unfortunately, these TiO₂ coatings do not provide any anti-adhesive property, since no difference has been observed between the number of bacteria grown on the bare glass substrates and those grown on the TiO₂ coatings without UVA illumination. Similarly Chorianopoulos and co-workers did not obtain any anti-adhesive effect on the *L. monocytogenes* ScottA bacteria grown onto glass coated with TiO₂ layers, without UVA irradiation (19).

After UVA activation of the TiO₂ layers, the surfaces present a strong bactericidal activity against both *L. monocytogenes* strains. This bactericidal effect can be related to the thickness of the TiO₂ layer and also to the TiO₂ crystalline phase as depicted in Figure 5. Indeed the presence of the rutile phase in addition to the anatase one in TiO₂ films thicker than 240 nm seems to be linked to the saturation effect undergone by the environmental strain *L. monocytogenes* ECL136.

Active species (ROS) are produced by the photocatalytic TiO₂ coating. Concerning our TiO₂ coupons, hydroxyl radical production may be involved in the bactericidal activity. The use of mannitol as a scavenger highlighted the [•]OH involvement in the MB discoloration, and thus in the photocatalytic activity. Other detection methods such as electron spin resonance observation, direct fluorescence or chemiluminescence exist. These methods are quantitative and accurate. However these methods require specific and expensive equipments to be performed (18). ROS as [•]OH affect the cell wall integrity as observed by SEM, while direct UVA radiations do not affect their cell morphology. Indeed UV radiations may damage DNA and cause mutations (67). UV resistance of bacteria differs between species and also depends on the age of organisms, growth stage and also bacterial form (biofilm or adherent cells) (31, 68, 69). In general, Gram-positive bacteria tend to be more resistant to UV radiations than Gram-negative bacteria (31, 67).

Listeria monocytogenes ScottA and ECL136 belong to the serotypes 4b and 1/2a, respectively. The observed differences in susceptibility may be related to variable responses to oxidative stress as it was highlighted in a recent study (70). Moreover the composition of the teichoic acids is different between 4b and 1/2a serotype (71, 72). The wall components are known to be a target of the ROS generated by the TiO₂. Consequently this may contribute to the difference in susceptibility of the two

Listeria strains

In conclusion, TiO₂ coatings deposited by RF sputtering technique on glass substrates and activated by UVA illumination exhibit bactericidal activity against the foodborne pathogen *L. monocytogenes*. Indeed a significant reduction of the adherent cells after 20 min of UVA exposure has been measured. 240 nm-thick TiO₂ coating is sufficient to promote optimal bactericidal activity against *L. monocytogenes* ECL316 whereas thicker films (~500 nm) are needed against *L. monocytogenes* ScottA. The TiO₂ surface functionalization paves the way to improve cleanability and disinfection in .

food industry environments. Work is under progress to grow such TiO₂ thin films onto stainless steel substrates in order to be applied in food plants.

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REFERENCES

1. Trachoo N. 2003. Biofilms and the food industry. *Songklanakarin J. Sci. Technol.* 25(6):807–815
2. Abdallah M, Benoliel C, Drider D, Dhulster P, Chihib N-E. 2014. Biofilm formation and persistence on abiotic surfaces in the context of food and medical environments. *Arch. Microbiol.* 196(7):453–472
3. Gil MI, Selma MV, López-Gálvez F, Allende A. 2009. Fresh-cut product sanitation and wash water disinfection: problems and solutions. *Int. J. Food Microbiol.* 134(1–2):37–45

4. Ibusquiza PS, Herrera JJR, Cabo ML. 2011. Resistance to benzalkonium chloride, peracetic acid and nisin during formation of mature biofilms by *Listeria monocytogenes*. *Food Microbiol.* 28(3):418–425
5. Soumet C, Méheust D, Pissavin C, Le Grandois P, Frémaux B, Feurer C, Le Roux A, Denis M, Maris P. 2016. Reduced susceptibilities to biocides and resistance to antibiotics in food-associated bacteria following exposure to quaternary ammonium compounds. *J. Appl. Microbiol.* 121(5):1275–1281
6. Colagiorgi A, Di Ciccio P, Zanardi E, Ghidini S, Ianieri A. 2016. A Look inside the *Listeria monocytogenes* biofilms extracellular matrix. *Microorganisms.* 4(3):1-12
7. Pilchova T, Hernould M, Prévost H, Demnerova K, Pazlarova J, Tresse O. 2014. Influence of food processing environments on structure initiation of static biofilm of *Listeria monocytogenes*. *Food Control.* 35:366–372
8. Bridier A, Sanchez-Vizueté P, Guilbaud M, Piard J-C, Naïtali M, Briandet R. 2015. Biofilm-associated persistence of food-borne pathogens. *Spec. Issue Predict. Model. Food.* 45, Part B:167–178
9. Carpentier B, Cerf O. 1993. Biofilms and their consequences, with particular reference to hygiene in the food industry. *J Appl Bacteriol.* 75(6):499–511
10. Reis-Teixeira FB, Alves VF, de Martinis ECP. 2017. Growth, viability and architecture of biofilms of *Listeria monocytogenes* formed on abiotic surfaces. *Braz. J. Microbiol.* 48(3) :587–591.
11. Joost U, Juganson K, Visnapuu M, Mortimer M, Kahru A, Nõmmiste E, Joost U, Kisand V, Ivask A. 2015. Photocatalytic antibacterial activity of nano-TiO₂ (anatase)-based thin films: Effects on *Escherichia coli* cells and fatty acids. *J. Photochem. Photobiol. B.* 142(Supplement C):178–185

12. Nakata K, Fujishima A. 2012. TiO₂ photocatalysis: Design and applications. *J. Photochem. Photobiol. C Photochem. Rev.* 13:169–189
13. Gopal M, Chan WJM, Jonghe LCD. 1997. Room temperature synthesis of crystalline metal oxides. *J. Mater. Sci.* 32(22):6001–6008
14. Navabpour P, Cooke K, Sun H. 2017. Photocatalytic properties of doped TiO₂ coatings deposited using reactive magnetron sputtering. *Coatings.* 7(1):433–449
15. Sirimahachai U, Phongpaichit S, Wongnawa S. 2009. Evaluation of bactericidal activity of TiO₂ photocatalysts: a comparative study of laboratory-made and commercial TiO₂ samples. *Songklanakarin J. Sci. Technol.* 31(5):517–525
16. Miao L, Tanemura S, Kondo Y, Iwata M, Toh S, Kaneko K. 2004. Microstructure and bactericidal ability of photocatalytic TiO₂ thin films prepared by RF helicon magnetron sputtering. *Appl. Surf. Sci.* 238(1–4):125–131
17. Ede S, Hafner L, Dunlop P, Byrne J, Will G. 2012. Photocatalytic disinfection of bacterial pollutants using suspended and immobilized TiO₂ powders. *Photochem. Photobiol.* 88(3):728–735
18. Nosaka Y, Nosaka AY. 2017. Generation and detection of reactive oxygen species in photocatalysis. *Chem. Rev.* 117(17):11302–11336
19. Chorianopoulos NG, Tsoukleris DS, Panagou EZ, Falaras P, Nychas GJ. 2011. Use of titanium dioxide (TiO₂) photocatalysts as alternative means for *Listeria monocytogenes* biofilm disinfection in food processing. *Food Microbiol.* 28(1):164–170
20. Kim B, Kim D, Cho D, Cho S. 2003. Bactericidal effect of TiO₂ photocatalyst on selected food-borne pathogenic bacteria. *Chemosphere.* 52(1):277–281

21. Thabet S, Weiss-Gayet M, Dappozze F, Cotton P, Guillard C. 2013. Photocatalysis on yeast cells: toward targets and mechanisms. *Appl. Catal. B Environ.* 140–141:169–78
22. Gogniat G, Thyssen M, Denis M, Pulgarin C, Dukan S. 2006. The bactericidal effect of TiO₂ photocatalysis involves adsorption onto catalyst and the loss of membrane integrity. *FEMS Microbiol. Lett.* 258(1):18–24
23. Heikkilä M, Puukilainen E, Ritala M, Leskelä M. 2009. Effect of thickness of ALD grown TiO₂ films on photoelectrocatalysis. *J. Photochem. Photobiol. Chem.* 204(2–3):200–208
24. Calabria A. J, Vasconcelos WL, Daniel DJ, Chater R, McPhail D, Boccaccini AR. 2010. Synthesis of sol–gel titania bactericide coatings on adobe brick. *Constr. Build. Mater.* 24(3):384–389
25. Bessergenev VG, Mateus MC, Morgado IM, Hantusch M, Burkel E. 2017. Photocatalytic reactor, CVD technology of its preparation and water purification from pharmaceutical drugs and agricultural pesticides. *Chem. Eng. J.* 312(Supplement C):306–316
26. Singh J, Khan SA, Shah J, Kotnala RK, Mohapatra S. 2017. Nanostructured TiO₂ thin films prepared by RF magnetron sputtering for photocatalytic applications. *Appl. Surf. Sci.* 422(Supplement C):953–961
27. Ferraris S, Perero S. 2016. 2 - Smart and composite inorganic coatings obtained by sputtering: a promising solution for numerous application fields. *Smart Composite Coatings and Membranes*, ed MF Montemor, pp. 33–60. Woodhead Publishing
28. Fleming DW, Cochi SL, MacDonald KL, Brondum J, Hayes PS, Plikaytis B, Holmes M, Audurier A, Broome C, Reingold A. 1985. Pasteurized milk as a vehicle of infection in an outbreak of Listeriosis. *N. Engl. J. Med.* 312(7):404–407

29. Chasseignaux E, G rault P, Toquin M-T, Salvat G, Colin P, Ermel G. 2002. Ecology of *Listeria monocytogenes* in the environment of raw poultry meat and raw pork meat processing plants. *FEMS Microbiol. Lett.* 210(2):271–275
30. Le Paven C, Le Gendre L, Benzerga R, Chevir  F, Tessier F, Jacq S, Traor -Mantion S, Sharaiha A. 2015. Growth of (Sr,La)-(Ta,Ti)-O-N perovskite oxide and oxynitride films by radiofrequency magnetron sputtering: Influence of the reactive atmosphere on the film structure. *J. Cryst. Growth.* 413:5–11
31. Barthomeuf M, Raymond P, Policarpo N, Castel X, Le Gendre L, Denis M, Pissavin C. 2017. Bactericidal efficiency of UVA-active titanium dioxide thin layers on bacteria from food industry environments. *Mater. Technol. Adv. Perform. Mater.* 32(13): 782–791
32. Tang H, Prasad K, Sanjin s R, Schmid PE, L vy F. 1994. Electrical and optical properties of TiO₂ anatase thin films. *J. Appl. Phys.* 75:2042–2047
33. Barka-Bouaifel F, Makaoui K, Jouan P-Y, Castel X, Bezzi N, Boukherroub R, Szunerits S. 2012. Preparation and photocatalytic properties of quartz/gold nanostructures/TiO₂ lamellar structures. *RSC Adv.* 2(32):12482–12488
34. Fu P, Luan Y, Dai X. 2004. Preparation of activated carbon fibers supported TiO₂ photocatalyst and evaluation of its photocatalytic reactivity. *J. Mol. Catal. - Chem.* 221(1):81–88
35. Hazrin-Chong NH, Manfield M. 2012. An alternative SEM drying method using hexamethyldisilazane (HMDS) for microbial cell attachment studies on sub-bituminous coal. *J. Microbiol. Methods.* 90(2):96–99
36. Casoti D, Orsini V, di Bona A, Gardonio S, Fanetti M, Valant M, Valeri S. 2018. Ageing effects on electrical resistivity of Nb-doped TiO₂ thin films deposited at a high rate by reactive DC magnetron sputtering. *Appl. Surf. Sci.* 455:267-275

37. Aarik J, Aidla A, Kiisler A-A, Uustare T, Sammelselg V. 1997. Effect of crystal structure on optical properties of TiO₂ films grown by atomic layer deposition. *Thin Solid Films*. 305(1):270–273
38. Daude N, Gout C, Jouanin C. 1977. Electronic band structure of titanium dioxide. *Phys. Rev. B*. 15(6):3229–3235
39. Camps E, Castrejon-Sanchez VH, Camacho-Lopez M, Basurto R. 2015. Influence of the nitriding process on the band-gap of TiO₂ thin films with phase mixture. *Thin Solid Films*. 581:54–58
40. Long H, Chen A, Yang G, Li Y, Lu P. 2009. Third-order optical nonlinearities in anatase and rutile TiO₂ thin films. *Thin Solid Films*. 517(19):5601–5604.
41. Liu HY, Huang RC. 2018. A study of anatase TiO₂-based thin film phototransistors by non-vacuum thin film deposition method. *IEEE Trans. Electron Devices*. 65(6):2517–2524
42. Nair PB, Justinictor VB, Daniel GP, Joy K, James Raju KC, Devraj K, Thomas P. 2014. Optical parameters induced by phase transformation in RF magnetron sputtered TiO₂ nanostructured thin films. *Prog. Nat. Sci. Mater. Int.* 24(3):218–225
43. Yuangpho N, Le STT, Treerujiraphapong T, Khanitchaidecha W, Nakaruk A. 2015. Enhanced photocatalytic performance of TiO₂ particles via effect of anatase–rutile ratio. *Phys. E Low-Dimens. Syst. Nanostructures*. 67(Supplement C):18–22
44. Van der Meulen T, Mattson A, Österlund L. 2007. A comparative study of the photocatalytic oxidation of propane on anatase, rutile, and mixed-phase anatase–rutile TiO₂ nanoparticles: Role of surface intermediates. *J. Catal.* 251(1):131–144
45. Ghosh M, Lohrasbi M, Chuang SSC, Jana SC. 2016. Mesoporous titanium dioxide nanofibers with a significantly enhanced photocatalytic activity. *Chem. Cat. Chem.* 8:2525–2535
46. Bickley RI, Gonzalez-Carreno T, Lees JS, Palmisano L, Tilley RJD. 1991. A structural

investigation of titanium dioxide photocatalysts. *J. Solid State Chem.* 92:178-190

47. Cheng TC, Yao KS, Yeh N, Chang CI, Hsu HC, Gonzales F, Chang CY. 2011. Bactericidal effect of blue LED light irradiated TiO₂/Fe₃O₄ particles on fish pathogen in seawater. *Thin Solid Films.* 519(15):5002–5006
48. Joo H-C, Lim Y-J, Kim M-J, Kwon H-B, Han J-H. 2010. Characterization on titanium surfaces and its effect on photocatalytic bactericidal activity. *Appl. Surf. Sci.* 257(3):741–746
49. Sisti L, Cruciani L, Totaro G, Vannini M, Berti C, Tobaldi DM, Tucci A, Aloisio I, Di Gioia D, Commereuc S. 2012. TiO₂ deposition on the surface of activated fluoropolymer substrate. *Thin Solid Films.* 520:2824–2828
50. Lee HU, Lee SC, Lee SM, Lee JW, Kim HJ, Lee J. 2013. Improved photocatalytic and antibacterial activities of three-dimensional polycrystalline anatase TiO₂ photocatalysts. *Appl. Catal. Gen.* 467:394–99
51. Perelshtein I, Applerot G, Perkash N, Grinblat J, Gedanken A. 2012. A one-step process for the antimicrobial finishing of textiles with crystalline TiO₂ nanoparticles. *Chem. Weinh. Bergstr. Ger.* 18(15):4575–4582
52. Liu X, Zhang H, Liu C, Chen J, Li G, An T, Wong PK, Zhao H. 2014. UV and visible light photoelectrocatalytic bactericidal performance of 100% {111} faceted rutile TiO₂ photoanode. *Catal. Today.* 224:77–82
53. Veréb G, Manczinger L, Bozsó G, Sienkiewicz A, Forró L, Mogyorosi K, Hernadi K, Dombi A. 2013. Comparison of the photocatalytic efficiencies of bare and doped rutile and anatase TiO₂ photocatalysts under visible light for phenol degradation and *E. coli* inactivation. *Appl. Catal. B Environ.* 129:566–574

54. Rincon AG, Pulgarin C. 2003. Photocatalytical inactivation of *E. coli*: effect of (continuous-intermittent) light intensity and of (suspended-fixed) TiO₂ concentration. *Appl. Catal. B-Environ.* 44(3):263–284
55. Kim C-H, Lee E-S, Kang S-M, de Josselin de Jong E, Kim B-I. 2017. Bactericidal effect of the photocatalytic reaction of titanium dioxide using visible wavelengths on *Streptococcus mutans* biofilm. *Photodiagnosis Photodyn. Ther.* 18:279–283
56. Zoltan T, Rosales MC, Yadarola C. 2016. Reactive oxygen species quantification and their correlation with the photocatalytic activity of TiO₂ (anatase and rutile) sensitized with asymmetric porphyrins. *J. Environ. Chem. Eng.* 4(4):3967–3980
57. Barnes RJ, Molina R, Xu J, Dobson PJ, Thompson IP. 2013. Comparison of TiO₂ and ZnO nanoparticles for photocatalytic degradation of methylene blue and the correlated inactivation of gram-positive and gram-negative bacteria. *J. Nanoparticle Res.* 15(2):1–11
58. Wu C-H, Chern J-M. 2006. Kinetics of photocatalytic decomposition of methylene blue. *Ind. Eng. Chem. Res.* 45(19):6450–6457
59. Campoccia D, Montanaro L, Arciola CR. 2013. A review of the biomaterials technologies for infection-resistant surfaces. *Biomaterials.* 34(34):8533–8554
60. Yoshinari M, Oda Y, Kato T, Okuda K. 2001. Influence of surface modifications to titanium on antibacterial activity in vitro. *Biomaterials.* 22(14):2043–2048
61. Claro EMT, Bidoia ED, de Moraes PB. 2016. A high-performance doped photocatalysts for inactivation of total coliforms in superficial waters using different sources of radiation. *J. Environ. Manage.* 177:264–270

62. Fisher MB, Keane DA, Fernández-Ibáñez P, Colreavy J, Hinder SJ, McGuigan KG, Pillai SC, 2013. Nitrogen and copper doped solar light active TiO₂ photocatalysts for water decontamination. *Appl. Catal. B Environ.* 130–131:8–13
63. Kaan CC, Aziz AA, Ibrahim S, Matheswaran M, Saravanan P. 2012. Heterogeneous photocatalytic oxidation an effective tool for wastewater treatment – A review. *Studies on Wat. Manag. Issues, InTech*, 219–236
64. Robertson JMC, J. Robertson PK, Lawton LA. 2005. A comparison of the effectiveness of TiO₂ photocatalysis and UVA photolysis for the destruction of three pathogenic micro-organisms. *J. Photochem. Photobiol. Chem.* 175(1):51–56
65. Guillard C, Kartheuser B, Lacombe S. 2011. La photocatalyse : dépollution de l'eau ou de l'air et matériaux autonettoyants. *Tech. Ing. Génie Procédés Prot. Environ.* Base documentaire : TIB327DUO.
66. Carré G, Hamon E, Ennahar S, Estner M, Lett M-C, Horvatovich P, Gies JP, Keller V, Keller N, and Andre P. 2014. TiO₂ Photocatalysis damages lipids and proteins in *Escherichia coli*. *Appl. Environ. Microbiol.* 80(8):2573–2581
67. Gailunas KM, Matak KE, Boyer RR, Alvarado CZ, Williams RC, Sumner SS. 2008. Use of UV light for the inactivation of *Listeria monocytogenes* and lactic acid bacteria species in recirculated chill brines. *J. Food Prot.* 71(3):629–633
68. Bonsaglia ECR, Silva NCC, Fernades Júnior A, Araújo Júnior JP, Tsunemi MH, Rall VLM. 2014. Production of biofilm by *Listeria monocytogenes* in different materials and temperatures. *Food Control.* 35(1):386–391

69. Vázquez-Sánchez D, Cabo ML, Ibusquiza PS, Rodríguez-Herrera JJ. 2014. Biofilm-forming ability and resistance to industrial disinfectants of *Staphylococcus aureus* isolated from fishery products. *Food Control*. 39:8–16
70. Huang Y, Morvay AA, Shi X, Suo Y, Shi C, Knøchel S. 2018. Comparison of oxidative stress response and biofilm formation of *Listeria monocytogenes* serotypes 4b and 1/2a. *Food Control*. 85:416–422
71. Fiedler F, Seger J, Schrettenbrunner A, Seeliger HPR. 1984. The biochemistry of murein and cell wall teichoic acids in the genus *Listeria*. *Syst. Appl. Microbiol*. 5:360–376.
72. Promadej N, Fiedler F, Cossart P, Dramsi S, Kathariou S, 1999. Cell wall teichoic acid glycosylation in *Listeria monocytogenes* Serotype 4b requires *gtcA*, a novel serogroup-specific gene. *J. Bacteriol*. 181:418–425.

FIGURE CAPTIONS

Figure 1. X-ray diffraction patterns of a) Bare glass substrate; b) TiO₂-80nm; c) TiO₂-170nm; d) TiO₂-240nm; e) TiO₂-310nm; f) TiO₂-400nm; g) TiO₂-480nm. (●) indicates anatase peaks and (*) indicates rutile peaks.

Figure 2. Surface morphology of the TiO₂ thin films observed by Scanning Electron Microscopy (×20 000): (A) TiO₂-80nm; (B) TiO₂-170nm; (C) TiO₂-240nm; (D) TiO₂-310nm; (E) TiO₂-400nm; (F) TiO₂-480nm.

Figure 3. TiO₂ film thickness effect on the photocatalytic discoloration of methylene blue. A) Absorbance of the methylene blue is related to the initial value according to UVA irradiation time. B) Logarithm of the absorbance ratio of methylene blue. First order linear kinetics. The value is a mean of 3 measurements. Bare glass substrate (◆); TiO₂-80nm (■); TiO₂-170nm (▲); TiO₂-240nm (×); TiO₂-310nm (▲); TiO₂-400nm (⊗); TiO₂-480nm (◇).

Figure 4. Influence of the TiO₂ coatings and UVA illumination on cell viability of 2 bacterial strains A) *L. monocytogenes* ScottA; B) *L. monocytogenes* ECL136. Surviving cells are numerated on agar plates, N₀ is the cell number deposited onto the coupon and N is the number of surviving cells after 3 hours and subsequent irradiation or not. Activity of TiO₂ under UVA radiations (20 min) (■) is measured and compared with that measured in the dark (■) and with the bare glass (negative control). Data reported here are the mean values of three replicates +/- standard deviation. Means with different lowercase letters differ significantly (p<0.05).

Figure 5. Variation of log reduction of adherent cells onto TiO₂ coatings after UVA activation versus TiO₂ thickness. TiO₂ phase indication on the figure associates the XRD results. (●) *L. monocytogenes* ScottA; (●) *L. monocytogenes* ECL136.

Figure 6. SEM observations (×5 000) of adherent cells of *L. monocytogenes* strains. *L. monocytogenes* ScottA (A, B, C, D) and *L. monocytogenes* ECL136 (E, F, G, H) onto bare glass substrates in the dark (A, E); TiO₂-240nm in the dark (B, F); bare glass substrates after 20 min of UVA illumination (C, G); TiO₂-240nm after 20 min of UVA illumination (D, H).

Figure 7. Absorbance spectra of the MB solution coming from the surface of the various coupons after 60 min of UVA illumination. (A) Bare glass substrate. (B) TiO₂-240nm. MB solution (0.002%) MB solution (0.002%) with mannitol (300 mM).

Table 1. Deposition parameters and characteristics of the TiO₂ thin films.

<i>Layer ID</i>	<i>Deposition time (min)</i>	<i>Substrate temperature (°C)</i>	<i>O₂/Ar ratio (%)</i>	<i>Thickness d (nm)</i>	<i>Crystalline phase</i>	<i>Band gap EG (eV)</i>	<i>Photocatalytic activity (% of MB discoloration after 60 min of UVA illumination)</i>
<i>TiO₂-80nm</i>	60	440	3	80	<i>Anatase</i>	3.30	23.2
<i>TiO₂-170nm</i>	120	440	3	170	<i>Anatase</i>	3.25	36.6
<i>TiO₂-240nm</i>	180	440	3	240	<i>Anatase</i>	3.30	50.4
<i>TiO₂-310nm</i>	240	440	3	310	<i>Anatase/Rutile</i>	3.25	64.1
<i>TiO₂-400nm</i>	300	440	3	400	<i>Anatase/Rutile</i>	3.15	89.1
<i>TiO₂-480nm</i>	360	440	3	480	<i>Anatase/Rutile</i>	3.20	87.1













