

# In vitro analysis of catalase and superoxide dismutase mimetic properties of blue tattoo ink

---

Homolak, Jan

Source / Izvornik: **Free Radical Research, 2022, 56, 343 - 357**

Journal article, Accepted version

Rad u časopisu, Završna verzija rukopisa prihvaćena za objavljivanje (postprint)

<https://doi.org/10.1080/10715762.2022.2102976>

Permanent link / Trajna poveznica: <https://um.nsk.hr/um:nbn:hr:105:168116>

Rights / Prava: [In copyright](#) / [Zaštićeno autorskim pravom](#).

Download date / Datum preuzimanja: **2024-08-21**



Repository / Repozitorij:

[Dr Med - University of Zagreb School of Medicine  
Digital Repository](#)



1 In vitro analysis of catalase and superoxide dismutase mimetic properties of blue tattoo ink

2

3 Jan Homolak<sup>1,2</sup>

4 <sup>1</sup> Department of Pharmacology, University of Zagreb School of Medicine, Zagreb, Croatia

5 <sup>2</sup> Croatian Institute for Brain Research, University of Zagreb School of Medicine, Zagreb,  
6 Croatia

7

8

9 Jan Homolak, MD

10 Department of Pharmacology,  
11 University of Zagreb School of Medicine,  
12 Salata 11, 10 000 Zagreb,  
13 Croatia

14 [homolakjan@gmail.com](mailto:homolakjan@gmail.com)

15 00385 91 9411 468

16 **Abstract**

17 Tattoo inks are comprised of different combinations of bioactive chemicals with combined  
18 biological effects that are insufficiently explored. Tattoos have been associated with oxidative  
19 stress; however, a recent N-of-1 study suggested that blue tattoos may be associated with  
20 suppressed local skin oxidative stress. The present study aimed to explore the attributes of the  
21 blue tattoo ink (BTI) that may explain its possible effects on redox homeostasis, namely the  
22 catalase (CAT) and superoxide dismutase (SOD)-mimetic properties that have been reported  
23 for copper(II) phthalocyanine (CuPC) – the main BTI constituent. Intenze™ Persian blue (PB)  
24 BTI has been used in the experiment. CAT and SOD-mimetic properties of PB and its pigment-  
25 enriched fractions were analyzed using the carbonato-cobaltate (III) formation-derived H<sub>2</sub>O<sub>2</sub>  
26 dissociation and 1,2,3-trihydroxybenzene autoxidation rate assays utilizing simple buffers and  
27 biochemical matrix of normal skin tissue as chemical reaction environments. CuPC-based  
28 tattoo ink PB and both its blue and white pigment-enriched fractions demonstrate CAT and  
29 SOD-mimetic properties *in vitro* with effect sizes demonstrating a substantial dependence on  
30 the biochemical environment. PB constituents act as inhibitors of CAT but potentiate its  
31 activity in the biochemical matrix of the skin. CuPC-based BTI can mimic antioxidant  
32 enzymes, however chemical constituents other than CuPC (e.g. the photoreactive TiO<sub>2</sub>) seem  
33 to be at least partially responsible for the BTI redox-modulating properties.

34

35 **Keywords:** tattoo; tattoo ink; oxidative stress; catalase; superoxide dismutase

36 **Conflict of interest statement:** No conflict of interest to disclose.

37 **Funding source:** None.

38 **Introduction:**

39 The art of tattooing dates back to the earliest stages of tribal communities and the oldest known  
40 tattoo belongs to the famous mummy *Ötzi the Iceman* (3000 BC)[1]. Throughout history, the  
41 prevalence of tattoos varied; however, in the last decades, the practice of tattooing spread  
42 throughout the Western world and became a mainstream form of body art. Recent estimates  
43 suggest that up to 25% of Europeans under the age of 20 and up to 38% of Americans under  
44 the age of 29 bear at least one tattoo [2]. Despite the omnipresence of tattooing, the biomedical  
45 effects of tattoos remain poorly explored, possibly because tattoo inks are comprised of  
46 different combinations of many bioactive chemicals with combined biological effects that are  
47 challenging to explore, let alone predict. In general, tattoo inks contain: i) organic (e.g. azo or  
48 polycyclic aromatic) or inorganic pigments (e.g. titanium dioxide (TiO<sub>2</sub>), barium sulfate  
49 (BaSO<sub>4</sub>), iron oxide, chromium oxide); ii) binders (e.g. polyethylene glycol,  
50 polyvinylpyrrolidone); iii) solvents (e.g. water, alcohol); and iv) additives (preservatives,  
51 surfactants)[2]. Additionally, impurities (e.g. nitrosamines or formaldehyde) may be present as  
52 well, and the ink injected into the body may contain nickel and chromium particles shredded  
53 from the needle during tattooing [3]. During the procedure of tattooing, all the constituents are  
54 delivered into the dermis where they become 100% systemically bioavailable due to direct  
55 contact with the blood and lymph. Although the kinetics of different tattoo ink constituents is  
56 still unknown, it is assumed that soluble components undergo rapid systemic distribution, while  
57 the insoluble pigments are mostly retained in the area of injection and in the draining lymph  
58 nodes where they may exert biological effects [2].

59 Although substantial efforts have been made to better understand the biological effects of tattoo  
60 inks utilizing *in vitro* and *in vivo* models, the results demonstrate that the observed effects are  
61 strongly dependent on the chemical constitution of the ink and the toxicological model utilized  
62 in the study. For example, Falconi et al. reported reduced viability and expression of the  
63 procollagen  $\alpha 1$  type I in primary human fibroblasts incubated with *Biolip 27* but not *Strong*  
64 *black* [4]. Regensburger et al. reported substantial variability in the potency of 19 commercially  
65 available tattoo inks in respect to their inhibitory effects on mitochondrial activity in primary  
66 human dermal keratinocytes exposed to UVA radiation [5]. Arl et al. compared the effects of  
67 blue, green, red, and black tattoo ink on cell viability and the generation of reactive oxygen  
68 species (ROS) and reported that incubation with red and green tattoo inks induced the most  
69 pronounced toxic effects on the human keratinocyte cell line [6]. Perplexing *in vivo* results  
70 have also been reported. For example, in studies on tattoo ink carcinogenicity, it has been  
71 reported that mice tattooed with red tattoo ink and exposed to ultraviolet radiation develop  
72 tumors slightly faster (214 vs 224 days) and show an increased tumor growth rate in  
73 comparison with sham-tattooed mice [7]. In contrast, black tattoo ink was protective against  
74 ultraviolet radiation-induced squamous cell carcinoma, delaying the tumor onset by  
75 approximately 50 days in tattooed mice [8]. Although it will be interesting to see the follow-  
76 up studies on the interaction between exposure to different tattoo inks and the carcinogenic  
77 potential of ultraviolet radiation (to address the uncertainty related to relatively small effects  
78 reported in [7] and [8]), the apparently discrepant results provide a good illustration of the fact  
79 that the biological effects of different tattoo inks seem to be too complex and specific to provide  
80 foundations for inductive reasoning on the effects of tattoo inks in general. To better understand  
81 the biomedical consequences of tattooing, a substantial effort should be made to i) elucidate  
82 the biological effects of individual chemicals present in different tattoo inks, and ii) explore

83 the synergistic, additive, or antagonistic effects of chemical constituents of different tattoo inks  
84 in model systems that resemble those found *in vivo*.

85 The present aim was to explore the properties of blue tattoo ink that may explain the recently  
86 reported observation that a blue tattoo was able to suppress local skin oxidative stress [9].  
87 Oxidative stress is a pathophysiological condition that ensues as a consequence of the inability  
88 of a system to maintain the balance between the electrophilic and the nucleophilic arm of redox  
89 homeostasis [10]. Considering redox homeostasis is critical for normal cellular functioning, it  
90 is no surprise that oxidative stress has been recognized as an important etiopathogenetic factor  
91 and a promising pharmacological target in pathophysiological conditions of the skin [11,12].  
92 Tattoo inks have generally been associated with increased levels of oxidative stress (e.g.  
93 [5,6,13–15]); however, this has so far only been supported by indirect findings from *in vitro*  
94 experiments and there is currently no direct evidence for tattoo-induced oxidative stress in  
95 humans. In contrast, there is some evidence indicating that blue tattoo ink may be able to reduce  
96 oxidative stress. In an N-of-1 study, skin tattooed with blue tattoo ink demonstrated increased  
97 surface reductive capacity and the interstitial and intracellular fluid-enriched capillary blood  
98 from the tattoo had an increased content of protein sulfhydryls, reductive capacity, and catalase  
99 (CAT) activity, and reduced lipid peroxidation in comparison with the sample obtained from  
100 nontattooed skin [9]. Copper(II) phthalocyanine (CuPC), the main constituent of blue tattoo  
101 inks, can both reduce and prevent lipid peroxidation in homogenates of the mouse brain,  
102 kidney, and liver and exerts a substantial protective effect in the deoxyribose degradation assay  
103 [16]. Furthermore, it has been reported that CuPC can act as a dual functional mimetic of CAT  
104 and superoxide dismutase (SOD), two important antioxidant enzymes and that this property  
105 may be responsible for its lipid peroxidation-suppressing effects [17].

106 The present study aimed to explore whether: i) a blue CuPC-based tattoo ink can act as a CAT  
107 and SOD mimetic *in vitro*; ii) CAT and SOD mimetic properties of blue tattoo ink are primarily  
108 present in the CuPC-enriched ink fraction; iii) blue tattoo ink and its CuPC-enriched and  
109 residual fractions potentiate or inhibit the effects of CAT and SOD in the complex biochemical  
110 matrix of normal skin tissue (i.e. in the presence of endogenous CAT, SOD, and regulators of  
111 their activity); iv) components of the tattoo ink may directly interact with components of the  
112 skin.

113

## 114 **Materials and methods:**

### 115 **Sample preparation**

116 Intenze™ Persian blue tattoo ink (PB) (Intenze, USA) was used in the experiment. The  
117 ingredients declared on the official material safety data sheet included: H<sub>2</sub>O (The European  
118 Community number (EC): 231-791-2), BaSO<sub>4</sub> (EC: 231-784-4), TiO<sub>2</sub> (EC: 215-280-1), CuPC  
119 (EC: 205-685-1), glycerine (EC: 200-289-5), isopropyl alcohol (EC: 200-661-7), *Hamamelis*  
120 *Virginiana* L. extract (EC: 283-637-9). Diluted PB samples were obtained by v/v dilution in  
121 pre-defined ratios in double-distilled H<sub>2</sub>O (ddH<sub>2</sub>O; 0.055 μS/cm). Dye fractionation was done  
122 by differential centrifugation. PB was first spun down for 30 minutes at a relative centrifugal  
123 force (RCF) of 12879 x g, and then the same process was repeated twice with both the  
124 supernatant (blue fraction) and the pellet (white fraction). The supernatant of the blue pigment-  
125 enriched fraction and the pellet of the white pigment-enriched fraction were used for  
126 subsequent analyses.

## 127 UV-Vis spectrophotometry

128 UV-Vis spectra were obtained by scanning the absorbance in the wavelength range from 220  
129 nm to 750 nm using The NanoDrop® ND-1000 (Thermo Fisher Scientific, USA).

## 130 Catalase-like activity

131 CAT solution was prepared by dissolving 1 mg of lyophilized bovine liver CAT powder (Sigma  
132 Aldrich, USA) in 10 ml of phosphate-buffered saline (PBS) (pH 7.4). CAT activity was  
133 measured using the method first described by Hadwan [18] and adapted in [19]. Briefly, the  
134 samples were incubated with 50 µl of the substrate solution (2-10 mM H<sub>2</sub>O<sub>2</sub> in PBS) and the  
135 reaction was stopped by adding 150 µl of the Co(NO<sub>3</sub>)<sub>2</sub> stop solution (5 mL Co(NO<sub>3</sub>)<sub>2</sub> x 6 H<sub>2</sub>O  
136 (0.2 g in 10 mL ddH<sub>2</sub>O) + 5 mL (NaPO<sub>3</sub>)<sub>6</sub> (0.1 g in 10 mL ddH<sub>2</sub>O) added to 90 mL of NaHCO<sub>3</sub>  
137 (9 g in 100 mL ddH<sub>2</sub>O)). The concentration of H<sub>2</sub>O<sub>2</sub> was determined indirectly by measuring  
138 the absorbance of the carbonato-cobaltate (III) complex ([Co(CO<sub>3</sub>)<sub>3</sub>]Co) at 450 nm using the  
139 Infinite F200 PRO multimodal microplate reader (Tecan, Switzerland). Due to interference, a  
140 unique baseline model was established for each sample by simultaneous incubation with  
141 substrate solutions of graded nominal concentrations between 1 and 10 mM H<sub>2</sub>O<sub>2</sub> and the  
142 Co(NO<sub>3</sub>)<sub>2</sub> stop solution. The amount of residual H<sub>2</sub>O<sub>2</sub> was estimated from the model for each  
143 sample and each time-point. CAT activity was assessed indirectly based on permutation-  
144 derived estimates of the baseline values (t = 0 s) and final values (t<sub>1</sub> = 60 s or 300 s)[20].

## 145 Superoxide dismutase-like activity

146 The SOD-like activity was measured by assessing the inhibition of 1,2,3-trihydroxybenzene  
147 (THB) autoxidation rate [21,22]. Briefly, 5 µl of each sample was placed in a 96 well-plate and  
148 incubated with freshly pre-mixed THB working solution (64 µl of 60 mM THB dissolved in 1  
149 mM HCl mixed with 3400 µl of 0.05 M Tris-HCl and 1 mM Na<sub>2</sub>EDTA adjusted to pH 8.2).  
150 THB autoxidation was measured by assessing the absorbance increment at 450 nm with  
151 repeated measurements obtained by the Infinite F200 PRO multimodal microplate reader  
152 (Tecan, Switzerland).

## 153 Preparation of the skin tissue constituents as the reaction matrix

154 To test whether the effects observed *in vitro* would be affected by the presence of skin tissue  
155 constituents present *in vivo*, a rat skin homogenate was prepared. Briefly, a piece of skin from  
156 a single rat euthanized in deep anesthesia (70 mg/kg ketamine; 7 mg/kg xylazine) was dissected  
157 and stored at -80 °C. The animal was in the control (untreated) group of another experiment  
158 and the tissue was dissected after decapitation in concordance with the 3Rs concept [23] in  
159 order not to interfere with the experimental protocol. The animal study from which the tissue  
160 was obtained was approved by the Ethics Committee of The University of Zagreb School of  
161 Medicine (380-59-10106-18-111/173) and the Croatian Ministry of Agriculture (EP 186/2018).  
162 The skin was rapidly dissected from the surrounding adnexa and placed in 1000 µl of lysis  
163 buffer (150 mM NaCl, 50 mM Tris-HCl, 1 mM EDTA, 1% Triton X-100, 1% sodium  
164 deoxycholate, 0.1% SDS, 1 mM PMSF, protease inhibitor cocktail (Sigma-Aldrich, USA) and  
165 PhosSTOP phosphatase inhibitor (Roche, Switzerland) adjusted to pH 7.5) on ice. The tissue  
166 was homogenized using Microson Ultrasonic Cell Disruptor (Misonix, SAD), centrifuged for  
167 10 min at 4 °C, and RCF of 12 879 × g, and the supernatant was stored at -80 °C. For the acute  
168 experiments, 5 µl of the tissue homogenate was used per well, and for the pretreatment  
169 experiments, 45 µl of the skin homogenate was incubated with either 5 µl of dd H<sub>2</sub>O, or 5 µl of  
170 the sample (1:10 PB, 1:10 blue, and 1:10 white fraction) for 180 min at 37°C. Bradford's



171 analysis of the protein concentration (using the bovine serum albumin (BSA) standard)  
172 indicated the biochemical matrix of the skin contained 4.37 µg protein per µl.

#### 173 Lateral flow assay for the assessment of the interaction between the constituents of the tattoo 174 ink and components of the skin, albumin, and catalase

175 A lateral flow assay (LFA) was conducted to assess the interaction between chemical  
176 constituents of the blue tattoo ink and biochemical components of the skin. Additionally, the  
177 LFA was employed to test the interaction of tattoo ink with catalase (to address the possibility  
178 of direct interaction as a mediator of biological effects), and BSA as a standard protein with a  
179 large intrinsic binding potential for a large diversity of small molecules. All samples (skin  
180 homogenate, CAT, BSA) were spotted onto the nitrocellulose strips (0.45 µm pore size;  
181 Amersham Protran; GE Healthcare Life Sciences, USA) in a way that each strip contained the  
182 free route for the uninterrupted analyte flow (control lane) and the sample-capturing lane  
183 (experimental lane). The membranes were left to air-dry for 15 minutes. Once dry, the strips  
184 were fixed in the glass holder in a way that the proximal end was available for the  
185 administration of the analyte (tattoo ink) followed by administration of the same volume of  
186 vehicle (ddH<sub>2</sub>O) to remove excess PB. An additional LFA experiment was conducted using  
187 nitrocellulose spotted PB and its blue and white fractions as the stationary samples and ddH<sub>2</sub>O  
188 as the mobile phase. In both experiments, analyte mobility was recorded and the signal density  
189 line profiles of the control and experimental lane for each sample were subsequently extracted  
190 for 5 time-points using Fiji (NIH, USA).

#### 191 Tattoo ink interaction electrophoretic mobility shift assays

192 Electrophoretic mobility shift assays (EMSA) were conducted to complement the LFA and  
193 provide additional information on the nature of the interaction between skin components and  
194 the tattoo ink constituents. Sample pre-incubation EMSA (SP-EMSA) was done by analyzing  
195 the mobility interference using parallel electrophoretic separation of the tattoo ink-treated and  
196 “naïve” skin homogenates and CAT. Pre-treated samples were incubated with PB to achieve a  
197 1:100 dilution of the ink, while the control samples were incubated with an equal volume of  
198 vehicle (ddH<sub>2</sub>O). The samples were mixed with the modified bromophenol blue-free sample  
199 buffer 4x stock containing 40% glycerol, 8% SDS, 200 mM Tris HCl (so that bromophenol blue  
200 does not interfere with the CuPC color), incubated with the sample buffer for 10 minutes at  
201 95°C, and loaded onto the TGX Stain-Free FastCast 12% polyacrylamide gels (Bio-Rad, USA)  
202 for electrophoretic separation. Spectral analysis of gels was done by ChemiDoc MP Imaging  
203 System (Bio-Rad, USA). Transfer onto the nitrocellulose was done using the Trans-Blot Turbo  
204 semi-dry transfer system (Bio-Rad, USA). The elution of CAT from the nitrocellulose (for  
205 subsequent spectral analysis) was done by incubating cut-out proteins in the 50% pyridine in  
206 0.1 M ammonium acetate (v/v; pH 8.9) for 120 min at 37 °C [24]. In addition to SP-EMSA,  
207 the interaction of the electrophoretically immobile CuPC with skin constituents and CAT was  
208 studied using the CuPC-capturing gradient electrophoretic separation (CCG-EMSA). Briefly,  
209 a capturing gel containing gradient concentrations of 1:850 PB mixed with a standard stacking  
210 polyacrylamide matrix was placed on top of the separating gel, and the skin and CAT samples  
211 were subjected to the electrophoretic separation to analyze the interaction of increased  
212 electrophoretic CuPC exposure (increased CuPC matrix path) and sample mobility.

213

## 214 Data analysis

215 Data were analyzed in R (4.1.0). In the experiments where multiple substrate concentrations  
216 and multiple substrate exposure times were used, CAT-like activity was analyzed using linear  
217 regression with enzymatic activity (permutation-derived estimates) defined as the dependent  
218 variable and sample, substrate concentration, and time defined as independent variables. Model  
219 assumptions were checked by visual inspection of the residual and fitted value plots. Model  
220 outputs were reported as point estimates of least-square means with accompanying 95%  
221 confidence intervals. Comparisons of the samples from the model were reported as effect sizes  
222 (differences of estimated marginal means with accompanying 95% confidence intervals).  
223 Alpha was set at 5% and p-values were adjusted using the Tukey method.

## 224 Results:

### 225 Persian blue tattoo ink acts as a weak catalase and superoxide dismutase mimetic *in vitro*

226 PB demonstrated dilution-dependent CAT-like activity *in vitro*, with the 1:10 dilution showing  
227 the ability to dissociate ~0.9 mM of H<sub>2</sub>O<sub>2</sub> in 300 s on average, in substrate concentrations  
228 ranging from 6 to 10 mM (**Fig 1A**). PB (1:10) dissociated 0.6 mM of H<sub>2</sub>O<sub>2</sub> in the presence of  
229 10 mM H<sub>2</sub>O<sub>2</sub> and 1 mM when incubated with 8 and 6 mM, indicating lower efficacy at high  
230 substrate concentrations. The 1:100 dilution of PB demonstrated no CAT-like activity. The  
231 largest tested PB concentration (1:10) exerted SOD-like activity as well, by reducing the rate  
232 of THB autoxidation in the first 300 s of the assay. After 300 s, the maximum suppressive  
233 capacity of 1:10 PB was reached and PB potentiated autoxidation (**Fig 1B**). Lower PB  
234 concentrations (1:100; 1:1000; 1:10 000) showed no SOD-like activity.

235

### 236 Blue and white fractions of the Persian blue tattoo ink show no catalase mimetic properties, 237 but demonstrate divergent superoxide dismutase-like behavior

238 Centrifugation-based fractionation of PB yielded a blue CuPC-enriched fraction and a white  
239 fraction most likely enriched with TiO<sub>2</sub> and BaSO<sub>4</sub> (**Fig 2A**). UV-Vis spectra of fractionated  
240 samples suggested that CuPC was primarily present in the blue fraction, as evident by the  
241 presence of the Soret peak (B-band) and the Q-band with the Davydov splitting characteristic  
242 for the phthalocyanine derivatives [25,26] (**Fig 2B**). Neither the blue nor the white fraction  
243 demonstrated CAT-like activity *in vitro* (**Fig 2C-E**). Interestingly, „negative estimates of the  
244 activity“ were obtained for the 1:10 dilution of both fractions indicating possible photocatalytic  
245 generation of H<sub>2</sub>O<sub>2</sub> [27]. The observed effect was substrate concentration-dependent and more  
246 pronounced for the white fraction, which also demonstrated a pronounced time-dependence  
247 (**Fig 2C-E**). While the CuPC-enriched blue fraction showed no SOD-like activity at  $t < 300$  s,  
248 the white fraction (1:10) potentiated THB autoxidation. At  $t > 300$  s, the blue PB fraction (1:10)  
249 demonstrated SOD-like activity (**Fig 2F**).

### 250 Persian blue tattoo ink and its blue and white pigment-enriched fractions inhibit catalase *in* 251 *vitro* but potentiate its action in the presence of biochemical constituents of the skin

252 Apart from acting as CAT/SOD mimetics, PB constituents may modulate redox balance by  
253 affecting the activity of endogenous enzymes. In the presence of bovine liver CAT, the CuPC-  
254 enriched PB fraction acted as a weak CAT inhibitor with no evident dose-response, while PB  
255 and the white fraction exhibited a pronounced dose-dependent inhibition of the enzyme (**Fig**  
256 **3A, B**). A different pattern was observed in the presence of biochemical constituents of the  
257 skin, where PB and its blue and white pigment-enriched fractions acted as potentiators of



258 endogenous CAT, with the largest effect observed in the presence of the white fraction (**Fig**  
259 **3C, D**). As the acute effects may not faithfully represent biochemical effects that may take  
260 place *in vivo*, an additional experiment was conducted in which the tested samples were first  
261 incubated with the biochemical constituents of the skin. Interestingly, following prolonged  
262 incubation (180 min at 37 °C), the pronounced effect of the white fraction was substantially  
263 attenuated, and the CuPC-enriched fraction induced the most pronounced effect on the activity  
264 of endogenous CAT (**Fig 3E, F**). In the presence of tissue constituents, both the blue and white  
265 fractions acted as SOD mimetics at  $t < 300$  s, while there was no difference between the effect  
266 of PB and the control condition (**Fig 3G**). After the 300 s time-point, the CuPC-enriched  
267 fraction demonstrated stable SOD mimetic activity, while the white fraction potentiated THB  
268 autoxidation (**Fig 3G**). Following the prolonged incubation at 37 °C, SOD potentiating effects  
269 of PB and its blue and white fractions were completely lost (**Fig 3H**).

### 270 Constituents of the blue tattoo ink interact with components of the biochemical matrix of the 271 skin

272 To better understand the nature of the observed effects chemical interaction between  
273 constituents of the tattoo ink and the components of the biochemical matrix of the skin was  
274 evaluated using the LFA, SP-EMSA, and CCG-EMSA. LFA indicated that skin homogenate,  
275 CAT, and BSA can all interact with constituents of PB that exhibit nitrocellulose lateral flow  
276 (Fig 4A). BSA demonstrated the largest PB flow-disrupting capacity both in terms of binding  
277 the flow front and resistance to subsequent elution by vehicle. Both CAT and the biochemical  
278 matrix of the skin were also able to bind the PB front and resist ddH<sub>2</sub>O elution (Fig 4A).  
279 Interestingly, upon elution, the skin homogenate demonstrated a wave pattern suggesting the  
280 presence of interaction with several separate components (Fig 4B). The CCG-EMSA and SP-  
281 EMSA were used as complementary methods to better understand the nature of the observed  
282 interaction. The CCG-EMSA revealed that the observed CAT-binding properties of PB were  
283 not able to resist the electrophoretic mobility of the enzyme indicating that the nature of the  
284 interaction was i) too weak to affect the electrophoretic flow, or ii) incompatible with the  
285 unfolded linear structure and/or negative charge introduced by the reductive environment and  
286 SDS (Fig 4C). Interestingly, although there was no evident electrophoretic mobility shift  
287 introduced by increasing path length through the PB-enriched stacking polyacrylamide for  
288 CAT this was not the case with skin homogenate where CCG-EMSA revealed a pronounced  
289 dose-response electrophoretic mobility shift regardless of the reducing environment and high  
290 SDS concentration (Fig 4C). The SP-EMSA confirmed the aforementioned findings as CAT  
291 electrophoretic mobility was relatively resistant to the effects of PB, while tattoo ink  
292 decelerated mobility of some biochemical constituents of the skin – speaking in favor of  
293 binding even in the reductive environment and in the presence of high SDS (Fig 4D). The exact  
294 chemical component (or components) of the ink responsible for the electrophoretic mobility  
295 shift, as well as primary components of the skin responsible for the observed interaction,  
296 remain to be further explored. Nevertheless, spectral analysis of the electrophoretic and lateral  
297 flow mobility membranes/gels provided additional information that may lay the groundwork  
298 for a better understanding of the observed interaction in the future. The SP-EMSA experiments  
299 suggest that the blue pigment (CuPC) demonstrates electrophoretic mobility only in the  
300 stacking polyacrylamide matrix (Fig 5A). Such a pattern indicates that CuPC either i) moves  
301 on its own in the electrical field achieved in the polyacrylamide gel electrophoresis (PAGE)  
302 setup (i.e. exerts electrophoretic mobility), or ii) moves together with CAT and some  
303 components of the skin as a result of molecular interactions that cannot withstand the resistance

304 of mobility through the dense portion of the resolving polyacrylamide. Electrophoretic mobility  
305 experiments with PB gradient stacking gel support latter as penetrance of the blue pigment  
306 didn't increase (or possibly even decreased) as a result of increased vertical exposure (Fig 5B)  
307 suggesting that the mobility shift of the skin homogenates may have been the result of the  
308 interactions at the level of capturing-adapted stacking polyacrylamide. Nevertheless, it is  
309 possible that i) some CuPC remained bound to proteins and caused electrophoretic deceleration  
310 in quantities that are too small to be detected by simple visual inspection, and/or ii) some other  
311 constituents of the tattoo ink demonstrated protein binding and caused deceleration in the  
312 resolving fraction of the gel. To test this, spectral analysis of LFA membranes and  
313 electrophoretic mobility gels was conducted. Spectral analysis of the LFA membranes revealed  
314 that the LFA mobility pattern of PB and both its blue and white fractions demonstrate at least  
315 3 general patterns: the sample pool (the area where the sample was deposited); the middle  
316 mobile phase (largely absent in the white fraction); and the mobile front (present in all  
317 samples)(Fig 5C). The sample pool and the middle mobile phase demonstrated a satisfactory  
318 quantum yield upon excitation (EX) at 302 nm combined with the wide 535-645 nm emission  
319 (EM) filter. All 3 LFA patterns (the sample pool and both mobile phases) for PB, blue, and  
320 white fractions were successfully visualized under 755-777 nm EX with the 810-860 nm EM  
321 filter, and a variety of conditions (e.g. EX/EM(nm): 460-490/518-546; 520-545/577-613; 625-  
322 650/675-725; 650-675/700-730) were found to enable a good representation of the mobile front  
323 (Fig 5C). Spectral analysis of the LFA membranes from the experiment with spotted CAT and  
324 biochemical matrix of the skin revealed that, in addition to the interaction with the blue fraction  
325 of the ink, both samples also captured components of the ink most likely representing the  
326 mobile front from the LFA experiment in which PB was used as the mobile phase (with CAT  
327 sample demonstrating greater mobile front binding capacity than the skin sample)(Fig 5D).  
328 Although treatment-naïve CAT has been shown to emit in the close spectral range (control  
329 CAT; Fig 5D), the comet pattern indicates the observed signal was most likely from the  
330 component of the mobile phase and not an endogenous signal from the spotted sample. Spectral  
331 analysis of the SP-EMSA polyacrylamide gels provides further evidence supporting the  
332 hypothesis that, in addition to CuPC, other components of the tattoo ink (primarily present in  
333 the white fraction) may interact with CAT and constituents of the skin (and affect their  
334 electrophoretic mobility)(Fig 5E). Spectral analysis of the SP-EMSA polyacrylamide gels  
335 confirms the observations from the LFA and indicates that another PB component (most likely  
336 originating from the white fraction) enters the resolving polyacrylamide (alone or bound to  
337 sample constituents) and possibly affects the sample electrophoretic mobility (even after  
338 accounting for the baseline spectral properties of PB and its blue and white fractions and the  
339 effects of the tattoo ink concentration)(Fig 5E, F). Interestingly, the presence of the component  
340 of the white fraction seems to have functional consequences as the ink-exposed sample shows  
341 the ability to potentiate the chemiluminescent reaction of luminol and H<sub>2</sub>O<sub>2</sub> (Fig 5G). To ensure  
342 that the observed effect was not due to the presence of CuPC present in quantities that are too  
343 small to be detected by visual inspection, both CAT samples were eluted from the membrane  
344 and subjected to spectral analysis (Fig 5H). To further ensure no CuPC was present, UV-Vis  
345 spectra of the eluates were measured and compared to the spectra of the same samples before  
346 PAGE showing a clear disappearance of the Q-band with the Davydov splitting characteristic  
347 for the phthalocyanine derivatives (Fig 5I).

348

349 **Discussion:**

350 The presented results support the hypothesis that PB, a blue CuPC-based tattoo ink, can act as  
351 a mimetic of CAT and SOD and provide a possible mechanistic explanation for the reduced  
352 levels of oxidative stress in the skin with a blue tattoo [9]. Although CuPC can act as a dual  
353 functional mimetic of CAT and SOD and suppress lipid peroxidation *in vitro* [17], it was  
354 hypothesized that the *a priori* assumption that PB would necessarily reflect the properties of  
355 its main component (CuPC) would be unjustified considering the unspecified concentration of  
356 CuPC and the presence of other chemicals that may theoretically annihilate or even reverse its  
357 potential antioxidant effects. The results indicate the caution was reasonable. Although PB  
358 demonstrated CAT and SOD-like activity, the observed H<sub>2</sub>O<sub>2</sub> dissociation capacity was  
359 relatively modest, and SOD-like activity was present only in the first part of the assay and  
360 demonstrated high variability across trials (**Fig 1**). Furthermore, the CAT-mimetic action was  
361 not persuasive once PB was fractionated (**Fig 2C-E**), while the SOD-like activity of the  
362 fractions (**Fig 2F**) suggested that the large variability and time-dependence observed in the first  
363 experiment (**Fig 1B**) may have reflected the opposing effects of chemical constituents on THB  
364 autoxidation. Despite the initial hypothesis that CuPC may be the main chemical constituent  
365 of tattoo ink responsible for the effects of a blue tattoo on skin redox homeostasis [9],  
366 potentiation of THB autoxidation by the white PB fraction (**Fig 2F**) indicated that there are  
367 likely at least two chemical mediators with possibly opposing actions. Although it was not  
368 possible to confirm the presence of individual chemical constituents in PB fractions, it is highly  
369 likely that BaSO<sub>4</sub> and TiO<sub>2</sub> were the main constituents of the white fraction, and that they may  
370 be responsible for the observed potentiation of THB autoxidation. Although both BaSO<sub>4</sub> and  
371 TiO<sub>2</sub> can induce oxidative stress in different models [28,29], TiO<sub>2</sub> may be a more likely  
372 mediator of the observed effect, as it stimulates the expression of antioxidant defense systems  
373 to a greater extent *in vitro* [30]. In addition, TiO<sub>2</sub> can generate superoxide radicals and other  
374 ROS by reducing oxygen, due to an increased number of conduction band electrons following  
375 light exposure [27,31]. In the context of the effects of blue and white PB fractions on SOD  
376 activity, the reported time-dependence of SOD-mimetic properties of PB (**Fig 1B**) may be  
377 related to the limited ability of blue fraction constituents to suppress THB autoxidation,  
378 potentiated by the chemicals present in the white fraction of the ink.

379 In addition to the observed CAT/SOD-mimetic activity *in vitro*, in order to affect redox balance  
380 *in vivo*, tattoo ink should be able to exert the effect in the presence of the complex biochemical  
381 matrix of normal skin tissue (i.e in the presence of endogenous CAT, SOD, and regulators of  
382 their activity). In the presence of CAT, PB inhibited the H<sub>2</sub>O<sub>2</sub> dissociation rate with the most  
383 pronounced inhibition observed with the white ink fraction (**Fig 3A, B**). Although little is  
384 known about the effects of BaSO<sub>4</sub> on CAT activity, it has been shown that TiO<sub>2</sub> can bind to  
385 CAT via electrostatic and hydrogen bonding forces, destabilize its structure and affect its  
386 activity in a dose-dependent manner [32]. Interestingly, the effects of tattoo ink on CAT were  
387 drastically altered in the presence of the biochemical constituents of normal skin, as all tested  
388 samples potentiated the relatively low endogenous H<sub>2</sub>O<sub>2</sub> dissociation potential (**Fig 3C, D**).  
389 The white fraction of the ink induced the most pronounced effect, increasing the activity 78-  
390 fold, while the blue fraction induced only „a modest” ~5-fold increment. A substantial  
391 increment in the dissociation potential observed with the white fraction is in line with the SP-  
392 EMSA results indicating that a constituent of the ink that does not contain CuPC (most likely  
393 originating from the white fraction) has a pronounced ability to degrade H<sub>2</sub>O<sub>2</sub> (Fig 5G-I).  
394 Interestingly, the potentiation of CAT observed with the unfractionated ink was somewhere in

395 between (~17-fold), indicating that chemical constituents of tattoo ink might either act as  
396 competitive activators or engage in some other form of interaction that is reflected in CAT  
397 activity. A similar pattern was observed regarding the SOD-mimetic action, where the  
398 constituents from the blue and white fractions exhibited SOD-like properties on their own but  
399 canceled each other out when added to the tissue homogenate together (PB) (**Fig 3G**). Why  
400 were both ink fractions able to potentiate SOD activity, and whether the observed effect was  
401 mediated by the intrinsic SOD-mimetic properties of the chemical constituents or their action  
402 on the endogenous enzyme, defies a simple explanation and remains to be further explored.  
403 Nevertheless, considering that TiO<sub>2</sub> can potentiate the activity of SOD [33], one possibility is  
404 that TiO<sub>2</sub> may exert a dose-dependent modulatory effect on SOD similarly as has been shown  
405 for CAT [32].

406 Finally, the effects of PB and its fractions have been tested upon prolonged (180 min)  
407 incubation with skin homogenates at homeothermic temperature (37 °C), to assess whether  
408 some of the effects may be transient (e.g. due to dependence on an endogenous substrate) and  
409 affected by physiological temperature. Interestingly, both CAT and SOD-mimetic properties  
410 were dramatically altered by pre-incubation and the most pronounced H<sub>2</sub>O<sub>2</sub> dissociation rate  
411 was observed for the blue ink fraction followed by PB (**Fig 3E, F**). The SOD-mimicking effect  
412 was annihilated by the pre-incubation procedure (**Fig 3H**). The exact nature of the observed  
413 phenomenon and whether the homeothermic pre-incubation more faithfully reflects the fate of  
414 the tattoo ink constituents in the human skin remains to be elucidated. On one hand, prolonged  
415 incubation at physiological temperature may provide more accurate environmental conditions  
416 for the biochemical reactions that may take place in the human body. On the other hand, the  
417 observed potentiation of the enzymatic activity may be dependent on a particular substrate  
418 present in the biochemical matrix of the tissue homogenate in limited quantities (in contrast to  
419 its continuous influx *in vivo*). Another possible explanation for the observed discrepancy might  
420 be a temperature-induced change in physicochemical properties of the tattoo ink constituents.  
421 Tattoo inks contain nanoparticles and both CuPC and TiO<sub>2</sub> can be found in the nanoparticle  
422 form in the blue tattoo ink (with the mean diameter of the CuPC/TiO<sub>2</sub> being 167 nm for the  
423 Intenze™ blue tattoo ink)[34,35]. Nanoparticles have an intrinsic potential to generate ROS,  
424 which has been recognized as a key mediator of nanotoxicity [36]. Considering that toxicity,  
425 photoreactivity, and ROS-generating potential depend on the particle size, shape, surface  
426 characteristics, and the crystal structure [31], a hypothetical reaction between the tattoo ink and  
427 either the tissue homogenate or the microtiter plate that may alter the structure of its  
428 nanoparticle components may provide an explanation for the observed alteration of the  
429 modulatory activity on CAT and SOD (**Fig 3**).

430 To further elucidate the nature of the CAT and SOD-mimetic actions of the blue tattoo ink a  
431 series of experiments was done to explore whether the observed functional alterations are  
432 accompanied by the ability of ink constituents to bind to CAT and the components of the skin  
433 matrix (**Fig 4,5**). Specific studies focused on the interaction of individual components are yet  
434 to be done. Nevertheless, preliminary experiments assessing a more general overview of the  
435 possibility that two complex and heterogeneous samples (tattoo ink and skin) contain  
436 molecules that show the ability to interact directly presented here (**Fig 4,5**) support the notion  
437 that the observed changes in the enzymatic activity may be a consequence of the interaction of  
438 at least several separate molecular entities from the skin, and definitely more than one chemical  
439 constituent of the tattoo ink.

440 In the context of previously reported redox-related changes in the skin with a blue tattoo, the  
441 results presented here support the hypothesis that the suppression of oxidative stress in the N-  
442 of-1 study may be related to the antioxidant properties of some constituents present in blue  
443 tattoo ink [9]. In the N-of-1 study, a 15% reduction in lipid peroxidation in the blue tattoo was  
444 associated with 11.8% greater CAT activity [9]. In concordance with this, in this study, the  
445 constituents of blue tattoo ink were able to potentiate CAT activity in the presence of the  
446 biochemical components of the skin (**Fig 3C-F**). Interestingly, in the same study, SOD activity  
447 was slightly higher in the tattoo sample; however, this result was taken as highly uncertain  
448 considering the difference was in the range of the coefficient of variation of the method [9]. In  
449 the context of the *in vitro* results presented here, it can be assumed that apart from the limited  
450 precision of the utilized method, SOD activity in the blue tattoo may have been unchanged due  
451 to the opposing action of different constituents of the tattoo ink (**Fig 3G**) or due to the same  
452 phenomenon responsible for the loss of SOD-mimetic activity following prolonged incubation  
453 at 37°C (**Fig 3H**).

#### 454 **Conclusion:**

455 The presented results confirm the hypothesis that blue, CuPC-based tattoo ink can act as a CAT  
456 and SOD mimetic *in vitro* and provide evidence that the antioxidant effects of a blue tattoo *in*  
457 *vivo* [9] may be mediated by the ability of CuPC and other chemical constituents of the blue  
458 tattoo ink to mimic the activity of endogenous antioxidant enzymes. In contrast to the  
459 assumption that the CAT and SOD-mimetic properties of the tattoo ink would be primarily  
460 explained by the presence of CuPC, the results suggest that both the CuPC-enriched blue and  
461 the residual white fraction may exert CAT and SOD-mimetic properties and affect redox  
462 balance, indicating that other chemical constituents (e.g. TiO<sub>2</sub>) may also be involved in  
463 modulation of redox homeostasis. Finally, it has been demonstrated that the ability of different  
464 constituents of the tattoo ink to potentiate and/or inhibit the activity of CAT and SOD depends  
465 on numerous factors (e.g. the presence of other constituents that exert synergistic, additive, or  
466 antagonistic effects; the concentration of the constituents and/or the substrate; the presence of  
467 compounds from the biochemical matrix of the skin; the incubation time and temperature) that  
468 should be taken in account.

#### 469 **Limitations:**

470 Several important limitations should be emphasized. First, it was not possible to analyze the  
471 presence, or the quantity of individual chemical constituents of the tattoo ink used in the  
472 experiment, and the presence of different chemicals was assumed based on the official material  
473 safety data sheet of the product. Apart from the CuPC that was most likely present based on  
474 the UV-Vis spectrum characterized by the Soret peak (B-band) and the Q-band with the  
475 Davydov splitting characteristic for the phthalocyanine derivatives, the existence of other  
476 chemicals (and possibly also impurities) could not have been confirmed experimentally.  
477 Furthermore, the presence of CuPC and TiO<sub>2</sub> nanoparticles was assumed based on the  
478 experimental data for the Intenze™ blue tattoo ink reported by Høgsberg et al. [35], however,  
479 the existence or the size of nanoparticles was not confirmed experimentally and the potential  
480 influence of the experimental conditions on the particle aggregation, size, shape, surface  
481 characteristics, or the crystal structure (important for the redox-related effects) was not  
482 assessed. Finally, the possibility that the chemical reaction with some of the reagents may have  
483 introduced bias in some measurements can never be completely ruled out. For example, it has  
484 been observed that 450 nm absorbance of some of the dilutions of some fractions was affected

485 by spectrophotometric measurements (possibly due to light exposure as some chemical  
486 constituents such as TiO<sub>2</sub> act as well-known photocatalysts [27])(**Supplement**). Nevertheless,  
487 precautionary steps were taken to prevent the chemical bias that may have been introduced due  
488 to unforeseen chemical reactions of samples and reagents (e.g. baseline validation model was  
489 established and analyzed for each sample individually to ensure that the expected changes such  
490 as the dissociation of H<sub>2</sub>O<sub>2</sub> can be assumed and quantified without the risk of chemical  
491 interaction) (**Supplement**).

492 **Funding source:**

493 None.

494 **Conflict of interest statement:**

495 No conflict of interest to disclose.

496 **Data availability statement:**

497 Data can be obtained from the author's GitHub repository (<https://github.com/janhomolak>).

498 **Author's contributions:**

499 **JH** conceived the study, conducted the experiments, analyzed data, and wrote the manuscript.

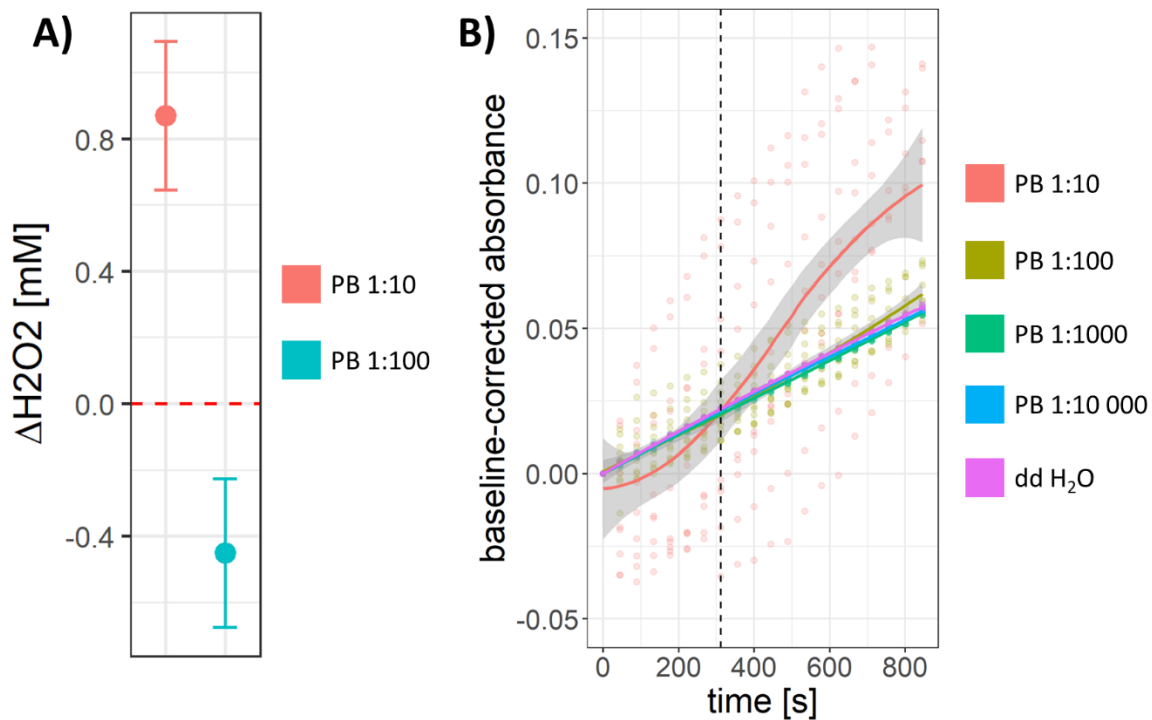
500 **References:**

- 501 [1] Pesapane F, Nazzaro G, Gianotti R, et al. A short history of tattoo. *JAMA Dermatol*  
502 2014;150:145.
- 503 [2] Giulbudagian M, Schreiber I, Singh AV, et al. Safety of tattoos and permanent make-up:  
504 a regulatory view. *Arch Toxicol* 2020;94:357–369.
- 505 [3] Schreiber I, Hesse B, Seim C, et al. Distribution of nickel and chromium containing  
506 particles from tattoo needle wear in humans and its possible impact on allergic  
507 reactions. *Particle and Fibre Toxicology* 2019;16:33.
- 508 [4] Falconi M, Teti G, Zago M, et al. Influence of a commercial tattoo ink on protein  
509 production in human fibroblasts. *Arch Dermatol Res* 2009;301:539–547.
- 510 [5] Regensburger J, Lehner K, Maisch T, et al. Tattoo inks contain polycyclic aromatic  
511 hydrocarbons that additionally generate deleterious singlet oxygen. *Exp Dermatol*  
512 2010;19:e275-281.
- 513 [6] Arl M, Nogueira DJ, Schweitzer Köerich J, et al. Tattoo inks: Characterization and in  
514 vivo and in vitro toxicological evaluation. *J Hazard Mater* 2019;364:548–561.
- 515 [7] Lerche CM, Heerfordt IM, Serup J, et al. Red tattoos, ultraviolet radiation and skin  
516 cancer in mice. *Experimental Dermatology* 2017;26:1091–1096.
- 517 [8] Lerche CM, Sepehri M, Serup J, et al. Black tattoos protect against UVR-induced skin  
518 cancer in mice. *Photodermatol Photoimmunol Photomed* 2015;31:261–268.
- 519 [9] Homolak J. The effect of a color tattoo on the local skin redox regulatory network: an  
520 N-of-1 study. *Free Radic Res* 2021;1–9.
- 521 [10] Homolak J. Redox Homeostasis in Alzheimer's Disease. *Redox Signaling and*  
522 *Biomarkers in Ageing* 2021;



- 523 [11] Rinnerthaler M, Bischof J, Streubel MK, et al. Oxidative Stress in Aging Human Skin.  
524 *Biomolecules* 2015;5:545–589.
- 525 [12] Wagener FADTG, Carels CE, Lundvig DMS. Targeting the Redox Balance in  
526 Inflammatory Skin Conditions. *Int J Mol Sci* 2013;14:9126–9167.
- 527 [13] Carotenuto R, Fogliano C, Rienzi M, et al. Comparative Toxicological Evaluation of  
528 Tattoo Inks on Two Model Organisms. *Biology (Basel)* 2021;10:1308.
- 529 [14] Høgsberg T, Jacobsen NR, Clausen PA, et al. Black tattoo inks induce reactive oxygen  
530 species production correlating with aggregation of pigment nanoparticles and product  
531 brand but not with the polycyclic aromatic hydrocarbon content. *Exp Dermatol*  
532 2013;22:464–469.
- 533 [15] Neale PA, Stalter D, Tang JYM, et al. Bioanalytical evidence that chemicals in tattoo  
534 ink can induce adaptive stress responses. *J Hazard Mater* 2015;296:192–200.
- 535 [16] Amaral GP, Puntel GO, Dalla Corte CL, et al. The antioxidant properties of different  
536 phthalocyanines. *Toxicol In Vitro* 2012;26:125–132.
- 537 [17] Qing F, Li L, Yongyan H, et al. Studies on metal phthalocyanine as a dual functional  
538 mimic enzyme. *Journal of Tongji Medical University* 2001;21:13–16.
- 539 [18] Hadwan MH. Simple spectrophotometric assay for measuring catalase activity in  
540 biological tissues. *BMC Biochemistry* 2018;19:7.
- 541 [19] Homolak J, Babic Perhoc A, Knezovic A, et al. The Effect of Acute Oral Galactose  
542 Administration on the Redox System of the Rat Small Intestine. *Antioxidants*  
543 2022;11:37.
- 544 [20] Homolak J, Perhoc AB, Joja M, et al. Non-alcoholic components of Pelinkovac, a  
545 Croatian wormwood-based strong liquor, counteract the inhibitory effect of high ethanol  
546 concentration on catalase in vitro. *BioRxiv* 2022;2022.01.07.475357.
- 547 [21] Li X. Improved Pyrogallol Autoxidation Method: A Reliable and Cheap Superoxide-  
548 Scavenging Assay Suitable for All Antioxidants. *J Agric Food Chem* 2012;60:6418–  
549 6424.
- 550 [22] Marklund S, Marklund G. Involvement of the superoxide anion radical in the  
551 autoxidation of pyrogallol and a convenient assay for superoxide dismutase. *Eur J*  
552 *Biochem* 1974;47:469–474.
- 553 [23] Graham ML, Prescott MJ. The multifactorial role of the 3Rs in shifting the harm-benefit  
554 analysis in animal models of disease. *Eur J Pharmacol* 2015;759:19–29.
- 555 [24] Parekh BS, Mehta HB, West MD, et al. Preparative elution of proteins from  
556 nitrocellulose membranes after separation by sodium dodecyl sulfate-polyacrylamide  
557 gel electrophoresis. *Anal Biochem* 1985;148:87–92.
- 558 [25] Caplins BW, Mullenbach TK, Holmes RJ, et al. Femtosecond to nanosecond excited  
559 state dynamics of vapor deposited copper phthalocyanine thin films. *Phys Chem Chem*  
560 *Phys* 2016;18:11454–11459.

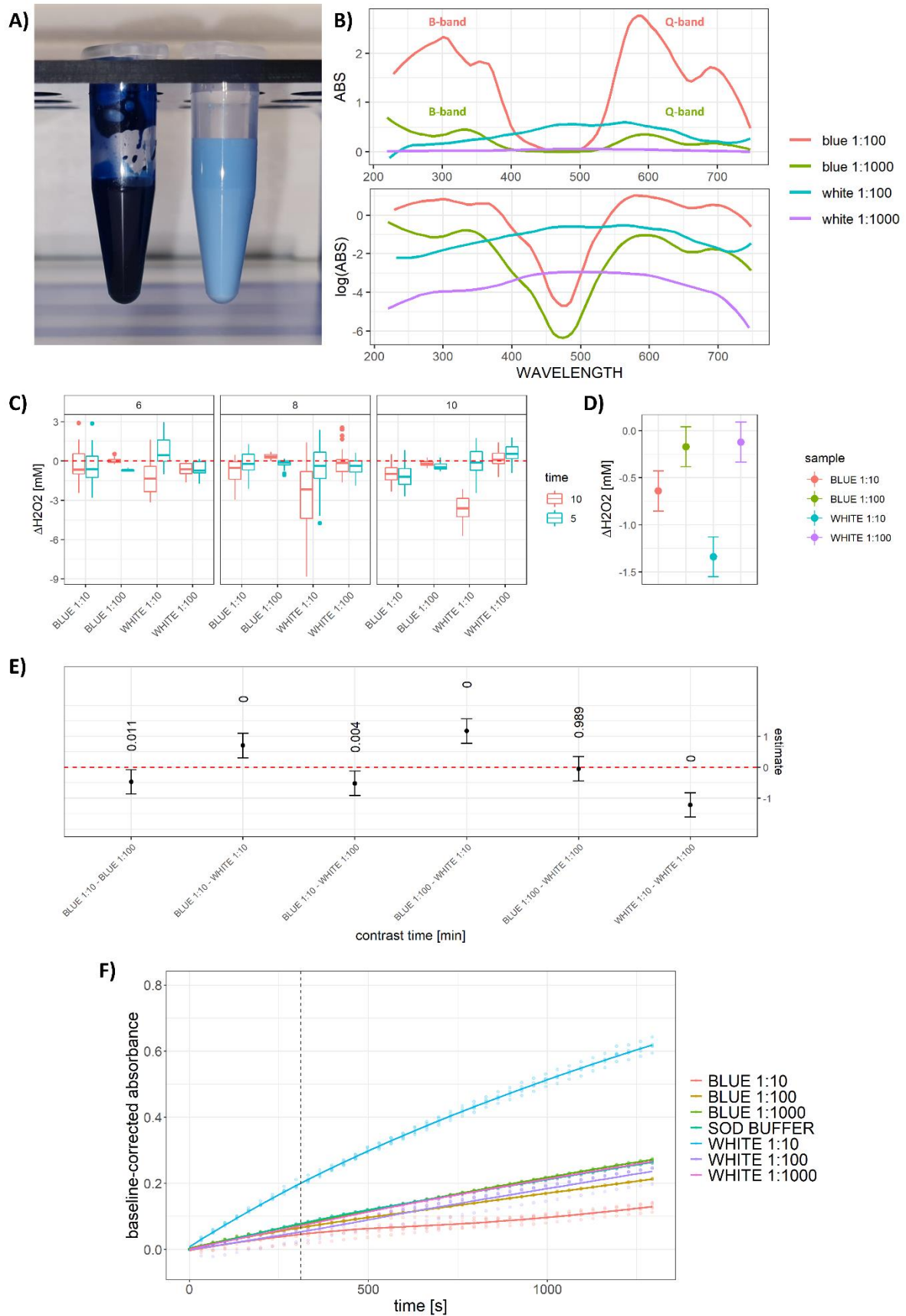
- 561 [26] Farag AAM. Optical absorption studies of copper phthalocyanine thin films. *Optics &*  
562 *Laser Technology* 2007;39:728–732.
- 563 [27] Hirakawa K. *Fundamentals of Medicinal Application of Titanium Dioxide*  
564 *Nanoparticles*. IntechOpen; 2015.
- 565 [28] Monteiller C, Tran L, MacNee W, et al. The pro-inflammatory effects of low-toxicity  
566 low-solubility particles, nanoparticles and fine particles, on epithelial cells in vitro: the  
567 role of surface area. *Occup Environ Med* 2007;64:609–615.
- 568 [29] Schwotzer D, Niehof M, Schaudien D, et al. Cerium oxide and barium sulfate  
569 nanoparticle inhalation affects gene expression in alveolar epithelial cells type II. *J*  
570 *Nanobiotechnology* 2018;16:16.
- 571 [30] Delaval M, Wohlleben W, Landsiedel R, et al. Assessment of the oxidative potential of  
572 nanoparticles by the cytochrome c assay: assay improvement and development of a  
573 high-throughput method to predict the toxicity of nanoparticles. *Arch Toxicol*  
574 2017;91:163–177.
- 575 [31] Li M, Yin J-J, Wamer WG, et al. Mechanistic characterization of titanium dioxide  
576 nanoparticle-induced toxicity using electron spin resonance. *Journal of Food and Drug*  
577 *Analysis* 2014;22:76–85.
- 578 [32] Zhang H-M, Cao J, Tang B-P, et al. Effect of TiO<sub>2</sub> nanoparticles on the structure and  
579 activity of catalase. *Chemico-Biological Interactions* 2014;219:168–174.
- 580 [33] Song U, Jun H, Waldman B, et al. Functional analyses of nanoparticle toxicity: a  
581 comparative study of the effects of TiO<sub>2</sub> and Ag on tomatoes (*Lycopersicon*  
582 *esculentum*). *Ecotoxicol Environ Saf* 2013;93:60–67.
- 583 [34] Bocca B, Sabbioni E, Mičetić I, et al. Size and metal composition characterization of  
584 nano- and microparticles in tattoo inks by a combination of analytical techniques. *J Anal*  
585 *At Spectrom* 2017;32:616–628.
- 586 [35] Høgsberg T, Loeschner K, Löf D, et al. Tattoo inks in general usage contain  
587 nanoparticles. *Br J Dermatol* 2011;165:1210–1218.
- 588 [36] Manke A, Wang L, Rojanasakul Y. Mechanisms of nanoparticle-induced oxidative  
589 stress and toxicity. *Biomed Res Int* 2013;2013:942916.
- 590



591

592 **Fig 1.** Catalase (CAT) and superoxide dismutase (SOD)-like activity of Persian Blue tattoo ink  
 593 (PB) *in vitro*. A) Output of the model including the tested dilutions and substrate concentrations  
 594 demonstrating dilution-dependent CAT-like activity of PB, with the 1:10 PB dilution acting as  
 595 CAT mimetic (substrate concentrations: 6, 8, and 10 mM H<sub>2</sub>O<sub>2</sub>; t = 300 s). B) Dilution-  
 596 dependent SOD-like activity of PB, with 1:10 PB demonstrating SOD-like properties at t < 300  
 597 s, and potentiation of 1,2,3-trihydroxybenzene autooxidation at t > 300 s. 1:100, 1:1000 and  
 598 1:10 000 dilutions show no SOD-mimetic activity.

599

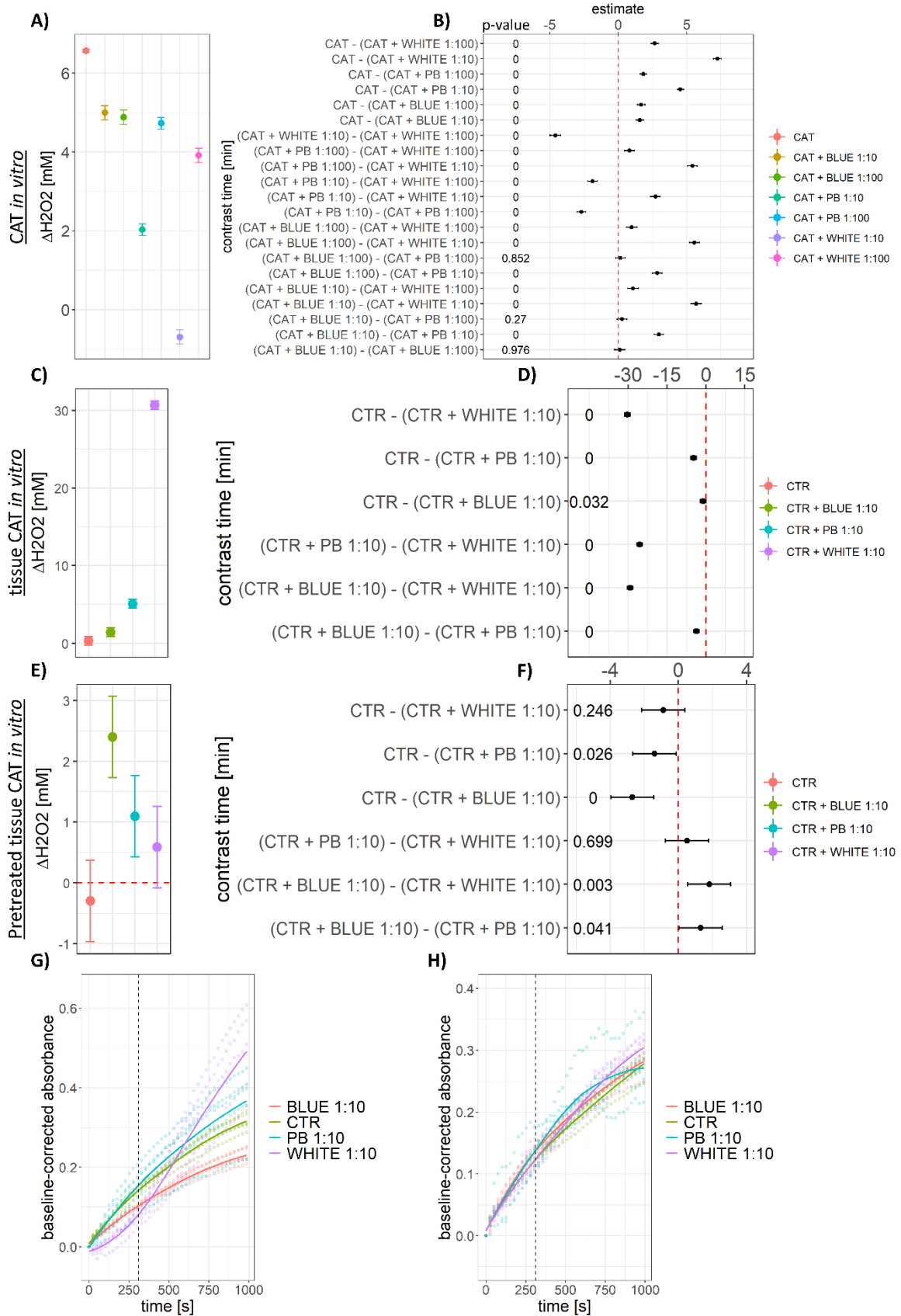


600

601 **Fig 2.** Catalase (CAT) and superoxide dismutase (SOD)-like activity of blue and white  
 602 fractions of the Persian Blue tattoo ink (PB) *in vitro*. A) A representative image of the blue

603 (left) and white (right) fractions of PB. B) Absorption spectra of the 1:100 (red) and 1:1000  
604 (green) dilution of the blue fraction, and the 1:100 (turquoise) and 1:1000 (purple) dilution of  
605 the white fraction of PB. The absorption spectrum of the blue fractions demonstrates the Soret  
606 peak (B-band) and Q-band, strongly indicating that copper phthalocyanine was only present in  
607 the blue fraction of PB. C) Results demonstrating no CAT-like activity of different dilutions of  
608 either fraction *in vitro* (substrate concentrations: 6, 8, 10 mM H<sub>2</sub>O<sub>2</sub>; t<sub>1</sub>= 300 s; t<sub>2</sub>= 600 s). D)  
609 Output of the model including tested dilutions of the blue and white fraction, time, and substrate  
610 concentration, demonstrating no observed CAT-like activity. E) Comparison of the observed  
611 CAT-like activities of two dilutions of the blue and white fraction at different substrate  
612 concentrations. P-values are reported above estimates of differences of estimated marginal  
613 means accompanied by 95% confidence intervals. F) Dilution-dependent SOD-like activity of  
614 PB fractions. The 1:10 dilution of the white fraction potentiates autooxidation of 1,2,3-  
615 trihydroxybenzene at t < 300 s, while all other dilutions of both fractions show no pronounced  
616 effects. At t > 300 s, the 1:10 dilution of the blue fraction demonstrates pronounced, while the  
617 1:100 dilution shows slightly less pronounced SOD-like activity. The 1:10 dilution of the white  
618 fraction shows a strong 1,2,3-trihydroxybenzene autooxidation potentiating effect.

619

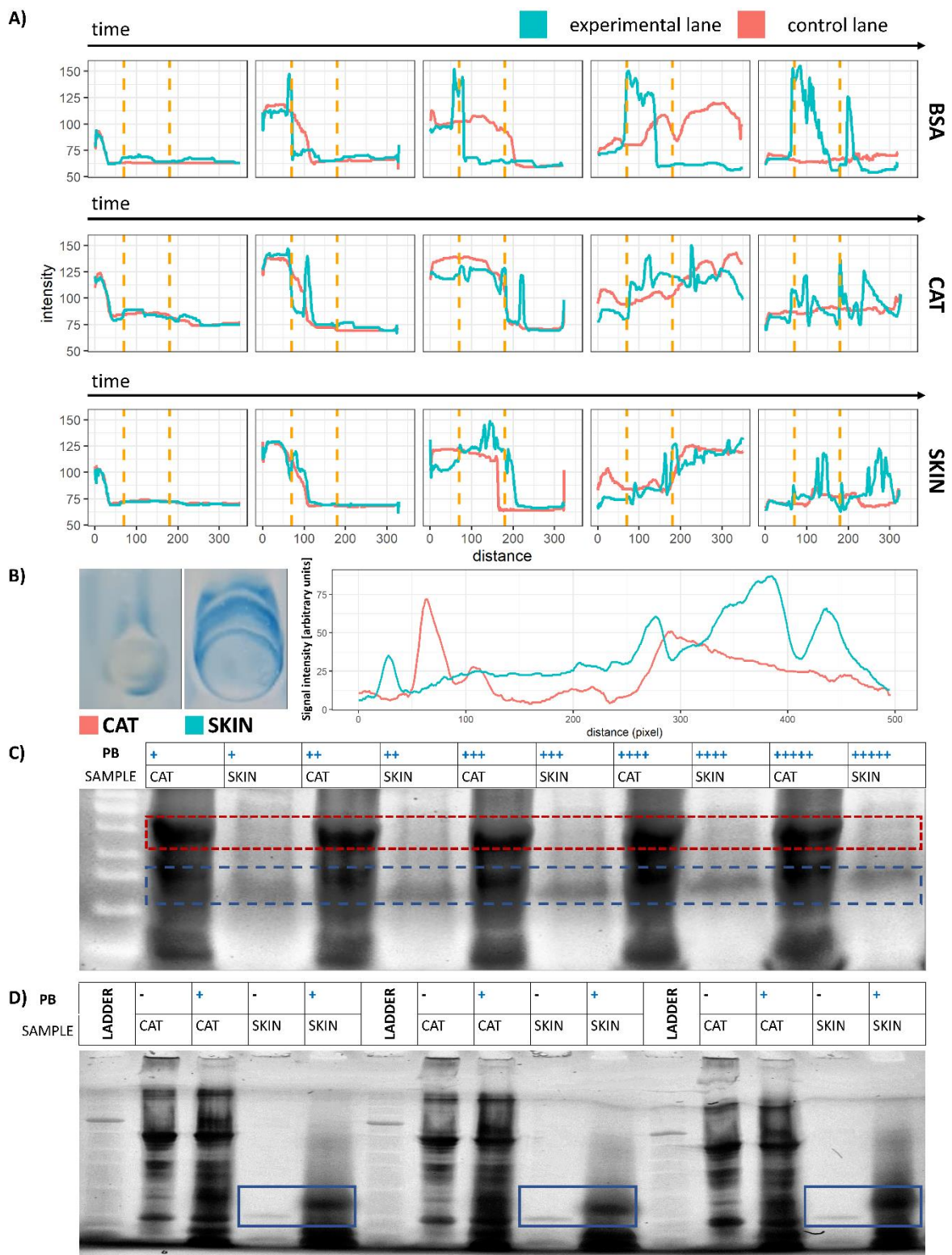


620

621 **Fig 3.** Catalase (CAT) and superoxide dismutase (SOD)-like activity of the Persian Blue tattoo  
 622 ink (PB) and its blue and white fractions *in vitro* in the presence of biochemical constituents of  
 623 the skin. A) Output of the model including tested dilutions of PB and its blue and white



624 fractions and substrate concentrations (6, 8, and 10 mM H<sub>2</sub>O<sub>2</sub>), demonstrating the ability of PB  
625 and its fractions to inhibit CAT *in vitro* (t = 60 s). While the effect was not dose-dependent for  
626 the blue fraction, the white fraction and PB showed a pronounced dose-dependent inhibition  
627 of the enzyme. B) Model results presented as point estimates of differences of estimated  
628 marginal means with 95 % confidence intervals for the model presented in A. C) Output of the  
629 model including tested dilutions of PB and the blue and white PB fractions demonstrating the  
630 ability of the samples to potentiate CAT activity in the complex biochemical matrix of normal  
631 skin tissue (substrate concentration: 10 mM H<sub>2</sub>O<sub>2</sub>; t = 600 s). D) Model results presented as  
632 point estimates of differences of estimated marginal means with 95 % confidence intervals for  
633 the model presented in C. E) Output of the model including tested dilutions of PB and the blue  
634 and white PB fractions demonstrating the effect of the samples on CAT activity in the complex  
635 biochemical matrix of normal skin tissue following pre-incubation of the dyes with the tissue  
636 samples (pre-incubation time: 180 min; pre-incubation temperature: 37 °C; substrate  
637 concentration: 10 mM H<sub>2</sub>O<sub>2</sub>; t = 600 s). F) Model results presented as point estimates of  
638 differences of estimated marginal means with 95 % confidence intervals for the model  
639 presented in E. G) SOD mimetic activity of PB and the blue and white PB fractions in the  
640 complex biochemical matrix of normal skin tissue. At t < 300 s, PB demonstrated no SOD-like  
641 activity, while both blue and white fractions acted as SOD mimetics. At t > 300 s, PB was  
642 associated with slight potentiation, while the white PB fraction induced pronounced  
643 autooxidation of 1,2,3-trihydroxybenzene. Conversely, the blue PB fraction demonstrated  
644 SOD-mimetic activity. H) SOD mimetic activity of PB and the blue and white PB fractions in  
645 the complex biochemical matrix of normal skin tissue following incubation of the dyes with  
646 skin tissue for 180 min at 37 °C. Pre-incubation of the dyes with the skin tissue constituents  
647 alleviated the effects observed in F.

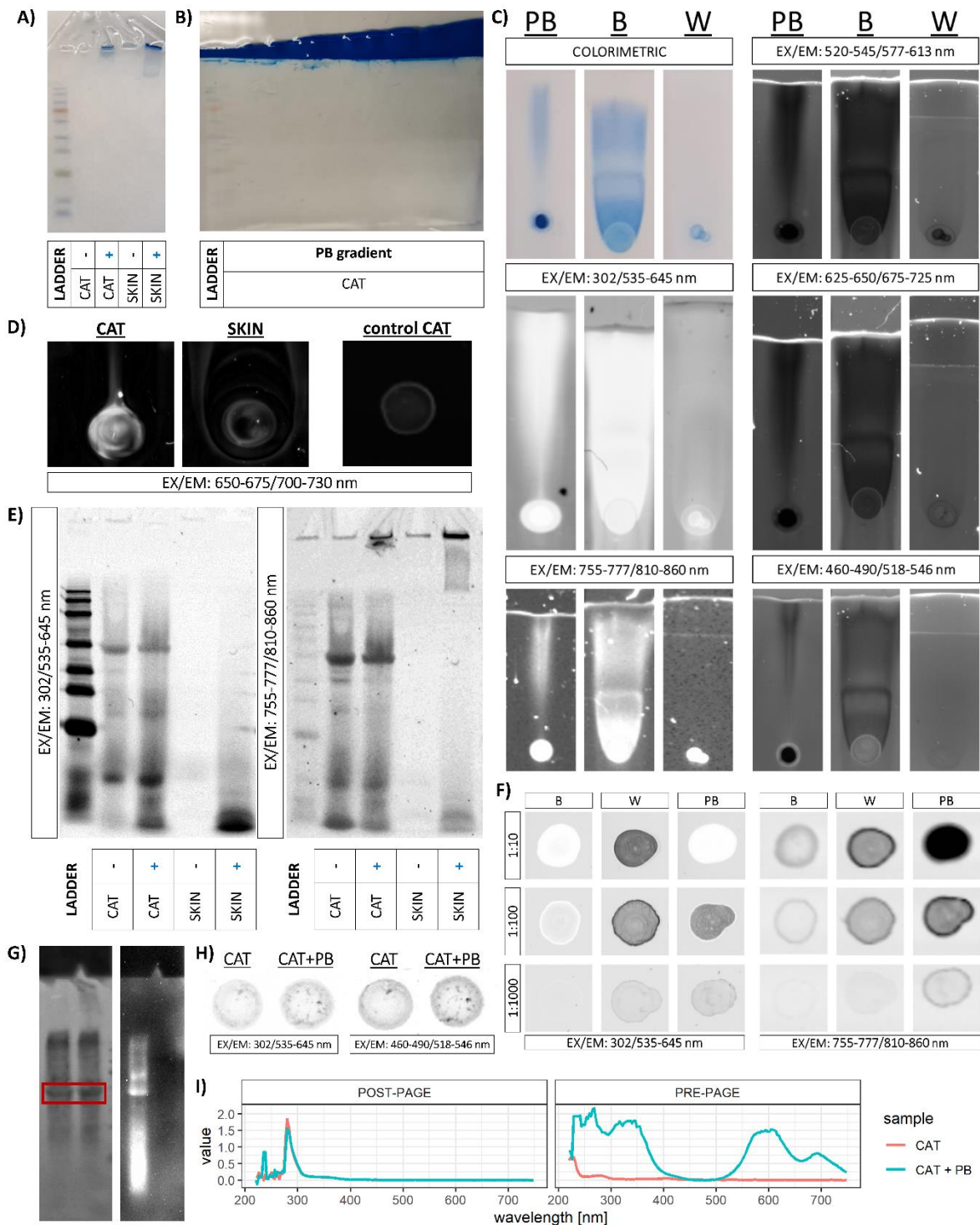


648

649 **Fig 4.** Interaction of the blue tattoo ink with constituents of the skin homogenate assessed by  
 650 the lateral flow assay (LFA), CuPC-capturing gradient electrophoretic mobility shift assay  
 651 (CCG-EMSA), and sample pre-incubation electrophoretic mobility shift assay (SP-EMSA). A)  
 652 Line profiles obtained from LFA with the Persian Blue (PB) tattoo ink used as a mobile phase.  
 653 Profiles obtained from the free route for the uninterrupted analyte flow (control lane) and the  
 654 sample-capturing lane containing two capturing pools (experimental lane; capturing pools are  
 655 marked with yellow lines) are shown for the control high binding capacity protein – bovine

656 serum albumin (BSA; top), catalase (CAT; middle), and the skin homogenate (SKIN; bottom).  
657 Both time (5 time-points) and the direction of the flow are aligned with the X-axis. B) CAT  
658 and skin homogenate after LFA with PB mobile phase followed by ddH<sub>2</sub>O (left). The skin  
659 sample shows a wave pattern suggesting the presence of interaction with several separate  
660 components. Line profiles of the samples presented on the left with 3 peaks associated with the  
661 skin sample suggest heterogeneous interaction patterns. C) The polyacrylamide gel from the  
662 CCG-EMSA experiment demonstrates the absence of the electrophoretic mobility shift for the  
663 CAT sample (red), and dose-dependent electrophoretic deceleration for the skin sample (blue).  
664 The trichalo-containing polyacrylamide gel was visualized using 302 nm excitation and 535-  
665 645 nm emission. A negative image is presented. D) The gel from the SP-EMSA experiment  
666 showing 3 technical replicates of pre-treated and untreated CAT and skin samples with no  
667 apparent deceleration in the CAT sample, and a prominent reduction in mobility of the  
668 prominent peak in the skin sample (blue). The trichalo-containing polyacrylamide gel was  
669 visualized using 302 nm excitation and 535-645 nm emission. A negative image is presented.

670



671

672 **Fig 5.** Interaction of the blue tattoo ink with constituents of the skin homogenate assessed by  
 673 the lateral flow assay (LFA), CuPC-capturing gradient electrophoretic mobility shift assay  
 674 (CCG-EMSA), and sample pre-incubation electrophoretic mobility shift assay (SP-EMSA)  
 675 spectral analysis. A) Native image of the polyacrylamide gel from the SP-EMSA experiment  
 676 after electrophoretic separation of catalase (CAT) and skin samples. B) Native image of the  
 677 polyacrylamide gel from the CCG-EMSA experiment after electrophoretic separation. C)  
 678 Spectral analysis of the LFA membranes using different excitation and emission wavelengths

679 demonstrates 3 general patterns: the sample pool (the area where the sample was deposited –  
680 lower portion of the images); the middle mobile phase (largely absent in the white fraction –  
681 the middle portion of the images); and the mobile front (present in all samples – upper portion  
682 of the images). D) CAT and the skin sample exposed to the Persian Blue tattoo ink (PB) mobile  
683 phase, and the control CAT sample (not exposed to the PB mobile phase to control for baseline  
684 spectral properties) emission at 700-730 nm upon excitation at 650-675 nm. A substantial  
685 increment in emission and the smearing pattern speak in favor of the interaction of CAT with  
686 the PB mobile front. E) Spectral analysis of the gel from the SP-EMSA experiment shows that  
687 both the PB-pretreated skin sample and PB-pretreated CAT emit a signal in concordance with  
688 the presence of constituents from the white fraction (see F). Notice the difference in the signal  
689 from the stacking gel and the resolving gel in the context of the ink fractions emission signals  
690 (presented in F). Negative images are presented. F) The effect of PB fractions and  
691 concentrations in two different spectral planes. Negative images are presented. G) Ponceau S  
692 staining of the nitrocellulose membrane with the PB-treated and PB-untreated CAT from the  
693 SP-EMSA experiment (left), and the corresponding membrane exposed to luminol and H<sub>2</sub>O<sub>2</sub>  
694 demonstrating a substantial H<sub>2</sub>O<sub>2</sub> dissociation potential only in the PB-treated CAT sample  
695 (right). The main CAT fraction is emphasized in red. The pattern indicates that both the PB-  
696 pretreated CAT and the front have the ability to promote H<sub>2</sub>O<sub>2</sub> dissociation. H) Negative  
697 images of the signal obtained from the PB-treated and PB-untreated CAT eluted from the  
698 membrane shown in G in two different spectral planes indicating the presence of the  
699 constituents associated with the white fraction. I) Confirmation of the absence of the CuPC  
700 from the samples containing CAT eluted from the membrane shown in G. UV-Vis spectra both  
701 CAT and PB-pretreated CAT before the polyacrylamide gel electrophoresis (PRE-PAGE) and  
702 after elution from the membrane (POST-PAGE).

703