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***In vitro* photodynamic inactivation of conidia of the phytopathogenic fungus *Colletotrichum graminicola* with cationic porphyrins**

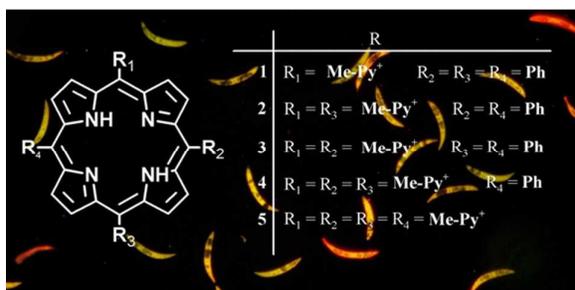
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GRAPHICAL ABSTRACT

Photodynamic inactivation (PDI) of the conidial form of the phytopathogen *Colletotrichum graminicola* was performed with five cationic *meso*-(1-methyl-4-pyridinio)porphyrins.



ABSTRACT

Photodynamic inactivation (PDI) is an efficient approach for the elimination of a series of microorganisms; however, PDI involving phytopathogenic filamentous fungi is scarce in the literature. In the present study, we have demonstrated the photoinactivating properties of five cationic *meso*-(1-methyl-4-pyridinio)porphyrins on conidia of the phytopathogen *Colletotrichum graminicola*. For this purpose, photophysical properties (photostability and ¹O₂ singlet production) of the porphyrins under study were first evaluated. PDI assays were then performed with a fluence

of 30, 60, 90 and 120 J cm⁻² and varying porphyrin concentration from 1 to 25 μmol L⁻¹. Considering the lowest concentration that enabled the best photoinactivation, with the respective lowest effective irradiation time, the *meso*-(1-methyl-4-pyridinio)porphyrins herein studied could be ranked as follows: triple-charged **4** (1 μmol L⁻¹ with a fluence of 30 J cm⁻²) > double-charged-*trans* **2** (1 μmol L⁻¹ with 60 J cm⁻²) > tetra-charged **5** (15 μmol L⁻¹ with 90 J cm⁻²) > mono-charged **1** (25 μmol L⁻¹ with 120 J cm⁻²). Double-charged-*cis*-porphyrin **3** inactivated *C. graminicola* conidia in the absence of light. Evaluation of the porphyrin binding to the conidia and fluorescence microscopic analysis were also performed, which were in agreement with the PDI results. In conclusion, the cationic porphyrins herein studied were considered efficient photosensitizers to inactivate *C. graminicola* conidia. The amount and position of positive charges are related to the compounds amphiphilicity and therefore to photodynamic activity.

INTRODUCTION

Photodynamic inactivation (PDI) is a technique based on the association of a photosensitizer, light and molecular oxygen with the objective of eliminating microorganisms by destructing their cell structures.¹⁻³ PDI can be employed for the inactivation of various microorganisms, including bacteria,^{4,5} viruses,⁶ fungi^{3,7-9} and parasites.^{10,11}

Among the photosensitizers employed for PDI, porphyrins have been extensively evaluated, especially their cationic derivatives. The attachment of positively charged groups to the macrocycle enhances porphyrin water solubility^{12,13} and improves its interaction with microorganism cell structures.^{3,13-15} In this way, cationic porphyrins have been evaluated as photosensitizers^{14,16-18} against Gram positive and Gram negative bacteria,^{5,19-22} yeast^{14,17,20,23} and filamentous fungi.^{9,18} It is important mentioning that due to the resistance offered by the fungal cell structures (e.g. cell wall), the inactivation of such organisms usually demands high photosensitizer concentrations, as well as high light intensities.¹⁸

Fungus *Colletotrichum graminicola* is the etiologic agent of corn (*Zea mays*) anthracnose,²⁴⁻²⁶ which is the most important disease that affects corn plants.^{25,27-29} Anthracnose causes a substantial decrease in the corn crops yield, which can be as large as 40%.^{26,29,30} *C. graminicola* is capable of surviving on corn residues previously infected,³¹ specially in the soil surface,³² which turns a cultivating area into a potential inoculum site.²⁶ In addition, the great genetic variability shown by *C. graminicola* makes the employment of hybrid plants ineffective as a tool for anthracnose control.³³⁻³⁵ The use of fungicides has only been partially effective for the treatment of

anthracnose. In addition, microorganism resistance against the most common fungicides has also been reported.^{36,37} Not least important, pesticide-based control of plant diseases has several negative implications for the environment and human health.³⁸

Studies involving PDI of filamentous fungi have been described in the literature.^{18,39} In the case of phytopathogenic fungi, PDI using hematoporphyrin has been utilized to eliminate a number of filamentous fungi (*Alternaria alternata*, *Aspergillus flavus*, *Fusarium avenaceum*, *Fusarium poae*, *Fusarium culmorum*, *Acremonium strictum*, *Trichothecium roseum* and *Rhizopus oryzae*) which are generally relevant to the food industry.⁹ Considering phytopatogens of the genus *Colletotrichum*, there are two reported PDI studies. Menezes et al. (2014)⁴⁰ employed phenothiazine dyes as photosensitizers for the inactivation of *C. acutatum* and *C. gloeosporioides*. The same authors⁴¹ also utilized the furocoumarins 8-methoxypsoralen and isopimpinellin, and a mixture of two coumarins to photoinactivate *C. acutatum*.⁴¹ As far as we are aware, porphyrins have never been utilized as photosensitizers for the photoinactivation of *Colletotrichum* spp.

In view of the potential application of photosensitizers in agriculture, as well as the lack of studies devoted to this approach, here we evaluated the photoinactivation of the conidia of *C. graminicola* using cationic porphyrins. The choice of the photosensitizers herein utilized (Fig. 1) was based on the fact that tetra-methylpyridinio porphyrin (**5**) has been largely utilized for the photoinactivation of bacteria^{4,19,21,42-46}, filamentous fungi¹⁸ and yeasts.^{23,47-49} Considering that different charge number and distribution could greatly affect the photoinactivating properties of this type of porphyrin, we included in the present study all five possible cationic porphyrin bearing phenyl or 1-methyl-4-pyridinio groups at the macrocycle *meso* positions.

EXPERIMENTAL

Reagents, Materials and General Methods

All reagents and solvents utilized were of reagent grade and they were used as obtained. Pyrrole, 4-pyridinecarboxaldehyde, *N,N*-dimethylformamide (DMF) and 3-diphenylisobenzofuran (DPBF) were purchased from Sigma-Aldrich[®]. Benzaldehyde, propionic acid and ethyl ether were purchased from VETEC[®]. Dimethyl sulfoxide (DMSO) and methyl iodide were from Merck[®]. Thin-layer chromatography (TLC) was performed on silica gel coated aluminum sheets 60 F₂₅₄ (Merck[®]) using solvent mixtures measured on a v/v basis. Column chromatography was carried out using silicagel 60 35-70 mesh (Fluka[®]).

Porphyrin characterization was performed by means of ¹H NMR spectroscopy, MALDI-TOF mass spectrometry and ultraviolet-visible spectroscopy with a Bruker AVANCE III 400 NMR

spectrometer, a MALDI-TOF/MS model Autoflex II Bruker Daltonics and UV-1800 Shimadzu spectrophotometer, respectively.

Materials used for the culture media preparation were oatmeal (Nestlé®), bacteriologic Agar (VETEC®) and Sabouraud Dextrose Agar (ASD, Kasvi®). Sterile 6-well plates (well volume: 15.53 mL) for photodynamic inactivation were purchased from TPP®.

The white light source used for the photodynamic and photophysical assays was a Lumacare LC 122A with a compatible fiber optic probe (400–800 nm) attached to a 250 W quartz/halogen lamp (LumaCare®, USA). Fluorescence measurements for the binding assay were performed with a RF-5301PC Shimadzu spectrofluorometer. Centrifugation employed for photosensitizer binding assay and microscopic analysis were performed with a centrifuge Sigma, model 1-14. Microscopic images were recorded using a Fluorescence Microscope (Olympus BX51TF) with FITC filter and microscopic magnification of eighty. Images were evaluated with Cell^F software, 5.0 version (Olympus Europe Software Information).

Porphyrin Synthesis

The five cationic porphyrins evaluated (Fig. 1) were synthesized according to a methodology that has been previously described,⁵⁰ with modifications. Briefly, a mixture of pyrrole, benzaldehyde, 4-pyridinecarboxaldehyde (4:1:3) in propionic acid was refluxed for 1 h. After reaction time, reaction mixture was concentrated by heating and porphyrins were precipitated by adding acetone to the concentrated mixture. The purple solids obtained corresponded to a mixture of six compounds, including tetraphenylporphyrin and the desired *meso*-pyridyl porphyrins. Porphyrin mixture was fractionated by flash chromatography on a silica gel column with chloroform: methanol (99:1) as mobile phase. Porphyrins containing one (0.9% yield), two-*trans* (1.1% yield), two-*cis* (1.0% yield), three (3.1% yield) and four (2.5% yield) *meso*-pyridyl groups were then obtained separately. Each of the *meso*-pyridyl porphyrins were subsequently submitted to a methylation reaction with excess methyl iodine, in DMF, to give cationic *meso*-(1-methyl-4-pyridinio)porphyrins **1** (iodide salt, 90% yield), **2** (diiodide salt, 38% yield), **3** (diiodide salt, 27% yield), **4** (triiodide salt, 60% yield) and **5** (tetraiodide salt, 64% yield).⁵¹ Synthesis procedures and compound characterization are detailed in the supplementary data file. Spectral properties of porphyrin **1–5** coincided with literature data.^{52,53}

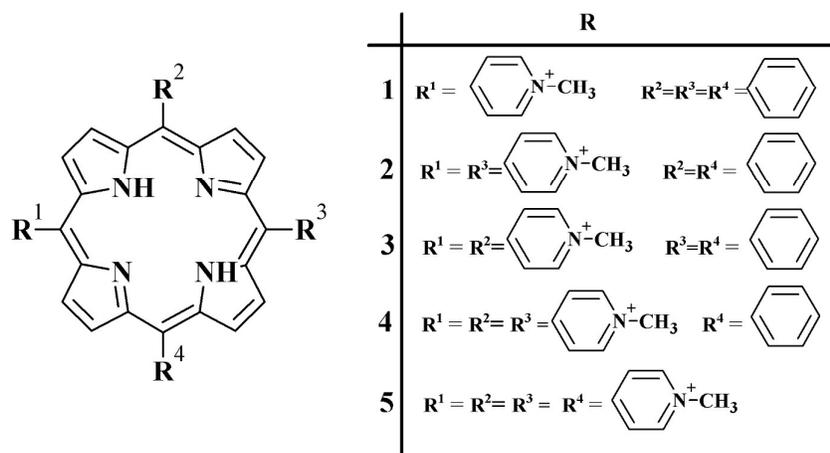


Fig. 1 Structure of the porphyrins used for the photoinactivation studies of *Colletotrichum graminicola* conidia.

Photosensitizer stock solutions

Photosensitizers stock solutions used in the photophysical and biological studies were prepared in DMSO at a concentration of 1 mmol L^{-1} and stored at 4°C .

Photostability Assays and Singlet Oxygen Generation

Photostability experiments were performed as previously described,¹⁸ differing at the concentration of the stock solutions for the porphyrin derivatives (1 mmol L^{-1} in DMSO). Photostability was estimated by irradiating the porphyrins dissolved in distilled water (2 mL) in a quartz cuvette under stirring, with the following parameters coinciding with those ones utilized for the PDI assays: irradiance of 100 mW cm^{-2} , at room temperature. After periods of 0, 1, 2, 3, 4, 6, 8, 10, 15 and 20 min, absorbance of Soret band were measured spectrophotometrically and referenced in percentage from the original absorbance (100%).

Singlet oxygen generation was determined using DPBF as singlet oxygen quencher, with irradiance of 9 mW cm^{-2} in a glass cuvette, using a cut-off filter for wavelengths $\leq 540 \text{ nm}$. A solution of each porphyrin (0.5 mmol L^{-1}) and DPBF (50 mmol L^{-1}) in DMF/H₂O (9:1) were utilized for the experiments. The absorption decay of DPBF at 415 nm was measured at irradiation intervals up to 20 min. The percentage of the DPBF absorption decay is proportional to the production of $^1\text{O}_2$.¹⁸

Preparation of conidia stock suspension

The strain of *Colletotrichum graminicola* was isolated at Campo Mourão, Paraná State, Brazil and it was obtained from the collection of phytopathogenic fungi at EMBRAPA Milho e Sorgo, Minas Gerais, Brazil. Fungus access was authorized by Conselho de Gestão do Patrimônio Genético, with number: 010850/2013-9. Microorganisms were cultivated in Oatmeal Agar (FAA, 60 g oatmeal flour, 15 g bacteriologic Agar, 1000 mL distilled water). Cultures were incubated at 27 °C for approximately one week until the development of a mycelium. The cultures were then removed from incubation and mycelium scrubbed to stimulate fungus sporulation. A new incubation using the same period of time was performed. After this period, for the preparation of conidia suspensions, a volume of 5 mL of phosphate buffered saline (PBS, 4 g of NaCl, 0.1 g of KCl, 0.72 g of Na₂HPO₄ and 0.12 g of KH₂PO₄ to a final volume of 500 mL and pH 7.4 ± 0.2)¹⁸ was added to the sterile glass tube and a portion of conidia was inserted and homogenized. To determine the concentration of conidia in the initial suspension, a hemocytometer was used and the concentration of conidia was expressed as colony-forming unit per milliliter (CFU mL⁻¹). The photoinactivation assays were performed with a concentration of conidia of 10⁵ CFU mL⁻¹.

PDI experimental setup

Initially, a series of experiments using porphyrin **5** was conducted in order to determine the most suitable concentration for the following comparative photoinactivation assays. Aliquots of conidia suspension (0.1 mL) were transferred to 6-well plates. Different volumes of the stock solution of **5** were added in order to obtain final concentrations of 5, 25, 50 and 75 µmol L⁻¹ in the final volume of 5 mL, fulfilled with PBS. The resulting mixtures were kept under stirring on melting ice to prevent heating during irradiation. Two controls were included in each irradiation experiment: a light control (LC) submitted to the same fluence as the samples, but without photosensitizer, and a dark control (DC) containing the photosensitizer at the highest concentration evaluated, in the absence of light. After initial experiments, higher concentrations, 50 and 75 µmol L⁻¹, demonstrated completely inactivation after a fluence of 30 J cm⁻². Therefore, concentrations evaluated were 5, 10, 15 and 25 µmol L⁻¹ for all derivatives under study. Samples of 100 µL were collected in the beginning of the test and after application of a fluence of 30, 60 and 90 J cm⁻² and spread-plated on Sabouraud Dextrose Agar for the determination of the concentration of viable conidia. Colonies formed after 48 h of incubation at 27 °C were counted. The average value of the duplicates was used as an estimate of the concentration of viable conidia in the suspension and expressed as CFU mL⁻¹. Three independent assays were conducted for each porphyrin under study, being the profile of inactivation of different photosensitizers constructed with the average and the standard deviation of

the results obtained. The survival of conidia of *C. graminicola* were plotted as logarithm of the concentration of viable conidia ($\log \text{CFU mL}^{-1}$) versus fluence (J cm^{-2}).¹⁸

Fluorescence Microscopy Studies

A padronized suspension of 10^7 conidia mL^{-1} was incubated with each photosensitizer, in dark for 20 min, at selected concentrations (based on preliminary microscopy results): $25 \mu\text{mol L}^{-1}$ for compounds **1** and **5** and $10 \mu\text{mol L}^{-1}$ for compounds **2**, **3** and **4**. Then, the photosensitizer unbound was removed by centrifugation at 11000 g during 5 min. Two washings with PBS were performed before new centrifugation. After addition of 1 mL of PBS in tubes, the slides were prepared with 50 μL of the resulting suspension, inserted between slide and coverslip.

Photosensitizer binding

Photosensitizer binding experiments were performed according to a methodology previously described,¹⁸ with modifications. The conidia (padronized suspension of 10^6 conidia mL^{-1}) were incubated in the dark at 30°C in the presence of $10 \mu\text{mol L}^{-1}$ (**2**, **3** and **4**) or $25 \mu\text{mol L}^{-1}$ (**1** and **5**) of cationic porphyrins (as defined for the fluorescence microscopy assay). After the incubation periods (0, 20 and 60 min), unbound photosensitizer was removed out of the suspension by centrifugation for 5 min at 11000 g. In order to evaluate the strength of the attachment of the porphyrin to the biological material, two series of aliquots were prepared: one set of conidia was digested immediately after centrifugation and the other was further washed with PBS, prior to digestion. For digestion, the pellets were resuspended in 1 mL of the digesting solution (aqueous NaOH 0.1 mol L^{-1}) and incubated at room temperature for 24 h.¹⁸ The fluorescence of the resulting solutions were then directly measured. The excitation wavelengths were 445 nm (**1**), 419 nm (**2**), 421 nm (**3**), 422 nm (**4**) and 426 nm (**5**), with the emission been measured in between 600-750 nm.

Statistical analysis

Statistical analysis was performed by using Graphpad Prism 5.0 for Windows. Data normality was evaluated and attested by the Shapiro-Wilks test. The significance of the PDI effect of each porphyrin derivative and of the irradiation time on conidial cells inactivation was assessed by one-way univariate analysis of variance (ANOVA) model with Newman-Keuls Multiple Comparison Test. A value of $p < 0.05$ was considered significant.

RESULTS

Porphyrin Photostability and Singlet Oxygen Generation

Table 1 shows photostability and $^1\text{O}_2$ generation results presented by porphyrins **1–5**. Photostability was estimated according to the percentages of the Soret band decay, which were recorded under an irradiance of 100 mW cm^{-2} . Table 1 photostability results refer to the remaining absorbance after irradiance of 100 mW cm^{-2} , where lower percentages reflect lower photostabilities. All porphyrins evaluated were considerably photostable. Porphyrin **1** was the least stable photosensitizer evaluated, which showed 88% of remaining absorbance after 20 min of irradiance.

The capacity of $^1\text{O}_2$ producing was determined by the indirect photooxidation method, which was based on the measuring of the DPBF absorbance decay at 415 nm, in the presence of each of the porphyrins herein studied, during 20 min at 9 mW/cm^2 of irradiance. According to Table 1, porphyrins **1** and **4** were the best $^1\text{O}_2$ producers, which decreased DPBF absorbance in 87 and 88%, respectively.

Table 1 Photostability and singlet oxygen generation of porphyrins **1–5**. ^aPhotostability results are expressed as percentage from the initial absorbance of porphyrins Soret band, after 20 min of irradiance (100 mW cm⁻²). Higher percentages values reflect higher photostabilities. ^bSinglet oxygen generation was assessed by the DPBF photooxidation (50 mmol L⁻¹; in DMF/H₂O 9:1) upon irradiation for 20 minutes with white light filtered through a cut-off filter for wavelengths <540 nm (9 mW cm⁻²), with or without photosensitizer (0.5 mmol L⁻¹). Percentage values indicate DPBF absorbance decay from initial absorbance. Higher percentage values reflect higher ¹O₂ generation. Complete monitoring (1–20 min) of photostability and ¹O₂ assays, is shown in the supplementary data file.

Compound	Photostability ^a (%)	DPBF absorbance decay ^b (%)
DPBF	---	12
1	88	87
2	95	82
3	90	80
4	96	88
5	99	78

Photodynamic Inactivation of the conidia of *Colletotrichum graminicola*

Results of the preliminary PDI experiments, which were performed using 25 μmol L⁻¹ of porphyrin concentration, are shown in Figure 2. These first experiments were also performed in order to evaluate if porphyrins **1–5** would be adequate photosensitizers against *C. graminicola* conidia, namely, if the tested porphyrins were active only in the presence of light and photosensitizer, simultaneously. For this purpose, conidia susceptibility was first evaluated with light, in the absence of photosensitizer (light control) and without light, in the presence of photosensitizer (dark control). At this stage, light control and PDI was conducted with a fluence of 120 J cm⁻². This evaluation indicated that porphyrins **2**, **4** and **5** efficiently eliminated *C. graminicola* in the PDI assay, showing no significant conidia killing in the dark. Porphyrin **1** presented a decreasing in conidia viability in the PDI assay that was considered low, taking in account the high porphyrin concentration utilized.

Differently, porphyrin **3** eliminated *C. graminicola* for both PDI and dark control assays. Porphyrin **3** was further evaluated under lower concentration values (1–15 μmol L⁻¹) in the dark;

however, a complete conidia killing was observed for all cases (data not shown). In this way, this porphyrin was not considered an appropriate photosensitizer and it was not employed for the following PDI assays.

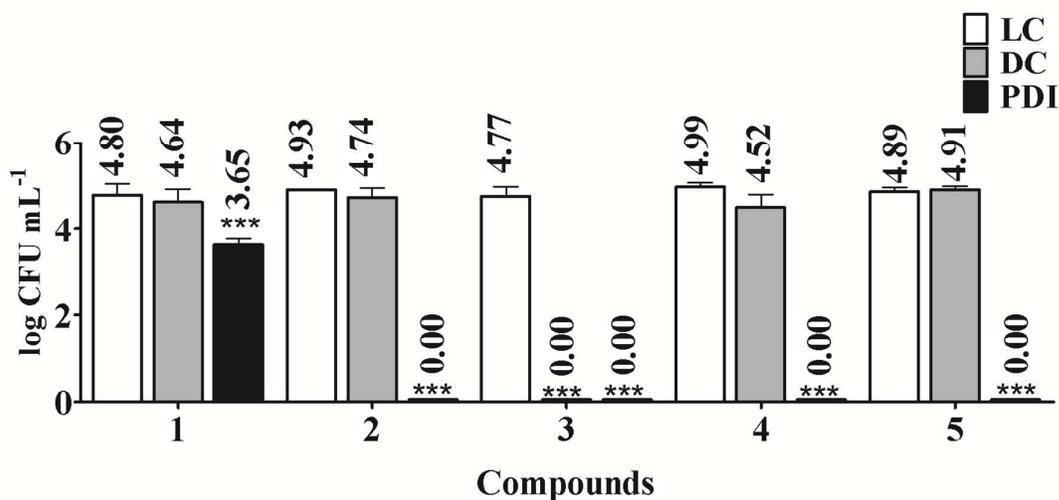


Fig. 2 Controls and preliminary PDI tests on *Colletotrichum graminicola* using cationic porphyrins 1–5 as photosensitizers. LC: light control using a fluence of 120 J cm⁻². DC: dark control, conducted with porphyrin concentration at 25 μmol L⁻¹. PDI experiments were performed with same concentration and fluence used for controls. Results are expressed as logarithm of viable colony-forming unit per milliliter (log CFU mL⁻¹). The average values are indicated above the bars. Asterisks indicate level of significance of conidia inactivation (***: p<0.001). Error bars represent standard deviation.

Based on the results shown in Figure 2, porphyrins 2, 4 and 5 were then more thoroughly studied (Fig. 3) by varying porphyrin concentrations with lower values (5, 10 and 15 μmol L⁻¹) and using fluences of 30, 60 and 90 J cm⁻². Porphyrins 2 and 4 promoted complete conidia inactivation under all porphyrin concentration and fluence evaluated. On the other hand, porphyrin 5 promoted a photoinactivation that was effective for most of the conditions tested, although it was considerably lower in comparison to porphyrins 2 and 4, especially for fluencies studied in Figure 3.

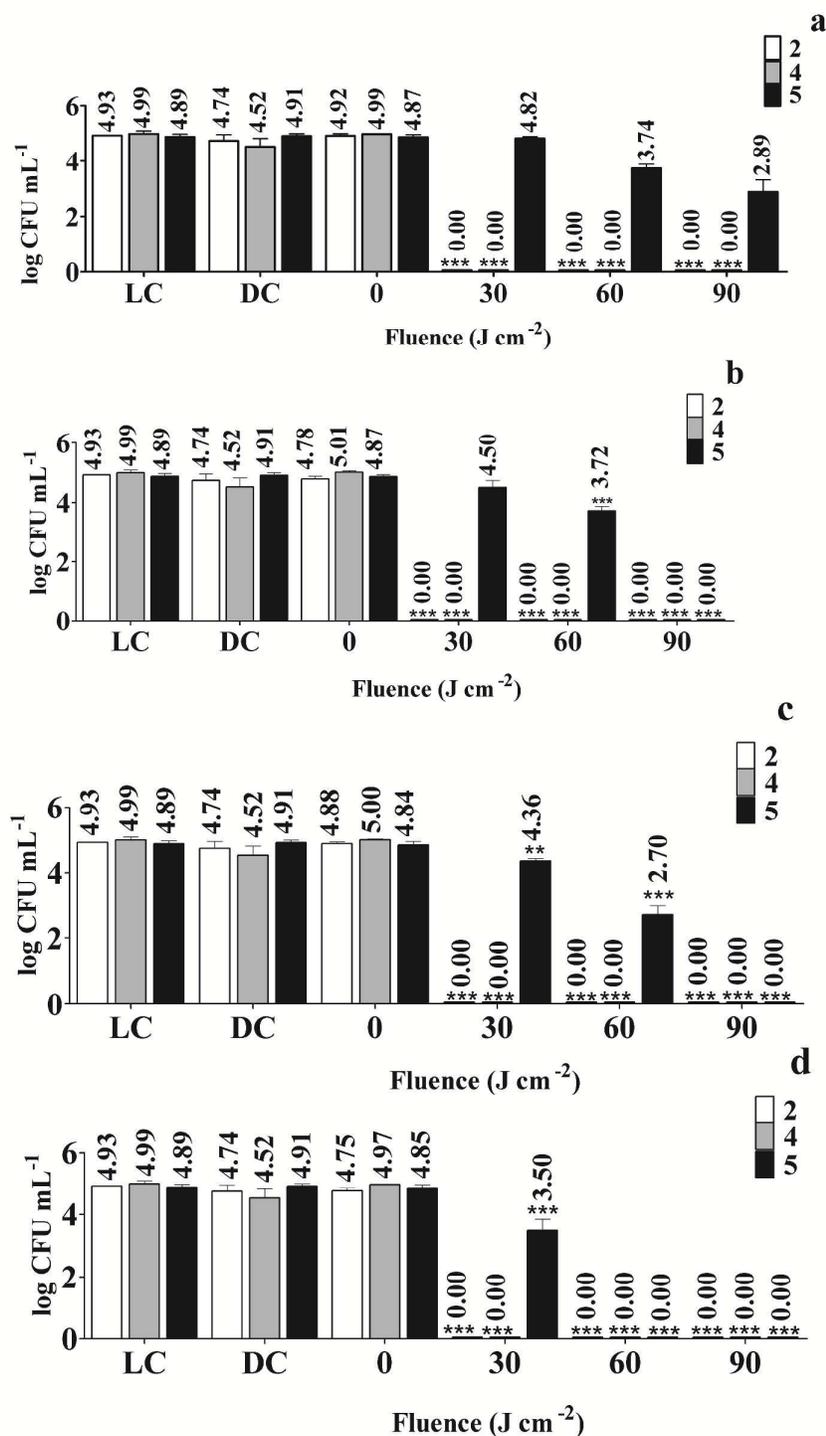


Fig. 3 Controls and PDI of *Colletotrichum graminicola* employing porphyrins 2, 4 and 5 in concentrations of $5 \mu\text{mol L}^{-1}$ (a), $10 \mu\text{mol L}^{-1}$ (b), $15 \mu\text{mol L}^{-1}$ (c) and $25 \mu\text{mol L}^{-1}$ (d), with fluence of 0, 30, 60 and 90 J cm^{-2} . Results are expressed as logarithm of viable colony-forming unit per milliliter ($\log \text{CFU mL}^{-1}$). The average values are indicated above the bars. Asterisks indicated level of significance of conidia inactivation (** $p < 0.01$, ***: $p < 0.001$). Error bars represent standard deviation.

In order to differentiate the photosensitizing efficiency of porphyrins **2** and **4**, even lower concentrations of these porphyrins were employed for the PDI experiments ($1 \mu\text{mol L}^{-1}$ and $2.5 \mu\text{mol L}^{-1}$) (Fig. 4). This evaluation indicated that porphyrin **4** photoinactivated *C. graminicola* with a higher efficiency in comparison with **2**. Porphyrin **4** was able to provide a complete inactivation of the conidia, even at $1 \mu\text{mol L}^{-1}$ under fluence of 30 J cm^{-2} while porphyrin **2** required 60 J cm^{-2} using the same concentration.

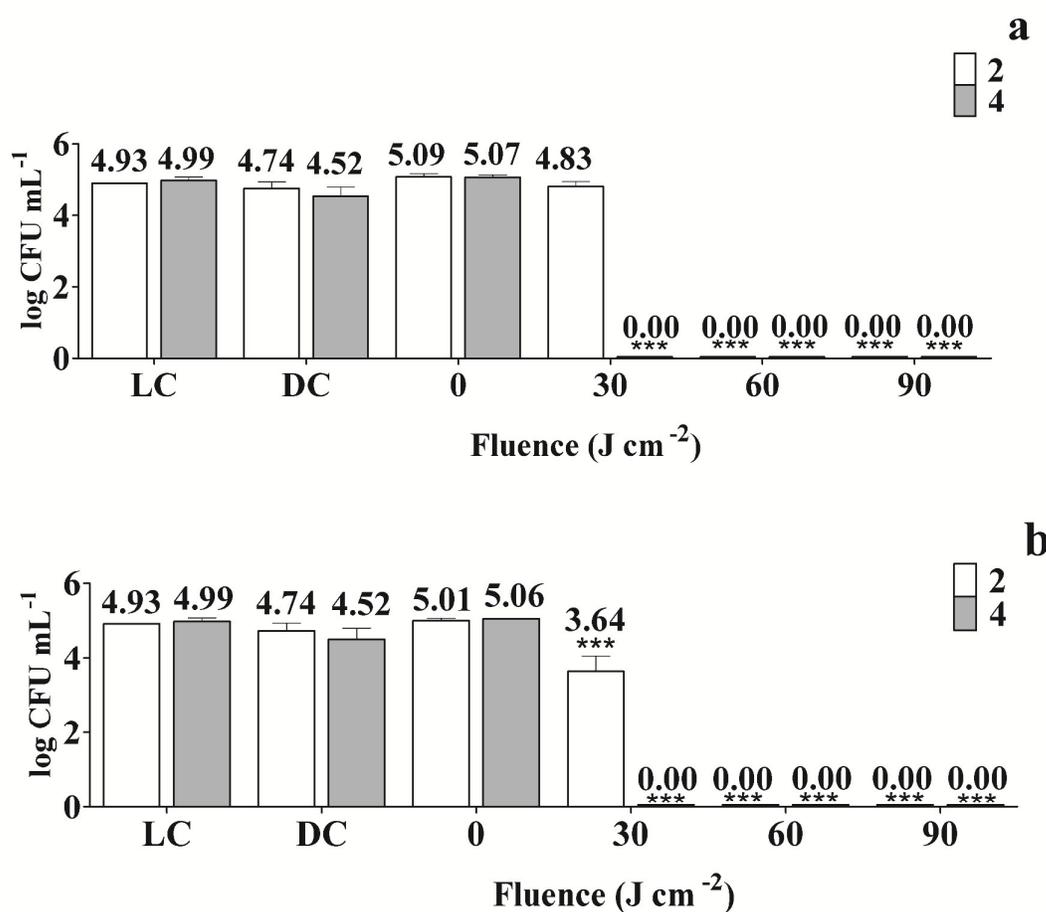


Fig. 4 Controls and PDI of *Colletotrichum graminicola* employing porphyrins **2** and **4** in concentrations of $1 \mu\text{mol L}^{-1}$ (a) and $2.5 \mu\text{mol L}^{-1}$ (b), with a fluence of 0, 30, 60 and 90 J cm^{-2} . Results are expressed as logarithm of viable colony-forming unit per milliliter ($\log \text{CFU mL}^{-1}$). The average values are indicated above the bars. Asterisks indicated level of significance of conidia inactivation (***: $p < 0.001$). Error bars represent standard deviation.

Fluorescence Microscopic Analysis

The fluorescence microscopy experiments shown in Figure 5 were performed with 25 $\mu\text{mol L}^{-1}$ (porphyrins **1** and **5**) or with 10 $\mu\text{mol L}^{-1}$ (porphyrins **2**, **3** and **4**). These concentrations were defined based on preliminary experiments that showed that the most active porphyrins (**2**, **3** and **4**) promoted an intense fluorescence when using concentrations higher than 10 $\mu\text{mol L}^{-1}$, which impaired a good visualization of the conidial structures. The images collected from the microscopic evaluation of the *C. graminicola* conidia and their interactions with the cationic porphyrin **1**–**5** are shown in Figure 5. The green image areas are related exclusively to the conidial structures and denoted absence of porphyrins. Red color is related to the fluorescence emitted by the porphyrin molecules that are not interacting with conidial structures. Yellow-colored areas denote interaction between porphyrin and conidial structures. Figure 5b indicated that porphyrin **1** was heavily present on the surface and inside of the conidia; however, the whole content of **1** was not necessarily interacting with conidial structures. The other porphyrins all seem to interact with conidial structures to some extent, with porphyrin **3** (Fig. 5d) causing evident conidial disrupting.

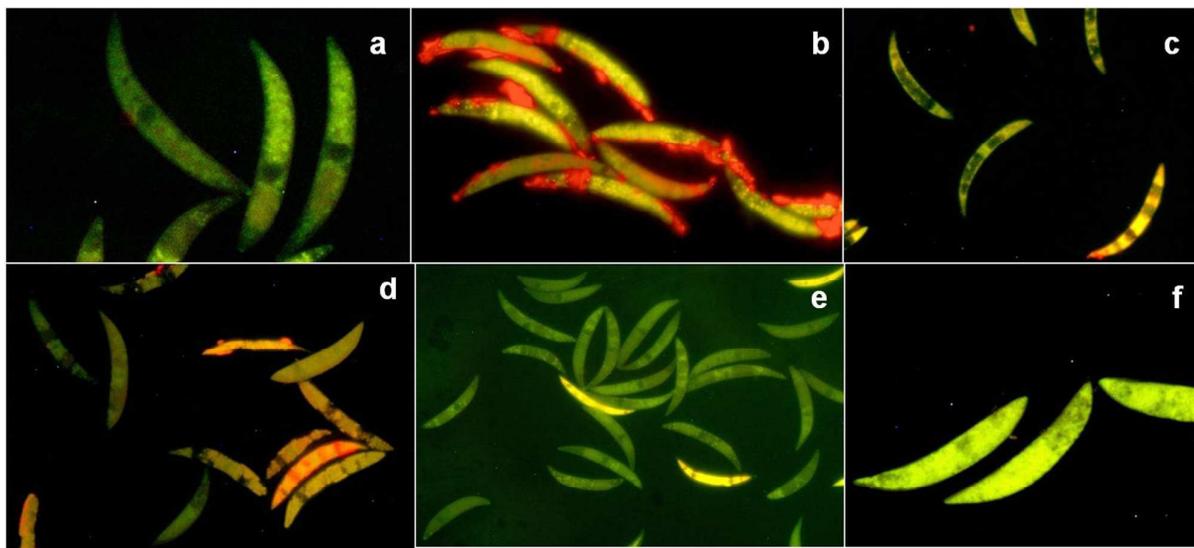


Fig. 5 Fluorescence microscopy assays of *Colletotrichum graminicola* conidia in the absence (a) and in the presence of cationic porphyrins **1** (b), **2** (c), **3** (d), **4** (e), **5** (f) in concentration of 10 $\mu\text{mol L}^{-1}$ for porphyrins **2**, **3** and **4** and 25 $\mu\text{mol L}^{-1}$ for **1** and **5**. Green color is related to conidial structures, red to porphyrins and yellow to the interaction between microorganism and porphyrins.

Porphyrin binding to the conidia of *Colletotrichum graminicola*

Porphyrin concentration utilized for the binding experiments were exactly the same as those utilized for the fluorescence microscopy experiments, namely, porphyrins **1** and **5** were assayed at $25 \mu\text{mol L}^{-1}$ and porphyrins **2**, **3** and **4** at $10 \mu\text{mol L}^{-1}$. Compounds **2** and **3** presented the higher binding values after 60 min of incubation, which were 4.35×10^9 and 5.16×10^9 molecules CFU^{-1} , respectively. Porphyrin **4**, at $10 \mu\text{mol L}^{-1}$, showed comparable binding values with porphyrins **1** and **5**, both at $25 \mu\text{mol L}^{-1}$, which were 8.46×10^8 , 1.48×10^9 , 1.20×10^9 molecules CFU^{-1} (60 min of incubation), respectively. The washing procedure served to eliminate those photosensitizer molecules that were not firmly associated to the fungal structures. As shown in Figure 6, the washings caused reduction on binding values for all porphyrins and incubation times evaluated.

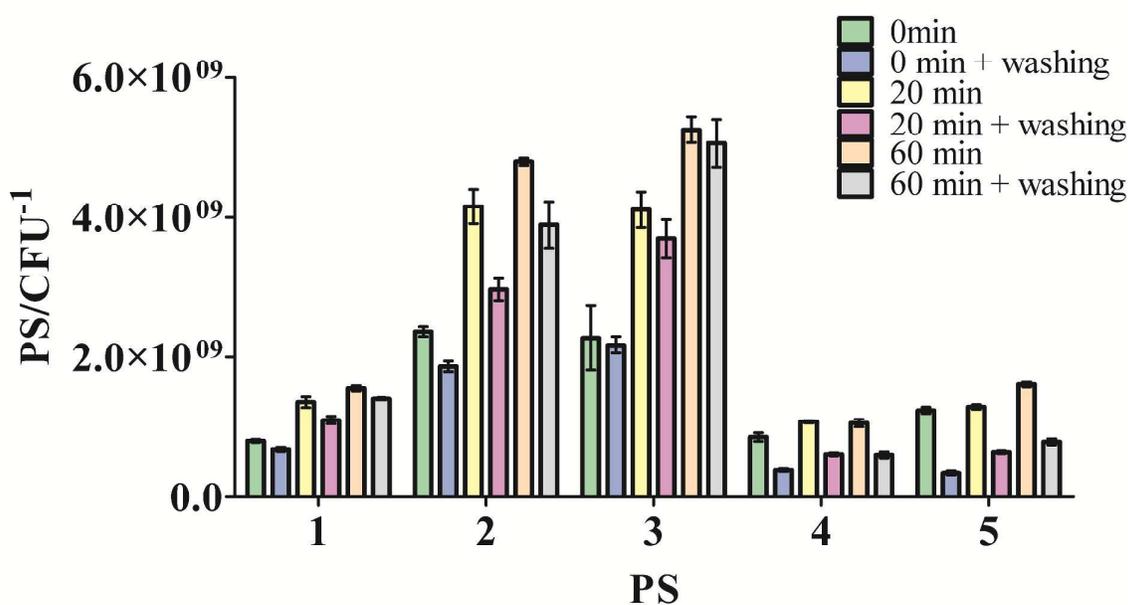


Fig. 6 Binding of the tested porphyrins to *Colletotrichum graminicola* conidia after incubation in the dark for 0, 20 and 60 min at 30 °C (with and without washings with PBS), using $25 \mu\text{mol L}^{-1}$ of porphyrins **1** and **5** and $10 \mu\text{mol L}^{-1}$ of porphyrins **2**, **3** and **4**. Binding values are expressed as number of porphyrin molecules per colony-forming unit ($\text{PS}/\text{CFU}^{-1}$). PS: photosensitizer. Error bars represent standard deviation.

DISCUSSION

Cationic porphyrins have shown to be suitable photosensitizers for the inactivation of diverse microorganisms by PDI. The photoinactivating properties of porphyrin **5** have been extensively evaluated in the literature.^{4,17,18,21,23} For this reason, we decided to study porphyrin **5**, together with closely related porphyrins, in order to verify if cationic *meso*-(1-methyl-4-pyridinio) porphyrins could be potentially useful as an alternative for the control of fungal phytopathogens, specifically for *C. graminicola*. As **5** presents four identical cationized *meso*-pyridyl groups, we synthesized porphyrins having different number or positioning of phenyl and 1-methylpyridinio groups among the *meso* positions of the macrocycle. It is well known that the above-mentioned structural differences play an important role on porphyrin physicochemical, photophysical and photodynamic properties.⁵⁴

Preliminary PDI assays (Fig. 2), which were performed with a high porphyrin concentration (25 $\mu\text{mol L}^{-1}$) demonstrated the suitability of the fluence utilized and also proved that porphyrins **1**, **2**, **4** and **5** could be considered proper photosensitizers, since they were active only in the presence of light. On the other hand, porphyrin **3** promoted a complete inactivation of *C. graminicola* in the absence of light, even using lower porphyrin concentrations. This behavior suggests a light-independent mode of action (and consequently a $^1\text{O}_2$ -independent action) that also operates for this porphyrin. This observation was supported by the results shown in Figure 6, which indicated a large binding of porphyrin **3** to *C. graminicola* conidia, with subsequent cell disruption (Fig. 5d). Simões *et al.* (2015),⁵⁵ Alves *et al.* (2009)⁵ and Kessel *et al.* (2003)⁵⁶ also comparatively studied the PDI of cationic porphyrins presenting different charge number and positioning. For the three studies mentioned, the porphyrin presenting two positive charges at adjacent *meso*-positions were the most active photosensitizers. This behavior was explained by the distortion of the porphyrin ring, which was directly caused by the electrostatic repulsion of the two close positive charges^{55,56}. For the present work, the high photoactivity expected for the doubly-charged *cis*-porphyrin (**3**) was somehow translated as the cytotoxicity in the dark observed. Considering the different PDI/dark susceptibilities shown by distinct microorganisms, previous study⁹ reported that *Aspergillus flavus* was inactivated by hematoporphyrin, in the absence of light, at a concentration of 5 $\mu\text{mol L}^{-1}$, while other fungi evaluated were only eliminated under PDI conditions. This literature data could indicate that the light independent inactivation promoted by porphyrins is related to species of the microorganism under study.

The preliminary PDI results (Fig. 2) also showed porphyrin **1** as exhibiting a photoactivity that was considerably lower than the other porphyrins. This compound (**1**), also differently of the other porphyrins evaluated, is poorly soluble in aqueous medium. This property is directly related to

the presence of only one positively charged group attached to the highly hydrophobic tetrapyrrole ring. The lack of water solubility can trigger an aggregative behavior, which has been recurrently observed for this type of compound.^{12,18,55,57} In this way, the lower photostability and the high estimative of $^1\text{O}_2$ singlet production presented by **1** (Table 1) could be, in part, artefacts raised from aggregation events. Aggregation could also explain the lower photoactivity observed by **1**. Even though this porphyrin presented a considerable binding value (Fig. 6), most of the photosensitizer aggregated on the surface of the conidia (Fig. 5b). This probably caused an inaccessibility of $^1\text{O}_2$ or other oxygen reactive species to important conidial structures, which reflected the low photoactivity observed.

Considering PDI experiments varying fluence and porphyrin concentration (Fig. 3 and 4), porphyrins **2** and **4** were arguably more photoactive than **5**. Porphyrin **5** required a fluence of 90 J cm^{-2} at $15 \mu\text{mol L}^{-1}$ in order to completely inactivate *C. graminicola*, while porphyrins **2** and **4** provided the same effect under all concentration and fluences outlined in Figure 3. Figure 4 experiments ultimately allowed the differentiation between porphyrins **2** and **4**, which indicated the later as the most efficient photosensitizer herein evaluated. Take in account the lowest concentration that enabled the best photoinactivation with the respective lowest effective fluence, the photosensitizers could be ranked as follows: **4** ($1 \mu\text{mol L}^{-1}$ with a fluence of 30 J cm^{-2}) > **2** ($1 \mu\text{mol L}^{-1}$ with 60 J cm^{-2}) > **5** ($15 \mu\text{mol L}^{-1}$ with 90 J cm^{-2}) > **1** ($25 \mu\text{mol L}^{-1}$ with 120 J cm^{-2}).

Taking in account the $^1\text{O}_2$ production and binding shown by porphyrins **2**, **4** and **5**, compound **4** owes most of its activity to the production of high levels of $^1\text{O}_2$ (Table 1). This observation is sustained by the low binding results presented by this porphyrin (Fig. 6). In this way, it is presumable that the high level of killing provided by the small amount of porphyrin **4** inside the conidia was made possible by its outstanding $^1\text{O}_2$ production per molecule. On the other hand, in comparison with porphyrin **4**, compound **2** presented a lower level of $^1\text{O}_2$ production, which was counterbalanced by an excellent porphyrin binding to the conidia. The lower photoactivity of porphyrin **5**, in comparison with **2** and **4**, could be explained by its $^1\text{O}_2$ production (comparable to **2**) and its low binding values (comparable to **4**).

According to Engelmann and coworkers (2007)⁵⁸ and Simões *et al.* (2015)⁵⁵, a proper photosensitizer should present both hydrophilic and hydrophobic character in order to trespass the biological membranes. In the present work, the sole evaluation of the binding results (Fig. 6) clearly indicated that the porphyrins presenting two positively charged groups (**2** and **3**) were the ones that bound effectively to *C. graminicola*, being two methylpyridinio groups (hydrophilic) and two phenyl groups (hydrophobic) the best ratio of those substituents at *meso*-positions of the macrocycle. The fact that porphyrin **2** gave the best binding value reinforces the importance of the

amphiphilic character, which is more pronounced for the *cis*-porphyrin that possess both hydrophobic and both hydrophilic groups of the same side of the molecule.

The number of bound molecules herein determined by the binding assay was from 846 million up to 5.16 billion of molecules per conidia. These numbers are substantially higher than those ones determined by Gomes *et al.* (2011)¹⁸ for *Penicillium chrysogenum*, which reached approximately 20 million per conidia. Considering that porphyrin **5** was included in the cited paper, it is presumable that the type of microorganism plays an important role in terms of photosensitizer binding.

PDI studies utilizing the same structurally related porphyrins herein evaluated are described in the literature, mainly for bacteria. Porphyrins **3**, **4** and **5** were evaluated in terms of their photoinactivating properties against the marine bacteria *Enterococcus seiolicida* and *Vibrio anguillarum*, and *Escherichia coli*.⁴⁶ In this case, compounds **3** and **4** were efficient on eliminating *V. anguillarum*, while only compound **4** effectively eliminated *E. coli*. The photoinactivation of *E. coli* and *Staphylococcus warneri*,¹⁹ which used porphyrin **5** as photosensitizer, served as reference for the evaluation of an analog containing three *meso* methylpyridino cationic groups and one pentafluorophenyl ring. For *E. coli*, both photosensitizers completely inactivated bacteria at 5 $\mu\text{mol L}^{-1}$. In the case of *S. warneri*, only the tricationic derivative was effective at a concentration of 0.5 $\mu\text{mol L}^{-1}$. In general, those studies are consistent with a higher photoinactivating efficiency of the unsymmetrical cationic porphyrins, which is in agreement with the study herein presented.

The PDI studies involving the genus *Colletotrichum* available in the literature indicated that phenothiazine dyes and coumarins require a concentration ranging from 5 to 50 $\mu\text{mol L}^{-1}$ to photoinactivate these microorganisms.^{40,41} In this way, cationic porphyrins **2** and **4** can be considered better photosensitizers than the compounds previously evaluated for the genus *Colletotrichum*.

Regarding the potential application of porphyrin derivatives in agriculture, it is important considering an alleged photodamage of the host plant (*Zea mays*). There are a number of publications indicating that superior plants are quite resistant in face of light-activated photosensitizers. In fact, photosensitizing processes naturally occur in plants – via endogenous phytoalexins,⁵⁹ thiophens,⁶⁰ root ketoalkenes and ketoalkines⁶¹ as defense mechanisms against phytopatogens and as natural physiological processes.⁶² To avoid photodamage, vegetal cells minimize oxygen reactive species and singlet oxygen action via superoxide dismutase, ascorbate peroxidase and glutathione reductase, which are present in the plant chloroplasts.⁶³ In addition, xanthophylls (plant secondary metabolites) dissipates the excess of energy from light through non-photochemical mechanisms.⁶⁴ Those natural protecting mechanisms presented by plants could spare the host plant against the photodamage promoted by porphyrins, which could favour the exclusive

photoinactivation of the infecting *C. graminicola*. Nevertheless, those are just indications of the potentiality of porphyrins for such purpose. The *in vivo* evaluation of porphyrins using *Zea mays* plants affected by *Colletotrichum* is an ongoing project in our laboratory and it will be reported soon.

Concluding Remarks

The present study demonstrated that cationic porphyrins structurally related to tetra-charged porphyrin (**5**), especially the *trans*-doubly-charged (**2**) and triply-charged (**4**) porphyrins, are promising photosensitizers for the PDI of phytopathogen *Colletotrichum graminicola*. The *cis*-doubly-charged porphyrin (**3**) showed fungicide properties in the absence of light by disrupting conidial structures. Single-charged **1** presented a low photoactivity, probably due to its lower solubility in aqueous medium.^{54,65} The doubly-charged porphyrins evaluated (**2** and **3**) appeared to subside to a more efficient binding to *C. graminicola* conidia. In general, porphyrins presenting a high ¹O₂ singlet production allied to a good binding value, which was mostly provided by appropriated balance between the hydrophilic and hydrophobic moieties of the porphyrin structure, were the most promising photosensitizers.

These results confirm the applicability of cationic porphyrins for the PDI of filamentous fungi and opens the possibility of using this type of compound as photosensitizers to be applied in agriculture.

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