

Photochemistry of Resveratrol: Beyond the Reactivity of Metal-Free Porphyrins Immobilized on Lignin

Elisa De Marchi,* Alessia Marino, Fabiana Fosso, Natalia Ceccotti Vlas, Davide Piccinino, Eliana Capecchi, Lorenzo Botta, Marcello Crucianelli, and Raffaele Saladino*

The photochemistry of resveratrol with singlet oxygen ($^1\text{O}_2$) under blue-LED irradiation is explored in the presence of three metal-free porphyrins as photosensitizers. Irradiation at 450 nm yields products of C=C bond scission, 6-electron electrocyclic ring closure, and [4 + 2] cycloaddition, including benzaldehydes, 2,4,6-trihydroxyphenanthrene, and resveratrol cyclic endoperoxide. The selectivity of the process is controlled by the structure of

the metal-free porphyrin and by the nominal capacity of the blue-LED photon. The scope of the reaction is extended to sustainable heterogeneous photosensitizers produced by immobilization of metal-free porphyrins on lignin, the most abundant polyphenol in nature characterized by beneficial photochemical properties.

1. Introduction

Among reactive oxygen species (ROS),^[1,2] singlet oxygen ($^1\text{O}_2$) is notable for the unique electrophilic nature, due to the high reactivity of the low-energy LUMO.^[3] Production,^[4] lifetime,^[5,6] and selectivity of $^1\text{O}_2$ in organic transformations are reported,^[7] often in connection with biomolecules of relevance for cell life. In human health, $^1\text{O}_2$ damages lipids, proteins, and DNA, improving inflammation, aging, and diseases.^[8–10] Nonetheless, the beneficial role of $^1\text{O}_2$ in photodynamic therapy (PDT) of cancer is well recognized.^[11] The photochemistry of $^1\text{O}_2$ with shikimic acid metabolites is still an open matter of study, with a particular focus on the reactivity of stilbene derivatives. Resveratrol, 5-(4-hydroxystyryl) benzene-1,3-diol,^[12–28] is a bioactive stilbene characterized by modulation of lipid metabolism, inhibition of oxidation of low-density lipoprotein (LDL) and platelet aggregation, and anti-inflammatory, anti-cancer, neuroprotective, and cardioprotective effects.^[29–34] It acts as radical-scavenger,^[35] offering protection from photo-oxidative damage. Resveratrol is isomerized at 350 nm to corresponding *cis*-isomer, with successive formation of 2,4,6-trihydroxyphenanthrene through 6-electron electrocyclic

ring closure and dehydrogenation.^[35] As an alternative, the irradiation at wavelengths above 493 nm yields cyclic endoperoxide by [4 + 2] cycloaddition at the phenolic ring.^[36] Thus, different photochemical pathways may occur depending on the energy associated to the photon. Recently, we reported that blue-LED photons at 450 nm and *meso*-tetraphenylporphyrin (*meso*-TPP) selectively generate $^1\text{O}_2$, providing a sustainable procedure for the coupling and functionalization of different phenols and terpenes.^[37–39] With the aim to explore the general scope of this oxidation, we report here the photochemistry of resveratrol with blue-LED photons and *meso*-TPP and other metal-free porphyrins at 450 nm. The study includes heterogeneous photosensitizers produced by immobilization of metal-free porphyrin on lignin, the most abundant polyphenol in nature that acts as a stabilizing platform in the generation of $^1\text{O}_2$.^[37–42] The reactivity balance between resveratrol and *cis*-resveratrol is discussed in relation to the formation of cyclic endoperoxide, 2,4,6-trihydroxyphenanthrene, and products of C=C bond scission.^[35] As a general trend, metal-free porphyrins favored the formation of 2,4,6-trihydroxyphenanthrene and benzaldehyde derivatives under both homogeneous and heterogeneous conditions.

2. Results and Discussion

Initially, we investigated the photochemistry of resveratrol (*trans*-1) under the experimental conditions previously applied in the photo-oxidation of terpenes.^[37] *Trans*-1 (22 mM) and *meso*-TPP (1 mol% with respect to 1) were dissolved in 2-methyltetrahydrofuran (2-MeTHF; 2 mL) and the solution was stirred at room temperature (200 rpm) for 48 h. The photoreactor consisted of a 4 mL vial inserted into a jacketed beaker with commercial blue LED (450 nm; nominal capacity m^{-1} 12 W) wrapped around it (photocatalytic set-up is in SI#1). The oxygen quantum yield ($\Phi^1\text{O}_2$) of *meso*-TPP was 0.60 as previously reported.^[40] We observed the formation of benzaldehydes 2 and 3 in similar (but low) yield (Table 1, entry 1). They are products of C=C bond scission. No

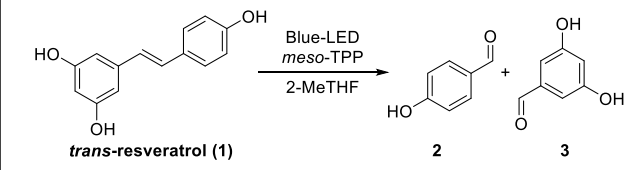
E. De Marchi, F. Fosso, N. Ceccotti Vlas, D. Piccinino, E. Capecchi, L. Botta, R. Saladino
Department of Biological and Ecological Sciences
University of Tuscia
Largo dell'Università, snc, I-01100 Viterbo, Italy
E-mail: elisa.demarchi@unitus.it
saladino@unitus.it

A. Marino, M. Crucianelli
Department of Physical and Chemical Sciences
University of L'Aquila
Via Vetoio, I-67100 L'Aquila, Italy

Supporting information for this article is available on the WWW under https://doi.org/10.1002/cptc.202500073

© 2025 The Author(s). ChemPhotoChem published by Wiley-VCH GmbH. This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

Table 1. Photo-oxidation of *trans*-resveratrol using blue-LED (12 W).^{a)}

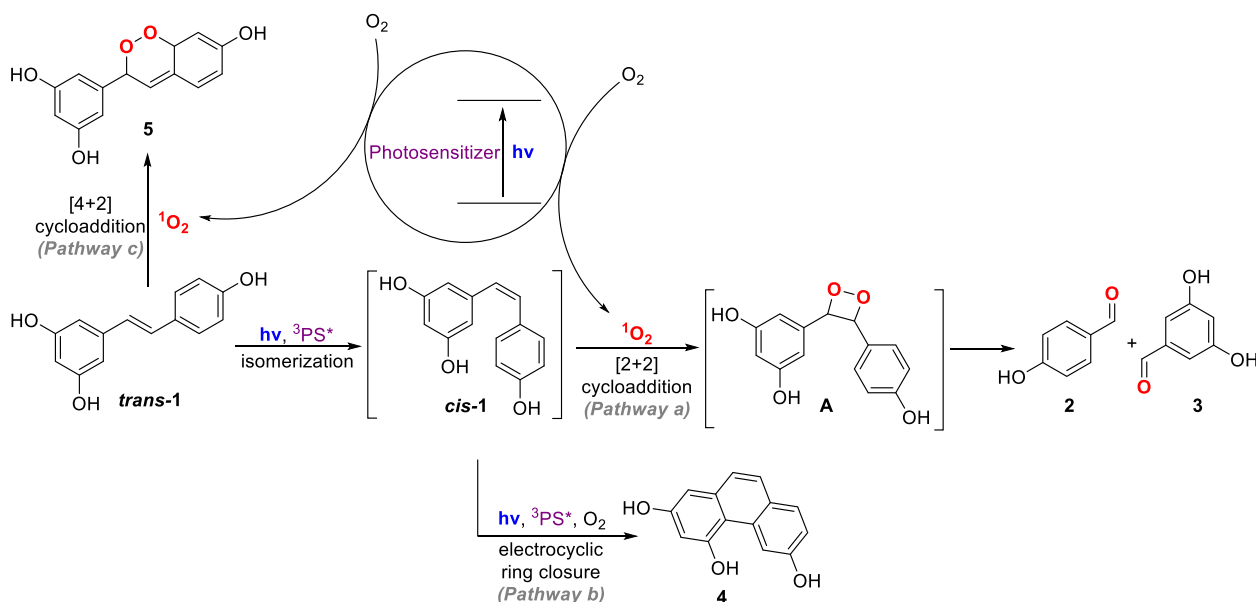
			
Entry	Product	Conv. [%]	Yield [%] ^{b)}
1	2 (3)	35	9 (8.7)
2 ^{c)}	2 (3)	60	30 (28.9)
3 ^{c),d)}	2 (3)	63	31 (29)

^{a)}The reaction was performed by solubilizing resveratrol (22 mM) and *meso*-TPP (1 mol% with respect to substrate) in 2-MeTHF. ^{b)}The yield was calculated on starting substrate (mmol). ^{c)}Reaction carried out by increasing the concentration of *trans*-1 to 65 mM. ^{d)}Reaction performed with 0.5 mol% *meso*-TPP.

trace amounts of *cis*-1, 2,4,6-trihydroxyphenanthrene **4** and cyclic endoperoxide **5** were detected (Scheme 1). The low mass balance was probably due to the formation of polar oxidative coupling products not isolated in our case. The reaction repeated in the absence of *meso*-TPP or in dark conditions was unproductive. Better results were obtained by increasing the amount of *trans*-1 (65 mM), in which case **2** and **3** were isolated in appreciable yield (Table 1, entry 2). *Meso*-TPP was active at 0.5 mol% with respect to substrate (Table 1, entry 3). The presence of oxygen radical species was ruled out by “coumarin” and TEMPO assays, respectively, while NaN₃ test confirmed the formation of ¹O₂ (SI#2).

Next, blue-LED photons with different nominal capacity P (14.4 and 18 W) were studied. P is defined by the following equation

$$P = N \cdot E \quad (1)$$



Scheme 1. Proposed reaction mechanism for the photo-oxidation of resveratrol with blue-LED photons. ³PS* is the long-lived triplet excited state of the photosensitizer.

where *N* is the number of photons emitted per second and *E* is the energy of the photon given by the Planck–Einstein equation. Briefly, *trans*-1 (65 mM) and *meso*-TPP (0.5 mol% with respect to **1**) were dissolved in 2-MeTHF (2 mL) in a photoreactor consisting of a 4.5 cm diameter glass vessel placed inside an additional 7.5 cm diameter glass container and illuminated with blue strip (450 nm; nominal power m⁻¹ P 14.4 W) for 24 h at room temperature. We observed the formation of *cis*-resveratrol (*cis*-1), benzaldehydes **2** and **3**, 2,4,6-trihydroxyphenanthrene **4**, and cyclic endoperoxide **5** (Table 2, entry 1). The ¹H NMR of the mixture between *trans*-1 and *cis*-1 recovered after purification of the crude at 450 nm and 14 W is reported in SI#3. Compounds **4** and **5** were assigned by comparison of the corresponding ¹H-NMR signals, in the reaction crude, with that of original references.^[35,36] Note that **5** was not previously isolated due to its low thermal stability.^[36] Characteristic ¹H NMR signals of endoperoxide **5** (and of **4**) are reported in SI#3 in the case of the reaction performed at 450 nm and 14 W in the presence *meso*-TPP. The yield of benzaldehydes **2** and **3** was measured on the basis of the amount of isolated compounds, while **4** and **5** were estimated by integration of characteristic ¹H NMR signals using *trans*-1 as a reference. Benzaldehydes **2** and **3** and 2,4,6-trihydroxyphenanthrene **4** prevailed in the reaction mixture. The selectivity observed at 450 nm was different with respect to that observed in previous irradiations at 350 nm and at wavelengths above 493 nm.^[35,36] Probably, the reaction pathway occurring at 450 nm (Scheme 1) involved the initial blue-LED photo-activation of *meso*-TPP followed by intersystem crossing with formation of a long-lived triplet excited state.^[43] This latter intermediate can facilitate the isomerization of *trans*-1 to *cis*-1 and (contemporary) the formation of ¹O₂. Examples of the effect played by long-lived triplet excited state in the *trans/cis* isomerization are reported with different photosensitizers,^[43–47] including the case of Pterin.^[47] Next, [2 + 2] cycloaddition of ¹O₂ to *cis*-1 may yield dioxetane

Table 2. Investigation of different photosensitizers for the photo-oxidation of resveratrol.^{a)}

Entry	Photosensitizer	LF [$\mu\text{mol mg}^{-1}$]	$\Phi^1\text{O}_2^{\text{b)}$	TON ^{c)}	Conv. [%]	2(3) [%] ^{d),e)}	4 [%] ^{d)}	5 [%] ^{d)}
1	meso-TPP	–	0.60	120	60	15(14)	20	5
2 ^{f)}	meso-TPP	–	0.60	146	73	36(34)	–	–
3	TCPP	–	0.53	44	22	2(traces)	16	–
4	MCPP	–	0.69	104	52	3(traces)	45	3
5	Rose Bengal	–	0.76	74	37	3(2)	10	15
6	EHL/TCPP	0.39	0.46 ^{f)}	70	35	2(3)	28	–
7	EHL/MCPP	0.18	0.66 ^{f)}	124	62	4(3)	51	–
8	EHLAc/TCPP	0.32	0.92 ^{f)}	100	50	1(traces)	53	–
9	EHLAc/MCPP	0.15	0.99	170	85	6(3)	69	–
10	EHLAc/MCPP	0.15	–	166	83	4(2)	67	–
11	EHLAc/MCPP	0.15	–	150	75	2(traces)	59	–
12	EHLAc/MCPP	0.15	–	142	71	3(2)	56	–
13	EHLAc/MCPP	0.15	–	130	65	traces	49	–

^{a)}The reaction was performed solubilizing **trans-1** (65 mM) and the photosensitizer (0.5 mol% with respect to substrate) in 2-MeTHF. The solution was gently stirred (200 rpm) under blue-LED irradiation (14.4 W, 450 nm) at 28 °C for 24 h. ^{b)} $\Phi^1\text{O}_2$ was measured by standard protocol.^[59] ^{c)}The turnover number (TON) was calculated using the following formula: TON = (moles of substrate converted)/(moles of catalyst used). ^{d)}Yield% was calculated on the basis of ¹H-NMR of the reaction crude. ^{e)}Products 2–3 were recovered in similar yield. ^{f)}Reaction carried out using blue-LED at 450 nm and 18 W.

intermediate **A** and rearrangement and C=C bond scission to **2** and **3** (Pathway a), or in alternative 6-electron electrocyclic ring closure and dehydrogenation to yield **4** (Pathway b). In this latter case, the role of oxygen has been associated with the dehydrogenation step.^[35,48,49] In addition, **trans-1** reacted with $^1\text{O}_2$ by [4 + 2] cycloaddition to yield cyclic endoperoxide **5** (Pathway c). Results suggest that the isomerization of **trans-1** to **cis-1** and successive photo-oxidation of **cis-1** were the prevalent transformation at 450 nm and 14.4 W. A better selectivity of the reaction was observed by irradiation at 18 W under similar experimental conditions. In this latter case, benzaldehydes **2** and **3** were obtained as the only recovered products in quantitative yield besides to unreacted substrate (Table 2, entry 2). These data are in accordance with the prevalence of formation of dioxetane **A** by improving the nominal capacity P of blue-LED photons.

The photocatalytic effect of two alternative metal-free porphyrins, tetrakis-(4-carboxyphenyl)-porphyrin (TCPP) and 5-(4-carboxyphenyl)-10,15,20-triphenylporphyrin (MCPP), was then evaluated. Porphyrins were selected due to the presence of carboxylic moiety useful for immobilization procedure.^[41,42] Rose Bengal was also studied as a positive reference. The $\Phi^1\text{O}_2$ of TCPP, MCPP, and Rose Bengal were 0.53,^[50] 0.69,^[51] and 0.76,^[52] respectively (Table 2). MCPP was prepared with a slight modification of previously reported procedure.^[51]

The oxidation of **trans-1** with TCPP proceeded with low conversion of substrate to yield **4** as the main reaction product, besides low amount of **2** and **3** (Table 2, entry 3). A better reactivity was observed with MCPP, in which case **trans-1** was converted in larger amount to afford **4** as the main reaction product besides the low amount of **2/3** and **5** (Table 2, entry 4). These results confirm that the porphyrin favors the isomerization of **trans-1** to **cis-1** and successive transformations with respect to alternative [4 + 2] cycloaddition (Pathway c). The 6-electron electrocyclic ring closure (Pathway b) prevailed with respect to [2 + 2] cycloaddition (Pathway a) in the presence of

the electron-withdrawing carboxylic moiety as a substituent on the porphyrin ring, as in the case of MCPP and TCPP. Note that Rose Bengal was less efficient than metal-free porphyrins showing lower selectivity; products deriving from **trans-1** (compound **5**) and **cis-1** (compounds **2/3** and **4**) were synthesized in similar total yield (Table 2, entry 5).

The scope of the transformation was further extended to heterogeneous photosensitizers produced by covalent immobilization of MCPP and TCPP on enzymatic hydrolytic lignin (EHL). Lignin is the most abundant polyphenol in nature characterized by beneficial chemical and physical properties in the immobilization of photocatalytic species, including eumelanin and pheomelanin.^[53–57] The electrochemical behavior of lignin is reported, as well as the capacity to generate $^1\text{O}_2$.^[53] For the immobilization procedure, MCPP and TCPP (0.18 mmol) were treated with EHL (200 mg) and triphenylphosphine (PPh_3 , 0.36 mmol) in THF (10 mL), followed by the dropwise addition of di-isopropyl azodicarboxylate (DIAD; 0.36 mmol) in EtOAc (2.5 mL). EHL/TCPP and EHL/MCPP (**Figure 1**) were isolated by dialysis. The loading factor was evaluated by ³¹P NMR analysis (SI#4) after phosphitylation (SI#5) with 2-chloro-4,4,5,5-tetramethyl-1,3,2 dioxaphospholane TMDP^[58] (Table 2, entries 6 and 7). The $\Phi^1\text{O}_2$ of EHL/TCPP and EHL/MCPP was measured by the comparative absorption method, based on 9,10-dimethylantracene (DMA). The absorption band of DMA at 398 nm was monitored in the presence of a selected catalyst at various time intervals after irradiation with blue-LED at 450 nm (14.4 W) (SI#6).^[59] Rose Bengal was used as a reference. $\Phi^1\text{O}_2$ of EHL/TCPP and EHL/MCPP was of the same order of magnitude as free porphyrins. The photocatalytic effect of EHL/TCPP and EHL/MCPP was then evaluated. Briefly, **trans-1** (65 mM) dissolved in 2-methyltetrahydrofuran (2-MeTHF; 2 mL) was treated with the appropriate catalyst (0.5 mol% of porphyrin with respect to **1**) and irradiated with blue-LED photon at 450 nm (14.4 W) under gentle stirring (200 rpm) at room temperature for 24 h. TCPP and MCPP retained their selectivity after the

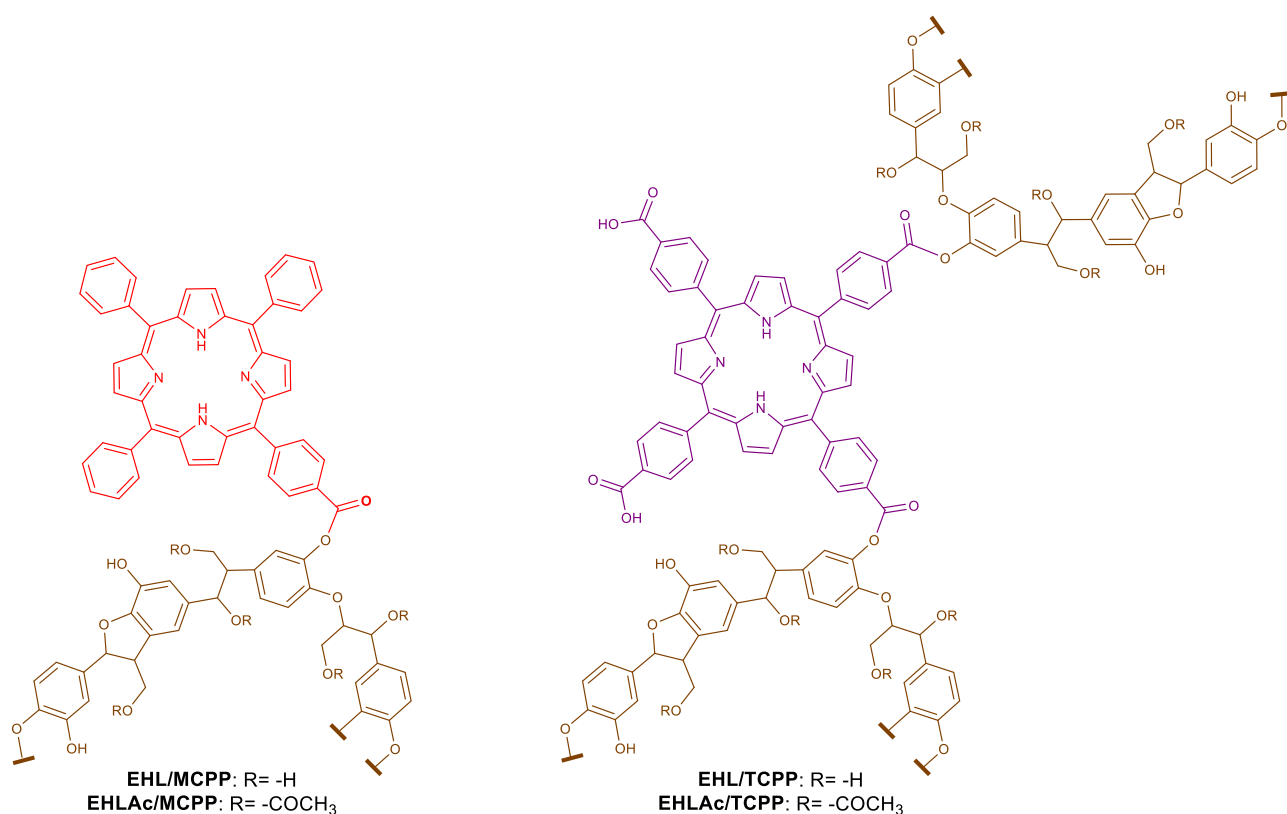


Figure 1. Proposed structure for EHL/MCPP and EHL/TCPP.

immobilization procedure affording 2,4,6-trihydroxyphenanthrene **4** as the main reaction product besides **2** and **3** (Table 2, entries 6 and 7). EHL/TCPP and EHL/MCPP showed a reactivity higher than parent TCPP and MCPP suggesting the beneficial effect of lignin in the overall transformation (Table 2, entries 3 and 4 versus entries 6 and 7). EHL/MCPP was the best photosensitizer for the synthesis of **4** (Table 2, entry 7).

Acetylation of EHL is reported to improve the generation of $^1\text{O}_2$.^[55] Indeed, the reduction of free hydroxyl groups is responsible for the loss of antioxidant activity.^[60,61]

We decided to perform the selective acetylation of aliphatic hydroxyl groups, leaving the phenolic counterpart free for the immobilization of porphyrins. Briefly, lignin (0.3 g) was dissolved in sulfuric acid and acetic acid (0.33:1.0 v/v) at 60 °C for 20 min (SI#7). Selective acetylation was confirmed by ^{31}P NMR analysis to afford EHLAc. Then, TCPP and MCPP were immobilized on EHLAc to yield EHLAc/TCPP and EHLAc/MCPP (Figure 1) by using the previously reported procedure. ^{31}P NMR was used to evaluate the loading factor (Table 2, entries 8 and 9). The $\Phi^1\text{O}_2$ of EHLAc/TCPP and EHLAc/MCPP (Table 2) was higher than EHL/TCPP and EHL/MCPP confirming the beneficial role played by acetylation in the generation of $^1\text{O}_2$. Accordingly, EHLAc/TCPP and EHLAc/MCPP demonstrated enhanced photocatalytic activity, resulting in increased conversion of *trans*-**1** and higher yield of **4** compared to their un-acetylated counterparts (Table 2, entries 8 and 9). Benzaldehydes **2** and **3** were again detected as by-products in very low amount. These findings agree with those reported in the literature for acetylated lignin.^[55,60,61] The turnover number (TON) of photosensitizers is also reported in Table 2. EHLAc/

MCPP showed the highest TON. In addition, the most active EHLAc/MCPP retained appreciable reactivity for at least 4 runs (Table 2, entries 10–13).

3. Conclusion

The impact of the photosensitizer and the effect of the nominal capacity of blue-LED photons at 450 nm in the selectivity of the photo-oxidation of resveratrol was described. Irradiation with metal-free porphyrins at 450 nm revealed a reaction profile significantly different from those previously observed with blue-methylene at wavelengths above 493 nm and in the absence of photosensitizer at 350 nm, respectively. Experimental conditions were identified to synthesize specific reaction products in the presence of homogeneous (*meso*-TPP, TCPP, and MCPP) and heterogeneous (EHL/TCPP, EHL/MCPP, EHLAc/TCPP, EHLAc/MCPP) photosensitizers. They include *meso*-TPP and blue-LED photons at 450 nm (P 18 W) for the C=C bond scission and formation of benzaldehydes **2** and **3**, and EHLAc/MCPP and blue-LED photons at 450 nm (P 14.4 W) for the 6-electron electrocyclic ring closure to 2,4,6-trihydroxyphenanthrene **4**. Irrespective of the experimental conditions, cyclic endoperoxide **5** was observed in a very low yield in the presence of porphyrins. Immobilization of the porphyrins on the surface of lignin enhanced the photocatalytic activity, especially in the case of acetylated lignin. The sustainability of the process was documented by the recyclability of the most active EHLAc/MCPP for more runs.

4. Experimental Section

Materials

Commercially available reagents were used without further purification. Chromatographic separations were performed on Merck silica gel 60 (230–400 mesh). R_f values are referred to as TLC carried out on 0.25 mm silica gel plates (F254) using the eluent indicated for column chromatography. All products were dried in a high vacuum (10^{-3} mbar) before characterization. ^1H NMR, ^{13}C NMR, and ^{31}P NMR were recorded on a Bruker Avance DRX400 (400/100 MHz) spectrometer. UV/Vis spectra were recorded on a Shimadzu UV-2600i spectrophotometer equipped with ISR-2600 integrating sphere and using 1 cm light path quartz cuvettes.

Photo-Oxidation of Resveratrol (*Trans*-1): General Procedure

***Trans*-1** (65 mM) and the photosensitizer (0.5 mol% with respect to substrate) were solubilized in 2-MeTHF (2 mL) in a photoreactor consisting of a 4.5 cm diameter glass vessel placed inside an additional 7.5 cm diameter glass container and illuminated with blue strip (450 nm; nominal power/m 14.4 W). The solution was gently stirred (200 rpm) under blue-LED irradiation at 28 °C. After 24 h, the reaction mixture was evaporated and the crude product was analyzed by ^1H -NMR (acetone- d_6) to estimate the yield of **4** and **5** by quantitative comparison with *trans*-1 as a reference. The crude product was purified by column chromatography (CH_2Cl_2 : MeOH 25:1).

4-Hydroxybenzaldehyde (2): R_f = 0.67 (CH_2Cl_2 : MeOH 25:1); ^1H NMR (400 MHz, CD_3OD): δ = 9.78 (s, 1H), 7.79 (d, J = 8.6 Hz, 2H), 6.93 (d, J = 8.6 Hz, 2H) ppm. ^{13}C NMR (100 MHz, CD_3OD): δ = 191.4, 163.8, 132.0, 127.6, 115.5 ppm.

3,5-Dihydroxybenzaldehyde (3): R_f = 0.61 (CH_2Cl_2 : MeOH 25:1); ^1H NMR (400 MHz, CD_3OD): δ = 9.79 (s, 1H), 6.81 (d, J = 2.1 Hz, 2H), 6.56 (t, J = 1.9 Hz, 2H) ppm. ^{13}C NMR (100 MHz, CD_3OD): δ = 192.7, 159.1, 138.7, 108.4, 107.3 ppm.

Synthesis of 5-(4-Carboxyphenyl)-10,15,20-Triphenylporphyrin (MCPP)

The 5-(4-carboxyphenyl)-10,15,20-triphenylporphyrin (MCPP) was prepared by a slight modification of the procedure reported in the literature.^[51] 4-Formylbenzoic acid (1.90 mmol) was dissolved in 2.70 mL of propionic acid in a 5 mL microwave vessel. Subsequently, benzaldehyde (5.80 mmol) and fresh distilled pyrrole (7.70 mmol) were added dropwise, as well as nitrobenzene (11.3 mmol). The reaction mixture was magnetically stirred at r.t. until complete dissolution of the reagents, followed by heating under microwave irradiation (250 W) at 120 °C for 30 min. After cooling, the crude mixture was precipitated in distilled water, filtered off, and dried under vacuum. The product was purified by flash chromatography (CH_2Cl_2 /EtOH 97:3) as a purple solid in 36% yield.

4-(10,15,20-Triphenylporphyrin-5-yl) benzoic acid (MCPP): R_f = 0.3. ^1H NMR ($\text{DMSO}-d_6$): δ = 8.85 (s, 8H), 8.40–8.33 (q, 4H), 8.23 (dd, J = 5.7, 1.9 Hz, 6H), 7.88–7.81 (m, 9H), –2.92 (s, 2H, NH) ppm. ^{13}C NMR (100 MHz, $\text{DMSO}-d_6$): δ = 167.9, 145.9, 141.6, 134.9, 134.7, 132.2, 129.7, 129.0, 128.6, 128.3, 127.5, 120.8, 120.6, 119.3 ppm. The spectral data were in accordance with the literature.^[62]

Preparation of Heterogeneous Photosensitizers

Heterogeneous photosensitizers were prepared by adapting a previously described method.^[59] 200 mg of the selected lignin (EHL or EHLAc) and selected porphyrin (0.18 mmol) were solubilized in THF (10 mL) in the presence of triphenylphosphine (0.36 mmol)

and left under vigorous stirring for 15 min at r.t. DIAD (0.36 mmol) in ethyl acetate (2.5 mL) was added dropwise and the mixture was kept at 65 °C for 24 h. EHL/TCPP, EHL/MCPP, EHLAc/TCPP, and EHLAc/MCPP were purified by dialysis bag (MW = 1000 Da) using THF as solvent (300 mL for 24 h, twice) and dried under vacuum. The loading factor of heterogeneous photosensitizers was calculated by ^{31}P NMR.

Acknowledgements

E.D.M. and A.M. contributed equally to this work. The authors acknowledge the project: “Sintesi prebiotica multicomponente di nucleotidi, nucleosidi e basi nucleiche dell’RNA variamente modificati e di loro oligonucleotidi con attività antitumorale” ORIGINALE – Project Code CN_0000041 Funded by the European Union – Next Generation EU, Mission 4, Component 2, Inv. 1.4 – CUP B63C22000610006. E.C. acknowledges the NRRP Next Generation EU – Mission 4, Component 2, Investment 1.5 – Project ECS 0000024 Rome Technopole – CUP B83C22002820006. M.C. acknowledges the PERCIVAL – CUP B85F21005400005.

Open access publishing facilitated by Università degli Studi della Toscana, as part of the Wiley - CRUI-CARE agreement.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available in the supplementary material of this article.

Keywords: heterogeneous catalysis • photo-oxidation • porphyrins • resveratrol • singlet oxygen

- [1] T. R. Koran, O. Otlı, A. B. Karabulut, *J. Lab. Med.* **2023**, 47, 1. <https://doi.org/10.1515/labmed-2022-0108>.
- [2] F. Collin, *Int. J. Mol. Sci.* **2019**, 20, 2407.
- [3] I. Pibiri, *ChemPhotoChem* **2018**, 2, 535.
- [4] M. C. DeRosa, R. J. Crutchley, *Coord. Chem. Rev.* **2002**, 233, 351.
- [5] M. Bregnhøj, M. H. K. Bhattarai, F. Jensen, P. R. Ogilby, *Phys. Chem. Chem. Phys.* **2016**, 18, 22946.
- [6] E. L. Clennan, A. Pace, *Tetrahedron* **2005**, 61, 6665.
- [7] E. L. Clennan, *Tetrahedron* **2000**, 56, 9151.
- [8] A. L. Petrou, A. A. Terzidaki, *Biochem. J.* **2017**, 474, 2713.
- [9] K. Murotomi, A. Umeno, M. Shichiri, M. Tanito, Y. Yoshida, *Int. J. Mol. Sci.* **2023**, 24, 2739.
- [10] T. W. Stief, *Med. Hypotheses* **2003**, 60, 567.
- [11] P. S. Maharjan, H. K. Bhattarai, *J. Oncol.* **2022**, 25, 7211485. <https://doi.org/10.1155/2022/7211485>.
- [12] X. Yin, J. Yu, Q. Kong, X. Ren, *Food Chem.* **2017**, 237, 1101.
- [13] Q. Kong, X. Ren, J. Qi, J. Yu, J. Lu, S. Wang, *Biomolecules* **2019**, 9, 268.
- [14] C. Li, X. Xu, Z. Tao, X. J. Wang, Y. Pan, *Food Chem.* **2015**, 173, 218.
- [15] W. Lu, J. Liu, *Chem. A Eur. J.* **2016**, 22, 3127.
- [16] J. A. Baur, D. A. Sinclair, *Nat. Rev. Drug Discovery* **2006**, 5, 493.
- [17] M. Das, D. K. Das, *Mol. Aspects Med.* **2010**, 31, 503.
- [18] J. A. Baur, K. J. Pearson, N. L. Price, H. A. Jamieson, C. Lerin, A. Kalra, V. V. Prabhu, J. S. Allard, G. Lopez-Lluch, K. Lewis, P. J. Pistell, S. Poosala, K. G. Becker, O. Boss, D. Gwinn, M. Wang, S. Ramaswamy, K. W. Fishbein, R. G. Spencer, E. G. Lakatta, D. Le Couteur, R. J. Shaw,

- P. Navas, P. Puigserver, D. K. Ingram, R. deCabo, D. A. Sinclair, *Nature* **2006**, 444, 337.
- [19] S. K. Lee, W. Zhang, B. J. S. J. Sanderson, *Agric. Food Chem.* **2008**, 56, 7572.
- [20] K. T. Howitz, K. J. Bitterman, H. Y. Cohen, D. W. Lamming, S. Lavu, J. G. Wood, R. E. Zipkin, P. Chung, A. Kisielewski, L.-L. Zhang, B. Scherer, D. A. Sinclair, *Nature* **2003**, 425, 191.
- [21] H. Y. Cohen, C. Miller, K. J. Bitterman, N. R. Wall, B. Hekking, B. Kessler, K. T. Howitz, M. Gorospe, R. de Cabo, D. A. Sinclair, *Science* **2004**, 305, 390.
- [22] S. D. Westerheide, J. Anckar, *Science* **2009**, 323, 1063.
- [23] J.-N. Lin, V. C.-H. Lin, K.-M. Rau, P.-C. Shieh, D.-H. Kuo, J.-C. Shieh, W.-J. Chen, S.-C. Tsai, T.-D. J. Way, *Agric. Food Chem.* **2010**, 58, 1584.
- [24] S. Quideau, D. Deffieux, C. Douat-Casassus, L. Pouységu, *Angew. Chem. Int. Ed.* **2011**, 50, 586.
- [25] A. Borriello, V. Cucciola, A. Oliva, P. Galletti, V. Zappia, F. Della Ragione, *Cell Cycle* **2007**, 6, 2495.
- [26] C. Counet, D. Callemien, S. Collin, *Food Chem.* **2006**, 98, 649.
- [27] A. L. Holme, S. Pervaiz, *J. Bioenerg. Biomembr.* **2007**, 39, 59.
- [28] P. Jeandet, R. Bessis, B. F. Maum, M. Philippe, D. Peyron, P. Trollat, *J. Agric. Food Chem.* **1995**, 43, 316.
- [29] L. E. Donnelly, R. Newton, E. Kennedy, P. S. Fenwick, R. H. F. Leung, K. Ito, R. E. K. Russel, P. J. Barnes, *Am. J. Physiol. Lung Cell. Mol. Physiol.* **2004**, 287, 774.
- [30] H. S. Liu, C. E. Pan, W. Yang, X. M. Liu, *World J. Gastroenterol.* **2003**, 7, 1474.
- [31] L. M. Hung, J. K. Chen, S. S. Huang, R.-S. Lee, M. J. Su, *Cardiovasc. Res.* **2000**, 47, 549.
- [32] K. S. Huang, M. Lin, G. F. Cheng, *Phytochemistry* **2001**, 57, 357.
- [33] H. Zhuang, Y. S. Kim, R. C. Koehler, S. Dore, *Ann. N.Y. Acad. Sci.* **2003**, 993, 276.
- [34] A. Y. Sun, A. Simonyi, G. Y. Sun, *Free Radical Biol. Med.* **2002**, 32, 314.
- [35] R. A. Rodríguez, I. R. Lahoz, O. N. Faza, M. M. Cid, C. S. Lopez, *Org. Biomol. Chem.*, **2012**, 10, 9175.
- [36] J. A. Celaje, D. Zhang, A. M. Guerrero, M. Selke, *Org. Lett.* **2011**, 13, 4846.
- [37] E. De Marchi, L. Botta, B. M. Bizzarri, R. Saladino, *Molecules* **2022**, 27, 8961.
- [38] D. Piccinino, N. Ceccotti Vlas, S. Gabellone, E. Capecchi, R. Saladino, *Eur. J. Org. Chem.* **2023**, 26, e202300356.
- [39] S. Gabellone, E. Capecchi, L. A. Ortelli, R. Saladino, *ACS Omega* **2022**, 7, 45688.
- [40] R. Schmidt, C. Tanielian, *J. Phys. Chem. A* **2000**, 104, 3177.
- [41] Y. Wang, X. Yu, S. Ma, S. Cao, X. Yuan, W. Zhu, H. Wang, *Green Chem.* **2024**, 26, 42.
- [42] T. S. E. Ho-Yin, S. C. Cheng, C. S. Yeung, C. Y. Lau, W. H. Wong, C. Dong, S. Y. Leu, *Green Chem.* **2019**, 21, 1319.
- [43] M. Mlakic, A. Ljubic, A. Šalic, V. Milašinovic, M. Gojun, B. Zelic, K. Molcanov, O. Horváth, I. Škoric, *Catalysts* **2022**, 12, 1510.
- [44] S. Prashanthi, P. H. Kumar, D. Siva, S. R. Lanke, V. J. Rao, S. Basak, P. R. Bangal, *J. Phys. Chem. C* **2011**, 115, 20682.
- [45] J. Isokuortti, K. Kuntze, M. Virkki, Z. Ahmed, E. Vourimaa-Laukkanen, M. A. Filatov, A. Turshatov, T. Laaksonen, A. Priimagi, N. A. Durandin, *Chem. Sci.* **2021**, 12, 7504.
- [46] M. Schmitt, P. R. Erickson, K. McNeill, *Environ. Sci. Technol.* **2017**, 51, 13151.
- [47] J. R. Neyra Recky, M. G. Tosato, A. A. Buglak, *Free Radic. Biol. Med.* **2024**, 216, 50.
- [48] R. Mattioli, D. Di Risola, R. Federico, A. Cogli, F. Gasparini, C. Villani, M. Fontana, A. Maggiore, M. d'Erme, L. Mosca, A. Francioso, *Molecules* **2022**, 27, 2348.
- [49] A. Francioso, A. Boffi, C. Villani, L. Manzi, M. D'Erme, A. Macone, L. Mosca, *J. Org. Chem.* **2014**, 79, 9381.
- [50] W. Li, N. Gandra, E. D. Ellis, S. Courtney, S. Li, E. Butler, R. Gao, *ACS Appl. Mater. Interfaces* **2009**, 1, 1623.
- [51] R. Chouikrat, A. Champion, R. Vanderesse, C. Frochot, A. Moussaron, *J. Porphyrins Phthalocyanines* **2015**, 19, 595.
- [52] J. J. M. Lamberts, D. R. Schumacher, D. C. Neckers, *J. Am. Chem. Soc.*, **1984**, 106, 5879.
- [53] L. R. Barclay, M. C. Basque, M. R. Vinqvist, *Can. J. Chem.* **2003**, 81, 457.
- [54] K. Fischer, M. Beyer, *Lenzinger Ber.* **2000**, 79, 25.
- [55] G. Marchand, C. A. Calliste, R. M. Williams, C. McLure, S. Leroy-Lhez, N. Villandier, A. Lignins, *ChemistrySelect* **2018**, 3, 5512.
- [56] J. Kim, T. V. T. Nguyen, Y. H. Kim, F. Hollmann, C. B. Park, *Nat. Synth.* **2022**, 1, 217.
- [57] E. Miglbauer, M. Gryszel, E. D. Głowacki, *Green Chem.* **2020**, 22, 673.
- [58] A. Granata, D. S. Argyropoulos, *J. Agric. Food Chem.* **1995**, 43, 1538.
- [59] J. Morgan, Y. J. Yun, A. J. L. Ayitou, *Photochem. Photobiol.* **2022**, 98, 57.
- [60] L. R. C. Barclay, J. K. Grandy, H. D. MacKinnon, H. C. Nichol, M. R. Vinqvist, *Can. J. Chem.* **1998**, 76, 1805.
- [61] K. Fischer, M. Beyer, H. Koch, *Holzforschung* **2009**, 49, 203.
- [62] A. Stallivieri, L. Colombeau, J. Devy, N. Etique, C. Chaintreuil, B. Myrzakhmetov, M. Achard, F. Baros, P. Arnoux, R. Vanderesse, C. Frochot, *Bioorg. Med. Chem.*, **2018**, 26, 688.

Manuscript received: March 6, 2025

Revised manuscript received: May 7, 2025

Version of record online: June 1, 2025