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1 **Real-time oxygen sensing as a powerful tool to investigate tyrosinase kinetics**
2 **allows revising mechanism and activity of inhibition by glabridin**

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Abstract

A new method for studying tyrosinase kinetics and inhibition by oxygen sensing is described and matched to the conventional spectrophotometric approach. The stoichiometric ratio of O₂ uptake to dopachrome formation was 1.5±0.2 for substrate L-tyrosine and 1.0±0.1 for L-DOPA. With both methods, we reinvestigated mushroom tyrosinase inhibition by glabridin from *Glycyrrhiza glabra*. The two methods agreed showing mixed-type inhibition for monophenolase and diphenolase activities, at variance with previous literature. Average K_I (K_{SI}) values for glabridin were 13.6±3.5 (281±89) nM and 57±8 (1312±550) nM, for monophenolase and diphenolase inhibition, respectively, with IC₅₀ of 80±8 nM and 294±25 nM, respectively, at 1 mM substrate. For reference kojic acid K_I (K_{SI}) were 10.9±8 (217±55) μM and 9.9±1.4 (21.0±5.2) μM, for monophenolase and diphenolase, respectively, with respective IC₅₀ of 33±8 μM and 17±3 μM. Glabridin's activity is among the highest in nature, being about three orders of magnitude higher than previously reported.

Keywords: glabridin, kojic acid, mushroom tyrosinase, inhibition kinetics, oximetry.

Products investigated in this study:

Mushroom Tyrosinase (EC 1.14.18.1), CAS: 9002-10-2

Glabridin, CAS: 59870-68-7 (PubChem CID: 124052)

Kojic acid, CAS: 501-30-4; (PubChem CID: 3840)

1. Introduction

Melanin is a group of organic pigments widely distributed in different kingdoms, from bacteria to fungi, to plants and animals, including humans (d'Ischia et al., 2015). It is biosynthesized from the oxidation and polymerization of phenolic precursors, mainly by the action of tyrosinase (TY) enzyme. Melanins, particularly Eumelanins, have important biological functions and properties, which are still the object of extensive research, most notably: photo-protection, protection from ionizing radiations, neuroprotection and antioxidant (d'Ischia et al., 2015; Guo et al., 2021). Their multiple properties justify the major interest melanins are receiving for the development of novel bioinspired materials (d'Ischia, Napolitano, Pezzella, Meredith & Buehler, 2020; Manini et al. 2019), including applications in food technology (Roy & Rhim, 2021).

Besides, inhibition of melanin biosynthesis also has distinct importance. Human skin hyperpigmentation, melasma and photo-induced dyschromia are consequences of dysregulated melanin biosynthesis (Nicolaidou & Katsambas, 2014). Therefore, inhibition of biosynthesis has been a long-term goal in biomedical and cosmetic science (Panzella & Napolitano, 2019).

Although formed from different phenolic precursors as compared to skin melanin, production of melanin-type pigments in food gives rise to a dark color (enzymatic browning), accompanied by other deterioration processes such as changes of flavor, unpleasant odor and loss of nutritional value, especially during postharvest processing and storage of vegetables and fruits (Moon, Kwon, Lee & Kim, 2020). Since the level of melanin is mainly regulated by tyrosinase activity, its inhibition has become a prominent strategy in food preservation (Martínez-Alvarez Lopez-Caballero, Montero & del Carmen Gomez-Guillen, 2020; Song, Ni, Zhang, Zhang, Pan & Gong, 2021; Yu & Fan, 2021; Shao et al., 2018), paralleling the importance of inhibiting autoxidation and microbial spoilage (Moon, et al., 2020).

Tyrosinase (EC 1.14.18.1), a polyphenol oxidase (PPO), is ubiquitous (Nawaz et al., 2017) and has a highly-conserved type III copper center in the active site (Olivares & Solano, 2009). It is involved in two consecutive yet different oxidative catalytic cycles: the *ortho*-hydroxylation of

60 monophenols (*e.g.* L-tyrosine) by oxygen to *o*-diphenols (monophenolase reaction) and the oxidation
61 of *o*-diphenols (*e.g.* L-DOPA) by oxygen to *o*-quinones (diphenolase activity) (Mondal, Thampi &
62 Puranik, 2018). Quinones then undergo further spontaneous reactions leading to melanin (Figure 1).
63 Tyrosinase inhibitors are most often assayed spectrophotometrically, using well established and
64 convenient mushroom tyrosinase (mTY) (Shao et al. 2018), which is incubated with L-tyrosine or L-
65 DOPA as the natural substrates to selectively monitor, respectively, monophenolase or diphenolase
66 reaction. Both reactions are monitored from the growth in absorbance at 475 nm due to the subsequent
67 spontaneous formation of colored dopachrome (DC), as schematized in Figure 1. Although the
68 method is very well established and convenient, it is not free from errors. For instance, it relies on the
69 detection of a late product. Additionally, other molecules (*e.g.* when testing extracts as inhibitors)
70 could absorb at 475 nm or be transformed to afford colored intermediates that might interfere with
71 the spectrophotometric reading (Mayr et al., 2019). Since oxygen is an obliged reactant in both
72 monophenolase and diphenolase cycles and its total consumption is stoichiometrically related to the
73 total formation of products (Naish-Byfield & Riley, 1992), we set to develop a method of real-time
74 monitoring of the kinetics of oxygen consumption during tyrosinase reaction, by means of a
75 miniaturized sensor based on near infrared (NIR) fluorescence quenching. The approach steps from
76 the extensive experience of our group in monitoring the kinetics of oxygen uptake in oxidative radical
77 reactions (Guo, Baschieri, Amorati & Valgimigli, 2021; Haidasz et al., 2016). Our hypothesis was
78 that it would well match with the conventional spectrophotometric monitoring of dopachrome
79 formation and afford a convenient and highly reliable combined method to investigate tyrosinase
80 kinetics and inhibition.

81 To date, a large number of compounds with tyrosinase inhibition activity, of synthetic or natural
82 origin, have been discovered (Zolghadri, et al, 2019); among them, certainly glabridin stands out.
83 Originally extracted from licorice roots (*Glycyrrhiza glabra*, L.) it was the first *G. glabra*
84 phytochemical with confirmed anti-tyrosinase activity, and the most potent (Nerya, Vaya, Musa,
85 Izrael, Ben-Arie, & Tamir, 2003). It was later found also in other botanical sources, and reported as

86 one of the most active natural mTY inhibitors, with 15-folds higher activity than kojic acid
87 (Yamauchi, Mitsunaga & Batubara, 2011), more effective than resveratrol and oxyresveratrol (Wang
88 et al., 2018). Owing to its potency glabridin has been taken as drug lead to develop novel synthetic
89 inhibitors (Jirawattanapong, Saifah, & Patarapanich, 2009), while pharmaceutical/food-grade licorice
90 extracts standardized in glabridin (*e.g.* 40%) have become commercially available (Tamura, 2017).
91 Nonetheless, the literature on its actual activity is quite confusing: IC₅₀ values of 5.25, 2.93, 0.77 and
92 0.09 μM have been reported for inhibition of mTY with substrate L-tyrosine (Nerya et al, 2003;
93 Yamauchi et al., 2011; Kim, Seo, Lee, Lee, 2005; Li, Li, Zhu, Lai, & Wu, 2021), spanning about two
94 orders of magnitude. There is only one complete kinetic study addressing the mechanism of mTY
95 inhibition, which was reported as noncompetitive both for monophenolase and diphenolase reactions,
96 with Michaelis-Menten (M-M) inhibition constants K_I of 0.38 mM and 0.81 mM, respectively (Nerya
97 et al, 2003). These surprisingly high values are at odds with the reported IC₅₀ values, and with the
98 much lower K_I values available for reportedly less effective inhibitors like kojic acid (K_I in the range
99 18-23 μM for monophenolase activity) (Kim, Yun, Lee, Lee, Min & Kim, 2002) – it should be
100 recalled that lower values indicate higher activity. Therefore, our hypothesis was that glabridin's
101 activity would require revision.

102 Given its importance, we re-investigated the activity of glabridin on mTY as a test-bench for our
103 new oxygen uptake kinetic approach, using kojic acid as reference inhibitor. Hence, the scope of our
104 study was first to set-up and validate our novel kinetic approach and, second, to afford revised
105 mechanism and kinetics for glabridin, as a key reference for future studies and applications.

106 <Figure 1 about here>

107 **2. Materials and methods**

108 *2.1 Materials*

109 Glabridin ($\geq 98\%$), L-tyrosine ($\geq 98\%$), L-DOPA (3,4-dihydroxy-L-phenylalanine; $\geq 98\%$), kojic acid
110 (5-Hydroxy-2-hydroxymethyl-4H-4-pyranone; $\geq 98.5\%$), water, acetonitrile and methanol (HPLC

111 grade) were purchased from Sigma-Aldrich (Milan, Italy). Commercial mushroom tyrosinase (EC
112 1.14.18.1, activity = 3130 units/mg) was purchased from Sigma-Aldrich and used without further
113 purification. Fresh solutions were prepared twice a week in potassium phosphate buffer solution (50
114 mM, pH 6.8) and stored in small aliquots at -20°C for daily use. Given the difficulty to maintain the
115 enzyme activity, tyrosinase activity was analysed spectrophotometrically every day during the
116 experimental period, in order to adjust solutions to fixed tyrosinase Sigma units for consistent results.
117 Briefly, one Sigma unit corresponds to the amount that will cause an increase in absorbance at 280
118 nm of 0.001 per minute at pH 6.8 in a 3 mL reaction mixture containing L-tyrosine. Sigma units were
119 used throughout this study. One Sigma unit corresponds to 1.65×10^{-4} international units (I.U.) for
120 monophenolase activity and to 2.24×10^{-2} I.U. for diphenolase activity, as defined by Fenoll et al.
121 (2002). All other reagents were analytical grade from Sigma-Aldrich-Fluka, Merck (Milan, Italy).

122 *2.2 Kinetics studies by UV-vis spectrophotometry*

123 Kinetic evaluation of monophenolase and diphenolase reaction of tyrosinase with or without
124 inhibitor was carried out using UV-Vis spectrophotometry similarly to previous methods (Song et al.,
125 2021; Chang et al., 2007), with modifications. Measurements were performed at 30°C in a Thermo
126 Scientific (Milan, Italy) Biomate 5, equipped with a multi-cell changer coupled with a Heto DBT
127 Hetotherm (Birkerød, Denmark) thermostating water circulator for temperature control. The samples
128 were analyzed in polystyrene low-volume cuvettes (1.5 mL, $l = 1$ cm, 12.5×12.5×45 mm).
129 Absorbance of dopachrome was measured at 475 nm for a time-period of 20 to 60 min (1 scan / 55s)
130 reading the solution against a reference cuvette containing all reaction components except the
131 substrate, which was replaced with potassium phosphate buffer (50 mM, pH 6.8). Absorbance
132 variation *vs* time at different substrate concentration allowed to obtain initial velocity ($V = \Delta A / \Delta \text{min}$)
133 which was converted in $\mu\text{M}/\text{min}$ according to Lambert-Beer law as follows: $V (\mu\text{M}/\text{min}) = V$
134 $(\Delta A / \Delta \text{min}) \times 10^6 / \epsilon_{\lambda_{\text{max}}} \times l$. The molar extinction coefficient (ϵ) for dopachrome at $\lambda_{\text{max}} = 475$ nm is
135 $3700 \text{ M}^{-1} \text{ cm}^{-1}$. Michaelis-Menten parameters (K_m e V_{max}) were obtained by processing initial velocity

136 vs substrate concentration data by nonlinear fitting to M-M equation (1), using Sigmaplot 11.0 (Systat
137 Software Inc., San Jose, California). Linearized Lineweaver-Burk equation (2) was instead used to
138 help identify the inhibition mode (Copeland, 2000). In both equations, V indicates the measured initial
139 rate of reaction (*vide supra*), $[S]$ is the initial substrate concentration, while V_{\max} and K_m are
140 respectively the maximum reaction rate (at saturating substrate concentration) and the M-M constant
141 (the substrate concentration yielding half-maximum reaction rate).

$$142 \quad V = \frac{V_{\max} [S]}{K_m + [S]} \quad (1)$$

$$143 \quad \frac{1}{V} = \frac{K_m}{V_{\max} [S]} + \frac{1}{V_{\max}} \quad (2)$$

144 The effect of inhibitors on enzyme reaction was evaluated at fixed tyrosinase units (3.85 U/mL
145 for L-DOPA, 7.70 U/ml for L-tyrosine) and varying substrate concentrations (6-7 levels of L-DOPA
146 and L-tyrosine, from 0 to 1.2 mM and 0 to 1.0 mM respectively), testing reactions without and with
147 glabridin (0 to 300 nM for diphenolase; 0 to 50 nM for monophenolase) or kojic acid (0 to 100 μ M).

148 2.3 Kinetics studies by oximetry

149 Evaluation of tyrosinase monophenolase and diphenolase kinetics and inhibition by glabridin or
150 kojic acid was carried out by monitoring the oxygen consumption, at 30°C, by a NIR (760-790 nm)
151 fluorescence oxygen sensor contained in a stainless-steel needle, connected to a FireSting-O2 (2
152 channels, FSO2-2) meter via an optical fiber (Pyrosience GmbH, Bremen, Germany). The samples
153 were contained in 2.4 mL glass flasks, which were hand-made by a local scientific glass blower,
154 provided with a PTFE coated stirring bar, immersed in a water bath controlled by Heto DBT
155 Hetotherm (Birkerød, Denmark) thermostating unit, and equipped with a submersed sealed magnetic
156 stirrer MixDrive 1 XS + Mix Control (2mag AG, Munchen, Germany). The equipment set-up is
157 illustrated in the Appendix. The oxygen consumption was recorded every second, and all reaction
158 components, except the inhibitor concentration, were maintained identical to those set for UV-vis
159 spectrophotometry. The raw data collected directly from the oxygen sensor is a percentage (P) of the

160 saturating oxygen concentration in the sample, corresponding to 0.236 mM at 30°C which reflects in
161 the sensor reading as 20% (P_0). Thus, the oxygen concentration during the time course of the
162 enzymatic oxidation of L-DOPA or L-tyrosine were converted into mM by the following equation:
163 $[O_2] \text{ (mM)} = P \times 0.236 \text{ (mM)} / 20\%$. The initial rate of oxygen consumption was obtained by
164 regression of the initial data range of oxygen consumption (ΔP) vs time (in seconds), as illustrated in
165 representative Fig. S3 and Fig. S4 (see Appendix), and they were converted by equation: $V \text{ (}\mu\text{M/min)}$
166 $= V (\Delta P/\Delta t) \times 0.236 \times 10^3 \times 60 / P_0$ (see Appendix, Table. S1), which were used for further analysis
167 by non-linear fitting to Michaelis-Menten kinetics (eq. 1). In order to match the kinetic of oxygen
168 consumption and that of dopachrome formation assessed spectrophotometrically (see paragraph 2.2),
169 the uninhibited reaction was monitored at different activity of the enzyme (1-25 U/mL) and fixed
170 concentration of substrate (1.6 mM for both L-DOPA and L-tyrosine), or at fixed activity of the
171 enzyme (7.70 U/mL or 3.85 U/mL) and variable concentration of substrate, in matched experiments,
172 comparing the initial rates of dopachrome formation and oxygen consumption at 30°C.

173 *2.4 Analysis of glabridin as a substrate of mushroom tyrosinase*

174 To verify whether glabridin is a substrate of mTY, beside being an inhibitor, we performed a
175 variant of the assay described by Mayr et al. (2019). Mushroom tyrosinase (mTY, 7.70 U/mL) was
176 incubated in phosphate buffer (pH 6.8) at 30°C with glabridin 200 nM and 1 mM in the absence of
177 other substrates, and the reaction was monitored either spectrophotometrically (full scan 200-600 nm)
178 or by the oxygen sensor over 1 hour, to record any sign of reaction.

179 *2.5 Statistical analysis*

180 Each measurement was performed in triplicate. Values of V_{\max} and V_{\max}^{app} , and of K_m and K_m^{app}
181 in the absence and presence of inhibitors were determined from non-linear regression of M-M plots
182 based on 5 to 7 concentrations of the substrate, which were analysed by Shapiro-Wilk Test with
183 significance set at $P \leq 0.05$. Results are expressed as regression value \pm standard error.

184 3. Results and Discussion

185 3.1 Parallel monitoring of the tyrosinase reaction by oximetry and spectrophotometry

186 In order to study monophenolase and diphenolase activities of mTY, L-tyrosine or L-DOPA were
187 used as substrate, respectively, following the *o*-hydroxylation of L-tyrosine to L-DOPA and its further
188 oxidation to *o*-dopaquinone, or just the second step, taking advantage of the higher rate of the
189 diphenolase reaction, which renders L-tyrosine hydroxylation rate-limiting when using it as the
190 substrate. The reaction was first monitored spectrophotometrically following the formation of
191 dopachrome (DC) at 475 nm at 30°C, according to the most established practice (Song et al, 2021;
192 Shao et al., 2018). Measurements performed at fixed concentration of mTY and variable
193 concentration of substrate afforded the typical sigmoidal kinetic profile, with an initial lag time when
194 the substrate was L-tyrosine. Plotting the initial rate of DC formation versus the substrate
195 concentration showed good M-M behavior (Figure 2A, C). Since tyrosinase activity is essentially an
196 oxidation process operated by oxygen, where oxygen is directly involved into the production of late
197 product DC, we set to improve the reliability of spectrophotometric measurements by parallel
198 oximetry studies. In matched experiments performed in closed vials, we monitored the oxygen
199 concentration as a function of time during the reaction progress, using a miniaturized oxygen sensor
200 based on NIR fluorescence quenching (see Appendix for instrumental settings). Results are compared
201 to those obtained by spectrophotometry in Figure 2 (plots B and D). It can be noted that the kinetic
202 profile of oxygen consumption also follows the typical M-M behavior, being complementary to the
203 formation of dopachrome and suggesting that both methods are suited to monitor the reaction kinetics.

204 <Figure 2 about here>

205 This result was expected, since oxygen is the obliged oxidant in both cycles and it can be
206 kinetically regarded as a substrate of tyrosinase (Fenoll et al., 2001). Our result also well matches the
207 pioneering work by Naish-Byfield & Riley (1992) showing Michaelis-Menten kinetic profiles of
208 oxygen consumption (monitored electrochemically) during the oxidation of 4-hydroxyanisol by

209 mTY, and by Rodriguez-López et al. (Rodriguez-López, Ros-Martínez, Varón & García-Cánovas,
210 1992) who showed complementarity between oxygen consumption (monitored electrochemically)
211 and product accumulation during the mTY oxidation of *tert*-butylcatechol.

212

213 *3.2 Correlation of the stoichiometry of oxygen consumption to dopachrome formation*

214 The stoichiometric ratios of oxygen consumption to dopachrome accumulation during mTY
215 reaction for substrates L-tyrosine and L-DOPA were previously investigated, respectively, by Naish-
216 Byfield & Riley (1992) and by Rodriguez-López et al. (1992) by electrochemical analysis (Clark
217 electrode) of oxygen in the reaction mixture.

218 In our study, the stoichiometric ratio was determined from comparison of the initial rates of O₂
219 consumption to that of DC formation, for both substrates L-tyrosine and L-DOPA, in matched kinetic
220 experiments with the two methods (Figure 3). We judged this approach more accurate than measuring
221 the total oxygen consumption and product formation at the end of the reaction, since the further
222 spontaneous transformation of DC (on the way to melanin) might influence the apparent DC
223 absorbance at the later stages of enzyme reaction. Our results were in full agreement with previous
224 findings that the stoichiometry of oxygen consumption depends on the substrate, being 1 mol O₂ : 1
225 mol of DC when the substrate is L-DOPA, and 1.5 mol of O₂ : 1 mol of DC when the substrate of L-
226 tyrosine (Naish-Byfield & Riley, 1992; Rodriguez-López et al., 1992).

227 This result agrees with the notation that 0.5 mol of O₂ is consumed to hydroxylate L-tyrosine to
228 L-DOPA and another 0.5 mol of O₂ is needed to oxidize L-DOPA to dopaquinone. However,
229 subsequent spontaneous cyclization forms cyclodopa (leukodopachrome) that is oxidized to
230 dopachrome by rapid redox reaction with dopaquinone (Mondal et al., 2018), which is reduced back
231 to L-DOPA. This last consumes another 0.5 mol of O₂ to be oxidized again to DOPAquinone (Naish-
232 Byfield & Riley, 1992; Rodriguez-López et al., 1992), as depicted in Figure 1.

233 Since it was reported that (for other substrates) the stoichiometry of oxygen consumption can
234 vary with the experimental conditions, particularly with the concentration of enzyme and substrate
235 (Peñalver, Hiner, Rodriguez-López, García-Canovas, & Tudela, 2002), we extended our correlation
236 of the initial rates of reaction to a broad range of enzyme and substrate concentrations, by performing
237 series of experiments at fixed substrate and variable enzyme activity and at fixed enzyme activity and
238 variable substrate concentration, using both L-DOPA alone and L-tyrosine alone as the substrate.
239 Results are summarized in Figure 3(C-F), and confirm that the stoichiometric ratio of oxygen
240 consumption / dopachrome formation was 1.0 ± 0.1 and 1.5 ± 0.2 (O_2 to DC) for substrate L-DOPA and
241 L-tyrosine, respectively, over the whole range of experimental settings.

242 <Figure 3 about here>

243 This result agrees with previous studies with L-tyrosine and L-DOPA (Naish-Byfield & Riley, 1992;
244 Rodriguez-López et al., 1992), but is at variance with a study in which *tert*-butylphenol (TBP) and
245 *tert*-butylcatechol (TBC) were used, respectively, to assess oxygen consumption during
246 monophenolase and diphenolase reaction, showing a variation of O_2 /product stoichiometric ratio for
247 very low substrate/enzyme concentration ratio (Peñalver et al., 2002). The different outcome is
248 possibly due to the higher stability in solution of the products formed from TBP/TBC, as previously
249 discussed in detail (Peñalver et al., 2002).

250

251 3.3 Validation of oxygen consumption kinetics on uninhibited activity of *mTY*

252 Upon establishing the actual stoichiometric ratio of oxygen consumption and dopachrome
253 formation, the kinetic measurements performed by the two approaches could be compared on
254 quantitative grounds. The initial rates of the reaction were analysed according to Michaelis-Menten
255 equation and the K_m and V_{max} values for the monophenolase and diphenolase activity were obtained
256 by non-linear regressions. For reaction with substrate L-tyrosine (monophenolase) K_m measured by

257 spectrophotometry and by O₂ sensing was 0.18±0.01 mM and 0.17±0.02 mM, respectively, while
258 V_{max} was 9.01±0.12 μM/min and 8.45±0.62 μM/min, respectively. Instead, for substrate L-DOPA
259 (diphenolase) K_m from spectrophotometry and O₂ sensing was 0.26±0.02 mM and 0.24±0.02 mM,
260 respectively, while V_{max} was 25.80±0.53 μM/min and 24.18±0.96 μM/min, respectively (results are
261 collected in Table S2 in Appendix). It can be noted that the two kinetic approaches afford results in
262 excellent agreement, being identical within experimental error. Our data also match well with
263 previous literature, *e.g.* Ros et al. (Ros, Rodríguez-López, García-Cánovas, 1994) reported K_m of
264 0.168 mM and 0.272 mM respectively for monophenolase and diphenolase reaction, while Fenoll et
265 al. (2001), in a very detailed study, reported K_m as 0.25 mM and 0.28 mM for the two reactions. This
266 provides good validation of our real-time oxygen consumption approach to investigate tyrosinase
267 kinetics.

268

269 *3.4 Inhibition kinetics by Glabridin and Kojic Acid*

270 Glabridin is claimed one of the most effective natural inhibitors of tyrosinase, but there is major
271 uncertainty on its actual activity on quantitative grounds, in spite of its role as reference compound,
272 as previously illustrated. Given its importance, we investigated its kinetic of inhibition addressing
273 both monophenolase and diphenolase activities, by both methods (spectrophotometry and oxygen
274 uptake) in matched studies. Results are summarized in Figure 4, in which non-linear fittings of M-M
275 plots were used for quantitative analysis, while linear Lineweaver-Burk plots helped identify the
276 mechanism. This choice aimed at increasing the accuracy, since obtaining V_{max} (and K_m) directly from
277 the intercept in Lineweaver-Burk plots is subject to higher intrinsic error (Copeland, 2000).

278 <Figure 4 about here>

279 Literature on the activity profile of this molecule indicates a noncompetitive inhibitory
280 mechanism (Nerya et al., 2003; Chen, Yu & Huang, 2016).), which implies that glabridin is capable
281 of binding with the same affinity both the free enzyme (E) and the complex enzyme-substrate (ES).
282 A kinetic consequence of this type of inhibition is that the apparent maximum reaction rate V_{max}

283 should decrease with the concentration of the inhibitor, while the apparent M-M constant K_m should
 284 remain unchanged (Copeland, 2000). However, both spectrophotometry and oximetry did not show
 285 noncompetitive but nearly competitive inhibition, as it can be judged from Lineweaver-Burk plots
 286 (eq. 2) in Figure 4 (C, D, G, H). In such plots the intercept on the Y-axis ($= 1/V_{max}$) is nearly constant
 287 in the absence of the inhibitor or with different concentrations of glabridin, which implies that V_{max}
 288 does not depend on the concentration of glabridin, as it is expected for a competitive inhibitor. On
 289 the contrary, noncompetitive inhibitors should show an intercept on the Y-axis which increases with
 290 the concentration of the inhibitor. Additionally, the intercept on the X-axis ($= -1/K_m$) becomes less
 291 negative on increasing the concentration of glabridin, meaning that K_m is increasing, which is typical
 292 of competitive inhibitors.

293 The activity of a competitive inhibitor is best quantified by the M-M derived inhibition constant
 294 K_I , which represents the dissociation constant of the Enzyme-Inhibitor (EI) complex (eq 1), hence the
 295 smaller the value the higher the inhibition. Since a closer inspection of Lineweaver-Burk plots shows
 296 some minor variation of V_{max} particularly in oxygen uptake plots (Figure 4 G, H), to a first judgment,
 297 inhibition by glabridin was considered of mixed-type. Mixed-type inhibitors interfere with both the
 298 free enzyme and enzyme-substrate (ES) complex, with two (different) dissociation constants K_I and
 299 K_{SI} (eqs 3, 4), the first relating to the inhibitor bonded to the free enzyme and the other indicating the
 300 inhibitor bonded to the ES complex. Noncompetitive inhibitors would show $K_I = K_{SI}$.

$$301 \quad K_I = \frac{[E][I]}{[EI]} \quad (3)$$

$$302 \quad K_{SI} = \frac{[ES][I]}{[ESI]} \quad (4)$$

303 To determine K_I and K_{SI} for a mixed-type inhibition from M-M kinetic treatment, it is useful to
 304 introduce the parameters α and an α' , which are given as follows:

$$305 \quad \alpha = \frac{K_m^{app}}{K_m} \alpha' \quad (5)$$

306
$$\alpha' = \frac{V_{max}}{v_{max}^{app}} \quad (6)$$

307 Here K_m and K_m^{app} are respectively the M-M constant (substrate concentration giving half-
 308 maximum rate) in the absence and in the presence of the inhibitor, and V_{max} and V_{max}^{app} are
 309 respectively the maximum rate measured in the absence and in the presence of the inhibitor. K_I and
 310 K_{SI} values were then obtained from eqs. 7 and 8 at each concentration of the inhibitor [I].

311
$$\alpha = 1 + \left(\frac{[I]}{K_I}\right) \quad (7)$$

312
$$\alpha' = 1 + \left(\frac{[I]}{K_{SI}}\right) \quad (8)$$

313 The kinetics parameters determined for inhibition by glabridin (from data in figure 4), both with
 314 L-tyrosine and L-DOPA, by monitoring both DC formation and O₂ uptake, are listed in Table 1.

315 **Table 1.** Kinetic parameters of tyrosinase activity inhibition by glabridin at 30°C (pH = 6.8).
 316 Kinetic data were obtained by non-linear fitting of M-M plots at different glabridin concentrations.^a

A. Kinetic parameters of tyrosinase diphenolase activity inhibition by glabridin.								
	Dopachrome (DC) formation				Oxygen (O ₂) consumption ^a			average
[Glabridin] (nM)	0	90	180	300	0	80	200	
V_{max} or V_{max}^{app}	25.80	24.81	22.74	20.04	24.18	22.50	19.66	
(μ M/min)	± 1.53	± 1.14	± 2.52	± 4.32	± 0.96	± 1.32	± 1.26	
K_m or K_m^{app} (mM)	0.26	0.67	1.08	1.31	0.21	0.47	0.66	
	± 0.02	± 0.06	± 0.02	± 0.46	± 0.02	± 0.08	± 0.05	
$\alpha = (K_m^{app} \times \alpha') / K_m$		2.63	4.79	6.65		2.34	3.87	
$\alpha' = V_{max} / V_{max}^{app}$		1.04	1.13	1.29		1.08	1.23	
$K_I = [I] / (\alpha - 1)$		55.21	47.54	53.10		59.86	69.68	57.08
(nM)								± 8.32
$K_{SI} = [I] / (\alpha' - 1)$		2250.40	1337.72	1034.48		1071.42	869.57	1312.72
(nM)								± 550.43

B. Kinetic parameters of tyrosinase monophenolase activity inhibition by glabridin.

[Glabridin] (nM)	Dopachrome (DC) formation				Oxygen (O ₂) consumption ^a			average
	0	15	37	50	0	20	40	
V_{\max} or V_{\max}^{app} ($\mu\text{M}/\text{min}$)	9.00 ± 0.12	8.26 ± 0.60	7.80 ± 0.24	7.56 ± 1.20	8.4 ± 0.06	7.92 ± 1.20	7.62 ± 1.38	
K_m or K_m^{app} (mM)	0.18 ± 0.01	0.29 ± 0.04	0.61 ± 0.03	0.97 ± 0.20	0.17 ± 0.02	0.39 ± 0.06	0.65 ± 0.08	
$\alpha = (K_m^{\text{app}} \times \alpha') / K_m$		1.78	3.86	6.25		2.43	4.21	
$\alpha' = V_{\max} / V_{\max}^{\text{app}}$		1.09	1.15	1.19		1.06	1.10	
$K_I = [I] / (\alpha - 1)$ (nM)		19.23	12.95	9.53		13.99	12.46	13.63 ± 3.54
$K_{SI} = [I] / (\alpha' - 1)$ (nM)		166.67	239.81	267.42		333.34	400.30	281.51 ± 89.34

317 ^a V_{\max} or V_{\max}^{app} refer to not inhibited and inhibited assays, respectively, and K_m or K_m^{app} refer to
318 not inhibited and inhibited assays, respectively. Data were obtained both by UV-vis
319 spectrophotometry and by oximetry. V_{\max} or V_{\max}^{app} were calibrated by using the stoichiometry ratio
320 of 1.5 for O₂/DC with substrate L-tyrosine and of 1.0 for O₂/DC with substrate L-DOPA.

321

322 Glabridin shows very potent activity in inhibiting both monophenolase and diphenolase reactions
323 already at nanomolar concentration. Notably, spectrophotometry and oximetry afford results in
324 excellent agreement, despite the major difference between the techniques. Both show only minor
325 variation of V_{\max} in the presence of the inhibitor, which becomes noticeable only at the highest
326 concentrations, while K_m grows significantly with glabridin's concentration. This provides
327 confirmation of the proposed mechanism (*vide supra*). Given the excellent agreement between results
328 from spectrophotometry and oximetry, the two sets of data were combined. Concerning the
329 mechanism of inhibition, it is also interesting to note that K_{SI} , quantifying the inhibition based on

330 interaction of glabridin (I) with the ES complex, is on average over 20-folds larger than K_I , describing
331 the competitive inhibition (interaction of I with E), both for monophenolase and diphenolase activity.
332 This roughly indicates that less than 5% the inhibition by glabridin is due to binding to ES *i.e.* to
333 uncompetitive behavior. For most of its activity glabridin competes with substrate (L-tyrosine or L-
334 DOPA) for the enzyme's active site in a classical competitive mode with K_I values of 13.63 ± 3.54 nM
335 and 57.08 ± 8.32 nM, respectively. This is at variance with the previously reported mechanism. Most
336 notably, the absolute values of K_I are four orders of magnitude lower than previously reported (!) for
337 inhibition of mTY monophenolase and diphenolase reactions (Nerya et al, 2003), indicating much
338 higher activity and supporting the reputation of glabridin as one of the most potent natural mTY
339 inhibitors.

340 To validate our kinetic measurements, particularly in the light of the major difference with
341 previous literature, we extended the study to kojic acid, which is often used as reference inhibitor.
342 As expected, kojic acid afforded good inhibition at micromolar concentration, with excellent
343 agreement between the kinetics of DC formation and O_2 consumption. Both methods converged
344 showing mixed type inhibition when the substrate was L-dopa with K_I and K_{SI} values of 9.91 ± 1.42
345 μ M and 20.97 ± 5.23 μ M, respectively, while inhibition is nearly competitive with L-tyrosine, with K_I
346 = 10.91 ± 0.99 μ M (see Figure S5 S6 and Table S3 in Appendix for full details) in good agreement
347 with previous literature (Chen, Wei, Rolle, Otwell, Balaban, & Marshall, 1991; Kim et al, 2002; Deri
348 et al., 2016).

349 Values measured here support the reportedly much higher activity of glabridin, which
350 outperforms kojic acid by 3 orders of magnitude for monophenolase inhibition and by 2 orders of
351 magnitude for diphenolase inhibition.

352

353

354 *3.5 Determination of IC₅₀ (half-maximal inhibitory concentration)*

355 In enzymology, inhibitors are usually described in terms of inhibition type and inhibition
356 constant, as we have discussed in the foregoing. This is the most valuable approach since it has a
357 clear connection with the inhibitory mechanism and offers quantitative kinetic bases, allowing full
358 comparison among different inhibitors and lab-to-lab transferability. However, enzyme inhibition is
359 of crucial importance also in pharmacology and in other disciplines, where focus is more on the
360 consequences of inhibition than on its mechanism. Therefore, it is most common to see the inhibition
361 performance being reported in the literature as IC₅₀ values. The IC₅₀ indicates the concentration of an
362 inhibitor that is able reduce the rate of enzyme reaction to 50% the value observed in the absence of
363 the inhibitor, under the same conditions. A dose-response diagram is used to track the effect of
364 inhibitors on the initial rate of enzymatic reaction at a fixed concentration of substrate, according to
365 Langmuir isotherm equation (eq. 9) (Copeland, 2000).

366
$$\frac{V_I}{V_0} = \frac{1}{1 + \frac{[I]}{IC_{50}}} \quad (9)$$

367 The IC₅₀ values of glabridin mTY inhibition against substrates L-tyrosine and L-DOPA at
368 different substrate concentration are reported in Table S4 (Appendix). It is clearly possible to see the
369 positive correlation between the IC₅₀ value and the concentration of substrates (see Figure 5), as it is
370 expected for inhibitors which are not purely noncompetitive (Copeland, 2000). Once again, the
371 agreement between values obtained by spectrophotometric monitoring of DC and those from oxygen
372 uptake kinetics was excellent, therefore they were averaged to afford more robust reference data
373 (Table S4 and Figures S7 and S8 in Appendix). A similar behaviour was recorded for kojic acid (see
374 Table S5 and Figures S9 and S10 in Appendix). The dependence on experimental settings somewhat
375 limits the usefulness of IC₅₀ in quantifying inhibitors' performance; thus, they were determined here
376 mainly as a reference to compare with current literature. IC₅₀ values measured for kojic acid, were in
377 good agreement with previous literature *e.g.* they were respectively 32.8±6.5 μM and 17.0±3.4 μM
378 for monophenolase and diphenolase activity with 1 mM substrate (see Table S5 for full data set) *vs*

379 reference 54 and 58 μM , respectively, with 1.8 mM substrate (Chang, Ding, Tai & Wu, 2007) or
380 12.24 μM against 0.7 mM L-tyrosine (Shao et al, 2018), and 19.2 against 0.5 mM L-DOPA (Song et
381 al. 2021). Instead, for glabridin, the IC_{50} measured with both substrates (L-tyrosine and L-DOPA) are
382 significantly smaller, compared to most literature data, which already contradict each-other spanning
383 over orders of magnitude: *e.g.* 2.93 μM against 1 mM tyrosine and 25.5 μM against 6 mM DOPA
384 (Yamauchi et al. 2011) to 0.09 μM against 1.2 mM tyrosine and 3.9 μM against 7 mM DOPA (Nerya
385 et al. 2003).

386 <Figure 5 about here>

387 At 1 mM substrate the IC_{50} values for glabridin, averaged between O_2 sensing and
388 spectrophotometry, were 79.5 ± 6.9 nM and 257.0 ± 12.7 nM, respectively, for monophenolase and
389 diphenolase activities. Hence, they agree with Nerya et al. (2003) only for inhibition of
390 monophenolase activity. For competitive inhibitors (or nearly competitive, like glabridin) the Cheng
391 and Prusoff's linear correlation described by eq. 10 is expected between the IC_{50} and the concentration
392 of substrate (Copeland, 2000), therefore a plot of IC_{50} vs $[\text{S}]$ should have intercept on the Y-axis
393 corresponding to K_i . Plots of Figure 5 have intercepts at 12 nM and 60 nM (spectrophotometry), and
394 14 nM and 65 nM (O_2 uptake), while the plots from averaged data (Figures S7 and S8) intercept the
395 Y-axis at 13 nM and 62 nM for monophenolase and diphenolase inhibition, hence they are fully
396 consistent with the K_i values for glabridin (independently determined from non-linear M-M fittings)
397 reported in Table 1, standing for the reliability of our current measurements.

$$398 \quad \text{IC}_{50} = K_i + \frac{K_i [\text{S}]}{K_m} \quad (10)$$

399 Interestingly, our IC_{50} values for glabridin are two-three orders of magnitude lower than values
400 recorded for kojic acid, for monophenolase-diphenolase inhibition, again supporting the reputation
401 of glabridin as one of the most effective natural tyrosinase inhibitors.

402

403 *3.6 Is glabridin a substrate for mTY?*

404 Several molecules with reported anti-tyrosinase activity have also been found to act as alternative
405 substrates for mTY. This is because mTY is a polyphenol oxidase (PPO) enzyme with no strict
406 specificity for only one substrate. Particularly, inhibitors with a relevant ability to access the enzyme's
407 active site (*e.g.* competitive inhibitors), with a non-hindered phenolic or polyphenolic structure, might
408 act as alternative substrates. For instance, this is the case for catechins (Seo, Sharma, & Sharma,
409 2003) caffeic acid, ferulic acid, neohesperidin and other phenolic compounds (Mayr et al. 2019).
410 Transformation of the inhibitor could form species with a UV-Vis spectrum able to interfere with the
411 detection of dopachrome, and it would cause a decrease of the effective inhibitor's concentration,
412 hence it could cause artefacts in the kinetic analysis of tyrosinase inhibition (Mayr et al. 2019). Since
413 glabridin is a phenolic compound, it cannot be excluded that it also acts as alternative substrate and,
414 to the best of our knowledge, this has never been assessed before. Incubation of mTY with glabridin
415 in the absence of other substrates showed no development of absorbance at 475 nm or in the UV-Vis
416 region when monitored spectrophotometrically (see Figure S11 in Appendix). This standard method
417 (Mayr et al. 2019) rules out interference in the spectrophotometrically measured enzyme kinetics (see
418 section 3.3), but it does not provide a conclusive proof of the absence of reaction, as it relies on the
419 formation of persistent, intensely absorbing products. To this end, we repeated the incubation of mTY
420 with glabridin 200 nM or 1 mM, under identical conditions used in the assays, in the absence of L-
421 tyrosine or L-DOPA, and monitored the reaction by our oxygen sensing method, recording no oxygen
422 uptake over 60 min (see Figure S12 in Appendix). Since the two tested concentrations of glabridin
423 correspond, respectively, to the highest level it was employed as inhibitor and the highest
424 concentration used for the natural substrate tyrosine, the absence of any detectable reaction allows to
425 exclude that glabridin acts as alternative substrate under our testing conditions. This study also
426 illustrates the distinctive usefulness of our real-time oxygen sensing approach.

427

428 **4. Conclusions and perspective**

429 A new method to investigate kinetics and inhibition of tyrosinase activity was described. It is
430 based on real-time sensing of oxygen via miniaturized NIR fluorescence probes, and showed to be
431 practical and reliable to investigate tyrosinase inhibition. When it was matched to the conventional
432 spectrophotometric approach, it proved to afford identical results. On the other hand, it offers higher
433 versatility, as it does not rely on the formation of specific products with characteristic UV-Vis
434 absorption. Therefore, it might prove of great value also to investigate the formation of allomelanins.
435 Its setup and operation is much simpler than other methods to analyse oxygen consumption in
436 solution, such as differential pressure transduction or electrochemical detection (Matera et al., 2015),
437 which makes it an ideal complement of conventional spectrophotometric approaches to improve
438 robustness and reliability in the study of tyrosinase inhibition, thereby favouring investigation in food
439 science.

440 With the help of this method, accurate quantitative analysis on the anti-tyrosinase activity of
441 glabridin were enabled, which prompted a revision of previously reported mechanism and kinetics.
442 Current results indicate that mTY inhibition by glabridin is of mixed type, with prevailing competitive
443 behavior both against substrate L-tyrosine and L-DOPA, affording, revised K_I values as 13.6 nM and
444 57.1 nM, for monophenolase and diphenolase inhibition, *i.e.* four orders of magnitude lower than
445 previously reported. These results, along with revised IC_{50} values in the nanomolar range (80 nM and
446 294 nM, respectively, at 1 mM substrate) allow settling the long-standing controversy on the actual
447 potency of this reference inhibitor, landing full support to the reputation of glabridin as one of the
448 most potent natural tyrosinase inhibitors, and offering a solid reference for future investigations in
449 food science.

450

451 **Declaration of interest**

452 The authors declare no competing financial interest.

453

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458

459 **Appendix A. Supplementary data**

460 Detailed description of instrument set-up and operation, tables and graphs of mTY inhibition by
461 Kojic acid, tables and plots of IC₅₀ values for glabridin and kojic acid, UV-Vis spectra and O₂ uptake
462 plots of glabridin incubated with mTY. Supplementary data associated with this article can be found,
463 in the online version, at ...

464

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Figures captions

608 **Figure 1.** (A) Oxidation of L-tyrosine and L-DOPA by oxygen catalysed by tyrosinase (TY),
609 and (B) tyrosinase inhibitors investigated in this study.

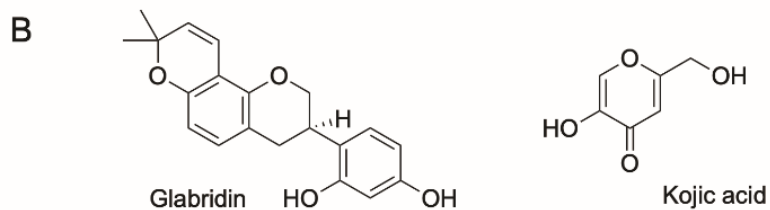
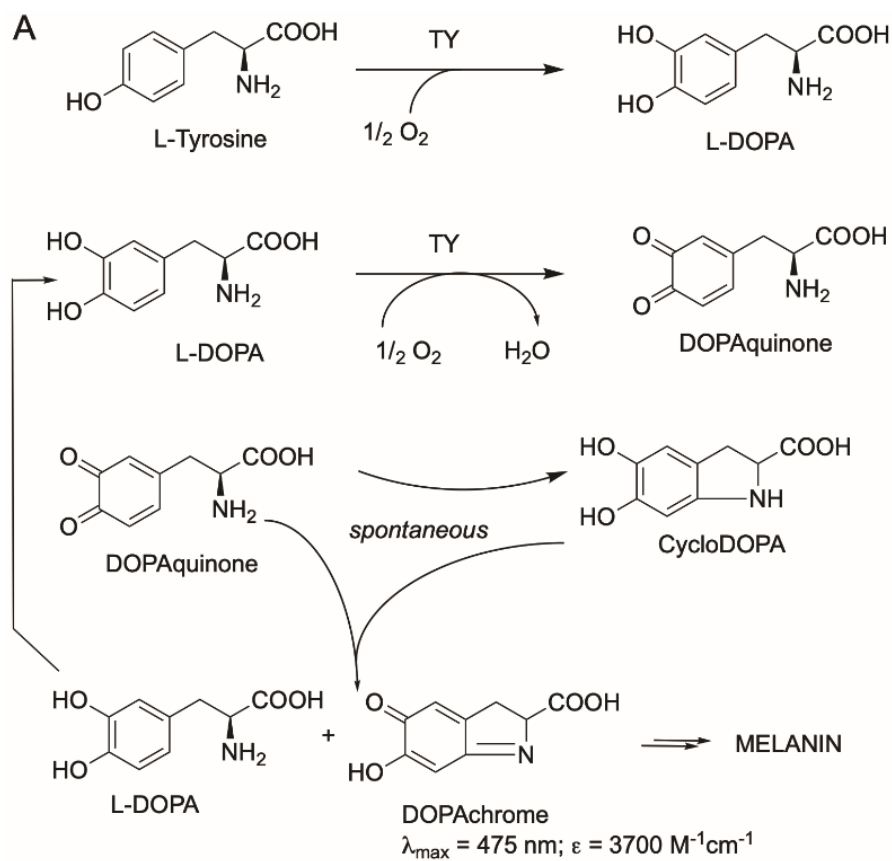
610 **Figure 2.** Time-course of dopachrome (DC) production (A, C) and O₂ consumption (B, D) during
611 the oxidation of L-dopa (A, B) and L-tyrosine (C, D) catalyzed by tyrosinase (3.85 U/ml for L-DOPA
612 and 7.70 U/ml for L-tyrosine). The inserts are the initial rates of O₂ consumption and DC formation
613 during the reaction fitted with Michaelis-Menten equation (solid lines).

614 **Figure 3.** (A, B) Representative traces of O₂ consumption (solid lines) and dopachrome (DC)
615 formation (dashed lines) during the oxidation of L-DOPA 1.6 mM (A: tyrosinase 3.85 U/mL); and
616 L-tyrosine 1.6 mM (B: tyrosinase 7.70 U/ml) at 30°C, pH 6.8. Regression lines were drawn using the
617 indicated (red) time-range. (C-F) Correlation of the stoichiometry of O₂ consumption to dopachrome
618 (DC) production during oxidation of L-tyrosine (A, B) and L-DOPA (C, D), as a function of: (A, C)
619 tyrosinase concentration at fixed substrate, and (B, D) substrate concentration at fixed enzyme.

620 **Figure 4.** Kinetics of mTY inhibition by glabridin at 30°C (pH = 6.8): non-linear Michaelis-
621 Menten fittings of diphenolase activity on L-DOPA (A, E) and of monophenolase activity on L-
622 tyrosine (B, F), studied by UV-Vis spectrophotometry (A, B) and oximetry (E, F). C, D, G and H are
623 the Lineweaver-Burk plots corresponding to A, B, C and D, respectively. Glabridin (Gla)
624 concentrations are indicated by the corresponding symbols in the plots. Enzyme concentration for
625 substrate L-dopa and L-tyrosine were 3.85 U/mL and 7.7U/mL respectively.

626 **Figure 5.** Dependency of IC₅₀ for glabridin inhibition of mTY on substrate concentration, both
627 for monophenolase (A) and diphenolase (B) reactions. Data (Table S4 in Appendix) were obtained
628 both by spectrophotometry and by oxygen sensing at 30°C (pH= 6.8).

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630

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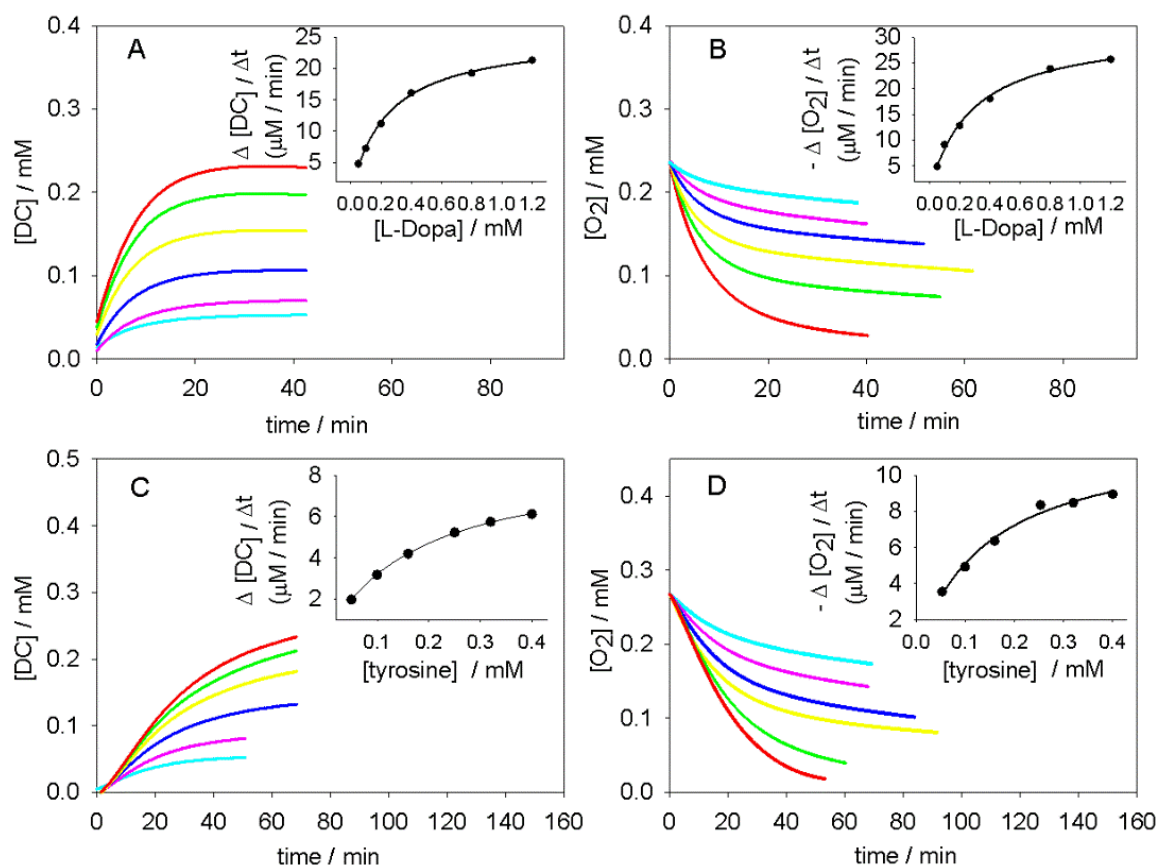
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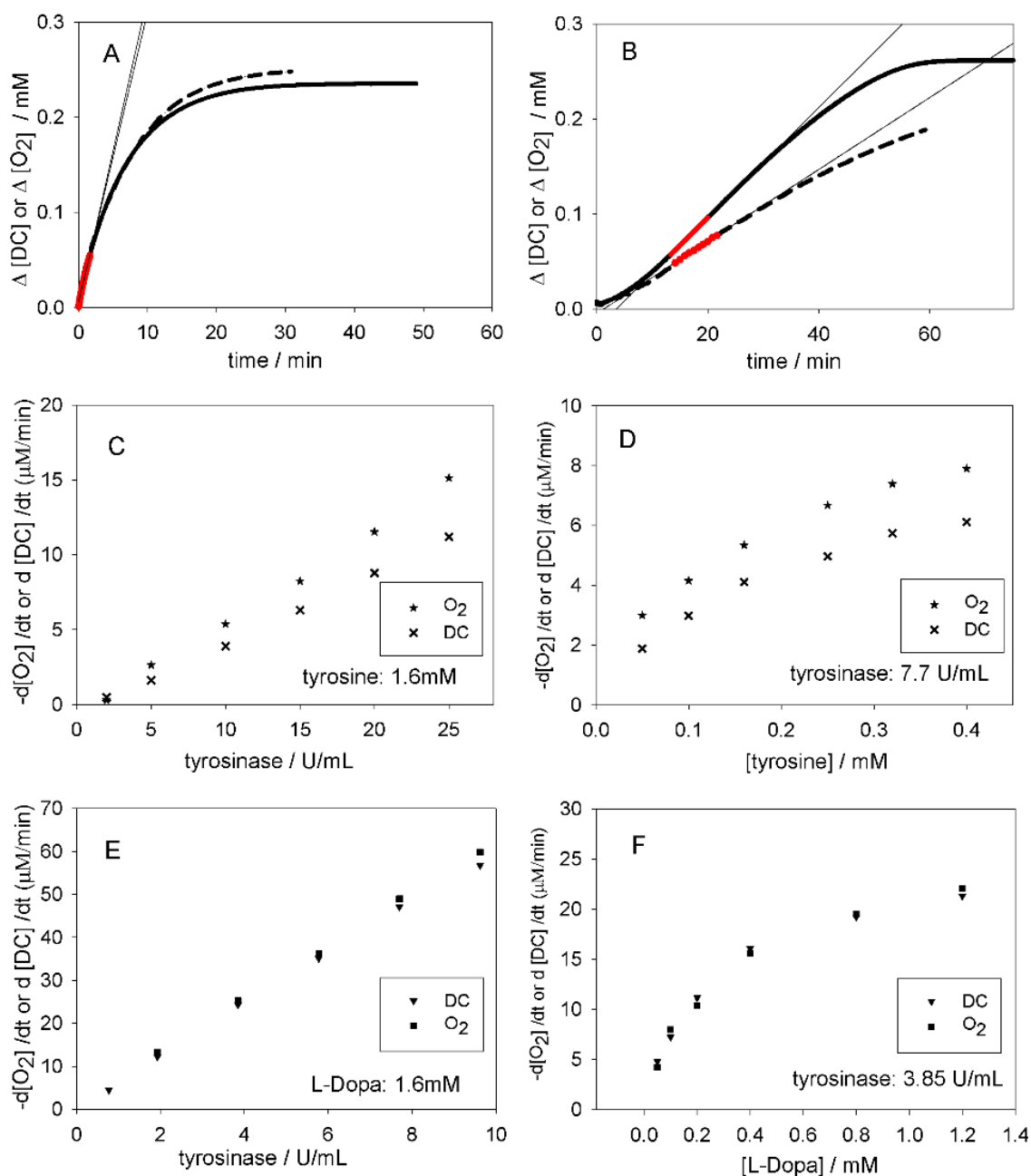
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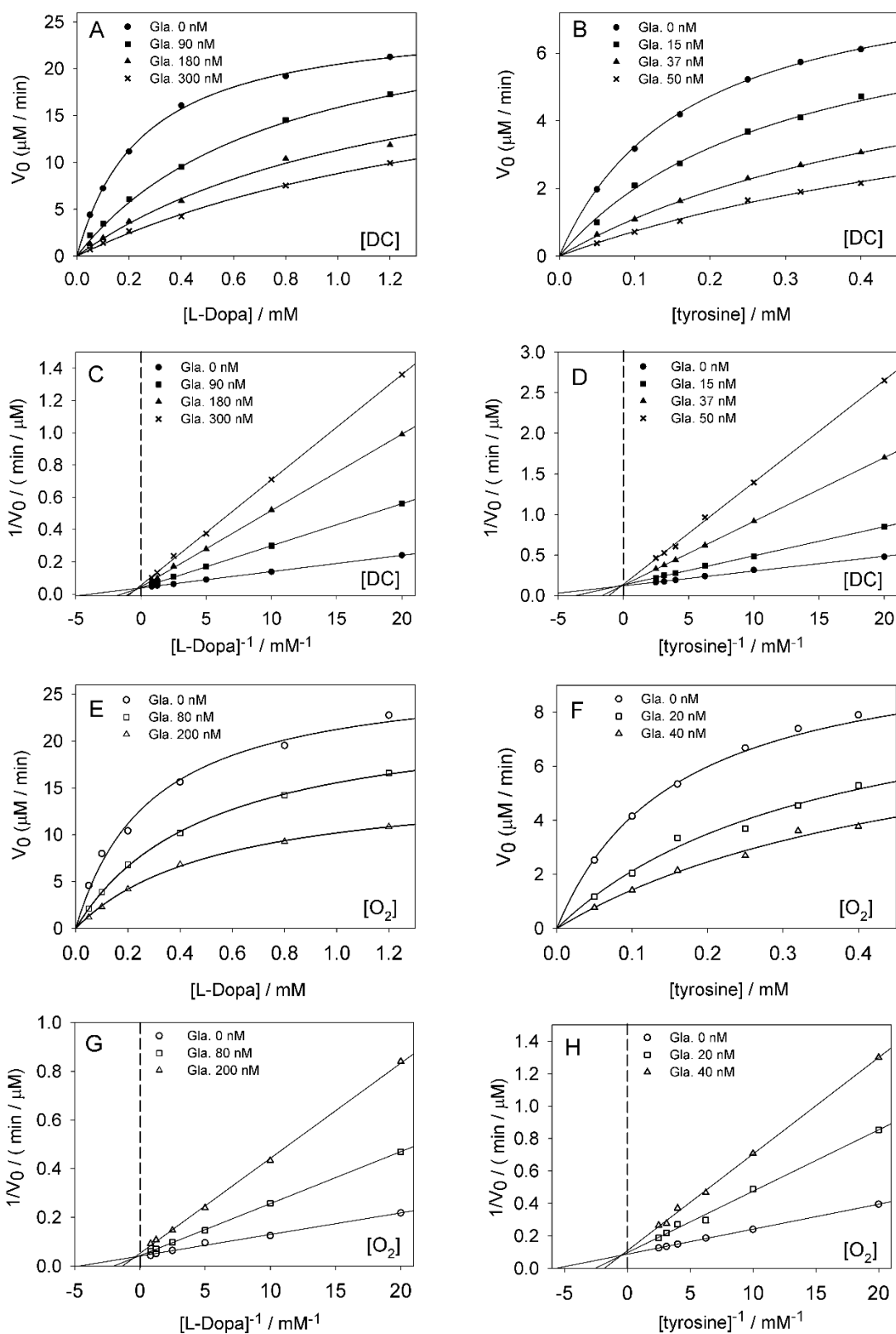
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651 **Figure 3.** (A, B) Representative traces of O_2 consumption (solid lines) and dopachrome (DC)
 652 formation (dashed lines) during the oxidation of L-DOPA 1.6 mM (A: tyrosinase 3.85 U/mL); and
 653 L-tyrosine 1.6 mM (B: tyrosinase 7.70 U/ml) at 30°C, pH 6.8. Regression lines were drawn using the
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 656 tyrosinase concentration at fixed substrate, and (B, D) substrate concentration at fixed enzyme.

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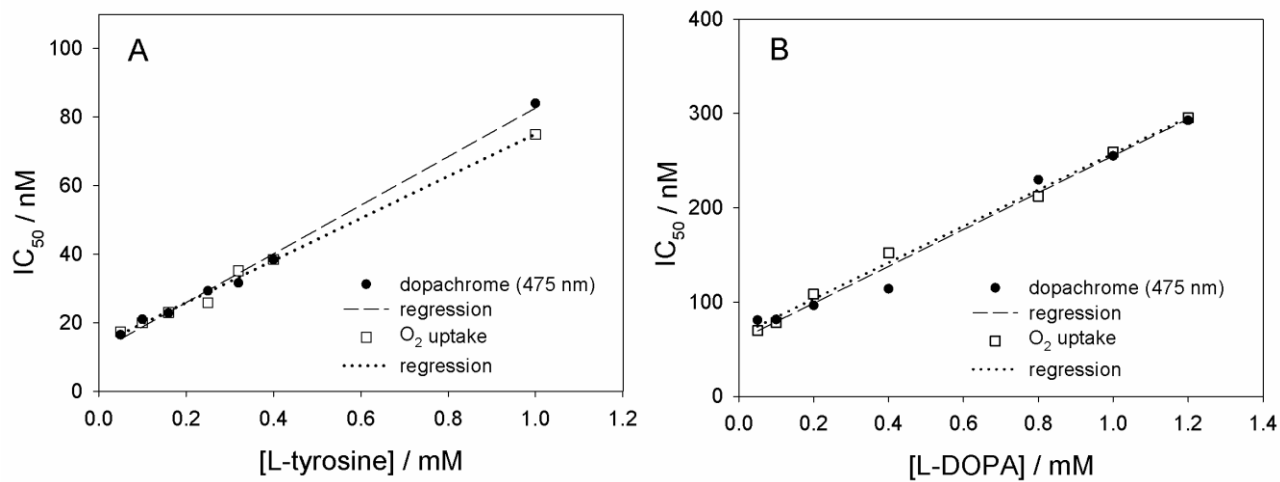


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659 **Figure 4.** Kinetics of mTY inhibition by glabridin at 30°C (pH = 6.8): non-linear Michaelis-Menten
 660 fittings of diphenolase activity on L-DOPA (A, E) and of monophenolase activity on L-tyrosine (B,
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668 **Figure 5.** Dependency of IC₅₀ for glabridin inhibition of mTY on substrate concentration, both for
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670 by spectrophotometry and by oxygen sensing at 30°C (pH= 6.8).

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Real-time oxygen sensing as a powerful tool to investigate tyrosinase kinetics allows revising mechanism and activity of inhibition by glabridin

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Setup of the real-time oxygen sensing equipment

The equipment setup is illustrated in Figure S1.

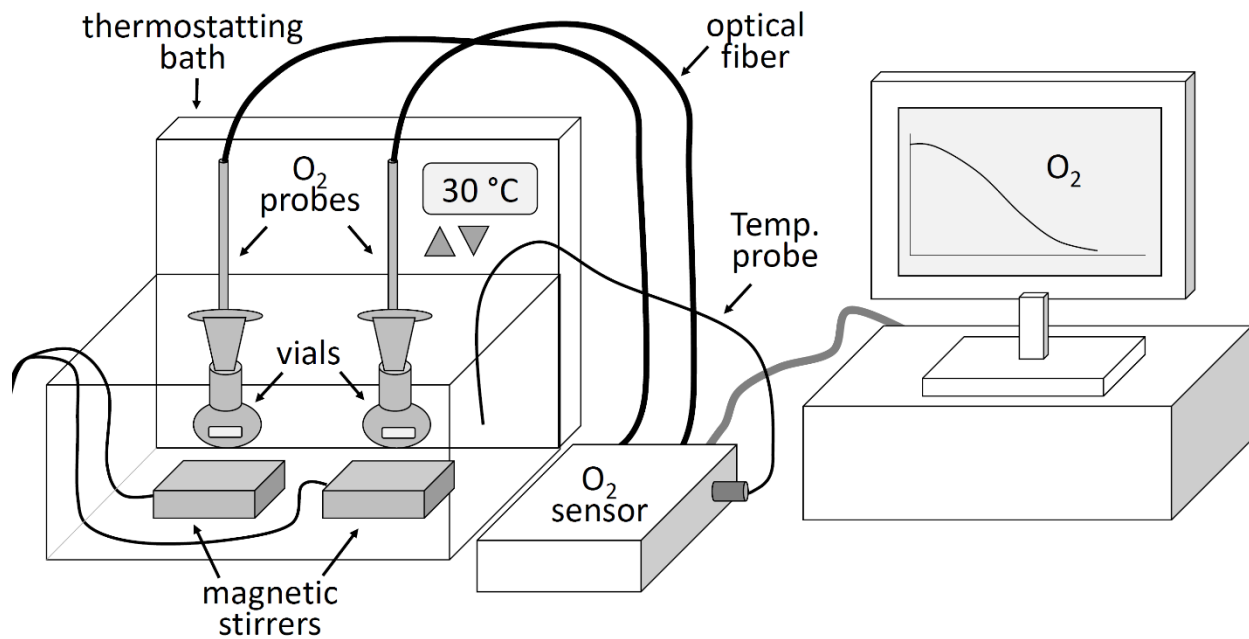


Figure S1. Scheme of the real-time oxygen sensing equipment (top) and images of the assembly of sample vials (int. volume 2.4 mL) with the oxygen probe sealed through the cap (bottom).

The equipment was set up using a commercial two channels Optical Oxygen Meter FireSting-O2 (model FSO2-2) connected via optical fibers to two IR fluorescence oxygen sensor probes (Robust type) contained in a 3 mm o.d. stainless-steel needle (Pyrosience GmbH, Bremen, Germany). The samples were contained in 2.4 mL glass flasks hand-made by a local scientific glass blower, sealed with a conical PP cap through which the O₂ sensor is inserted (after drilling the cap along the main axis) so that the sensor tip is protruding for about 3-4 mm inside the flask and is air-tight sealed. On closing the flask, care is taken to leave no air bubble, so that the entire volume is occupied by the (air-saturated) aqueous reaction mixture. The sample flask is provided with a PTFE-coated stirring bar and is completely submerged in a water bath controlled by Heto DBT Hethotherm (Birkerød, Denmark) thermostating unit. Mixing is provided by submerged sealed magnetic stirrers MixDrive 1XS controlled by an external Mix Control (2mag AG, Munchen, Germany). The oxygen meter is connected to a temperature sensor (immersed in the water bath) for automatic correction of the sensor response, and to a PC via USB port for data collection.

Protection of the oxygen sensing probe from organic components

The O₂ sensor probes are designed and indicated by the manufacturer for use in aqueous solution, in the bare form, i.e. without any protection. Since the content in organic material in our samples was very limited, in principle the probes could be used, as indicated, without protection. However, on performing multiple measurements with the same probes, we noted a progressive loss in sensitivity with time, which we attributed to the deposition of thin layers of insoluble melanin on the surface of the polymeric matrix containing the fluorescent dye, in the sensor tip (only the lower surface is exposed to the solution, while the rest of the matrix is protected by the stainless-steel structure of the probe). Such loss of performance could not be overcome by accurate cleaning of the surface without causing damage to the probe itself. Therefore, we decided to protect the tip of the probe by coating with a polymeric membrane, which would allow sufficient permeability to oxygen to produce no interference with the kinetic measurements.

In order to protect the oxygen probe, several polymeric membranes were comparatively tested in reference kinetic assays for oxygen consumption, namely: 1) the time-course of oxygen concentration in a freshly prepared solution of 8 mM Na₂SO₃ in distilled water; 2) the autoxidation

of 10% (v/v) tetrahydrofuran (THF) in aqueous phosphate buffer (pH 7.4) initiated by the thermal decomposition of 50 mM azobisamidinopropane dihydrochloride (AAPH) at 30°C; 3) the autoxidation of 0.15% (w/v) soy lecithin in aqueous phosphate buffer (pH 7.4) initiated by 75 mM AAPH at 30°C. Tested membranes were: a) silicon 500 μm ; b) LDPE 100 μm ; c) LDPE 25 μm ; d) LDPE/HDPE 12 μm ; e) Teflon[®] (PTFE) 100 μm ; f) Teflon[®] (PTFE) 76 μm . Among them, d) and f) offered the best compromise between oxygen permeability and mechanical properties: both offered no significant barrier to the consumption of oxygen at rates of ca. 0.1 mM/s, with measured rates of oxygen consumption differing less than $\pm 5\%$ with respect to the bare (uncoated) probe. Teflon[®] (PTFE) 76 μm was selected for our kinetic measurements with tyrosinase for its inertness.

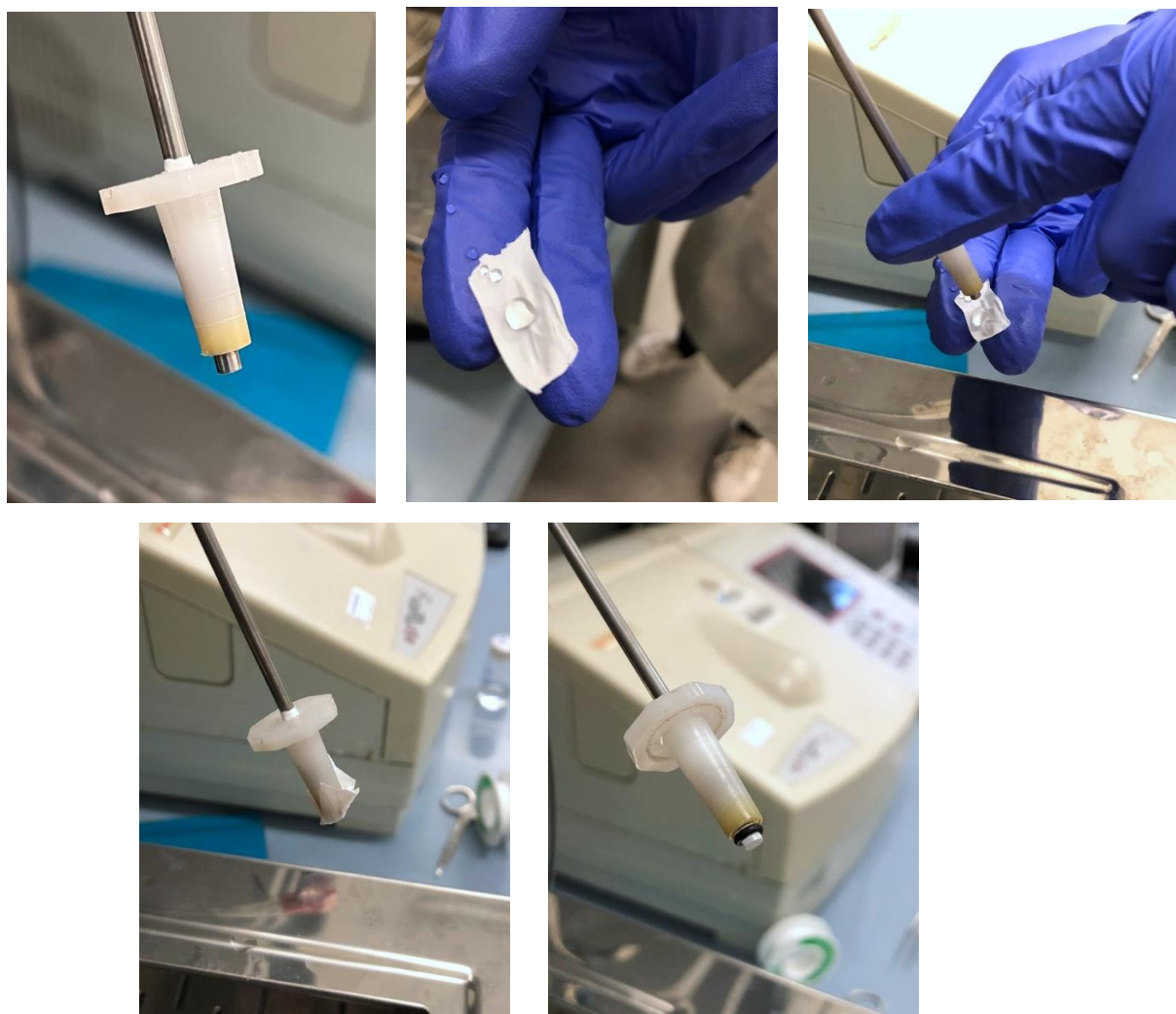


Figure S2. Stepwise procedure for coating the O₂ probe tip with a protective PTFE film (76 μm) held in place by an O-ring.

To guarantee reproducible measurements with no interference of the membrane, we found it is important to have both sides of the membrane “hydrated” *i.e.* in contact with water so that the diffusion of O₂ through the membrane follows the path water-membrane-water. To this end, we always took care of leaving a thin layer of buffered water (the same medium used for kinetic measurements) between the membrane and the lower (sensitive) surface of the oxygen probe. To do so, we applied a drop of buffer solution on the membrane and used it to obtain intimate adhesion of the membrane itself to the tip of the probe, then we fixed the membrane tightly in place with an O-ring, applied with the help of a micropipette tip (*e.g.* Gilson type), taking care of leaving no air bubble between the membrane and the tip of the probe, as illustrated in Figure S2. The membrane could be (gently) washed externally after every use and was replaced every day or every second day of experiments.

Measurements of mTY kinetics and inhibition

Oximetric evaluation of tyrosinase monophenolase and diphenolase kinetics was carried at 30°C by the real-time oxygen sensing equipment previously described. L-Tyrosine (0.05 – 1.0 mM) and L-DOPA (0.1 – 1.2 mM) were used, respectively as the substrate. Mushroom tyrosinase (3130 Units/mg; Sigma-Aldrich, Milan, Italy) solutions were prepared twice a week, stored at -20°C and checked on daily basis for activity, according to the manufacturer method (UV-Vis spectrophotometry), so to adjust dilution to the desired final activity. All activities were expressed in Sigma Units. The uninhibited reaction was monitored at different activity of the enzyme (1-25 U/mL). The raw data collected directly from the oxygen sensor is a percentage (P) of the oxygen saturation in the flask, corresponding to 0.236 mM at 30°C which reflects in the computer reading as 20%. Thus, the initial rate of the oxygen consumption (Table S1) was obtained by regression of the initial data range of oxygen consumption *vs* time using Sigmaplot software (Figure S3), upon converting the P value by the equation: $V (\mu\text{M/s}) = V (\Delta P / \Delta s) \times 0.236 \times 10^3 / P_0$ or $V (\mu\text{M/min}) = V (\Delta P / \Delta s) \times 0.236 \times 10^3 \times 60 / P_0$, as needed, to obtain the velocity in the desired units. In both equations P₀ is the oximetry reading value of the starting point, which usually is 20 after calibration of the oxygen sensor.

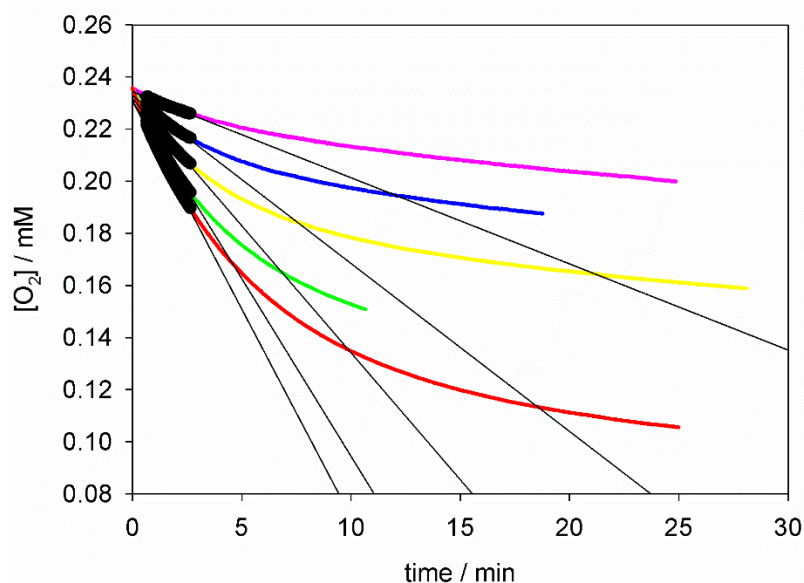


Figure S3. Example of time progresses of O₂ consumption during the oxidation of L-dopa at different initial concentration from 0.1 mM (purple line) to 1.2 mM (red line), inhibited by glabridin (80 nM). The black lines are the linear regression (*V*) for every L-dopa concentration, taken in the highlighted time range (40s to 160s).

Table S1. Example of rates obtained from the linear fitting by Sigamplot software of initial portions of oxygen consumption plots for different L-dopa concentrations (data from Figure S3).

[L-dopa] (mM)	0.1	0.2	0.4	0.8	1.2
<i>V</i> = slope of O ₂ uptake (μM/min)	3.429	6.812	10.186	14.227	15.755

Initial velocity was plotted against the corresponding concentration of the substrate (*e.g.* L-dopa for diphenolase reaction) to obtain the Michaelis-Menten plot (Figure S4), which was analysed by non-linear regression. The non-linear analysis was conducted by fitting of experimental data point with the hyperbola equation $y = \frac{a x}{b + x}$ using sigmaplot software, where *y*, *x*, *a* and *b* represent *V*₀, [S], *V*_{max} and *K*_m respectively, for uninhibited kinetics, thereby representing M-M equation. An example of fitting results is shown in Figure S4.

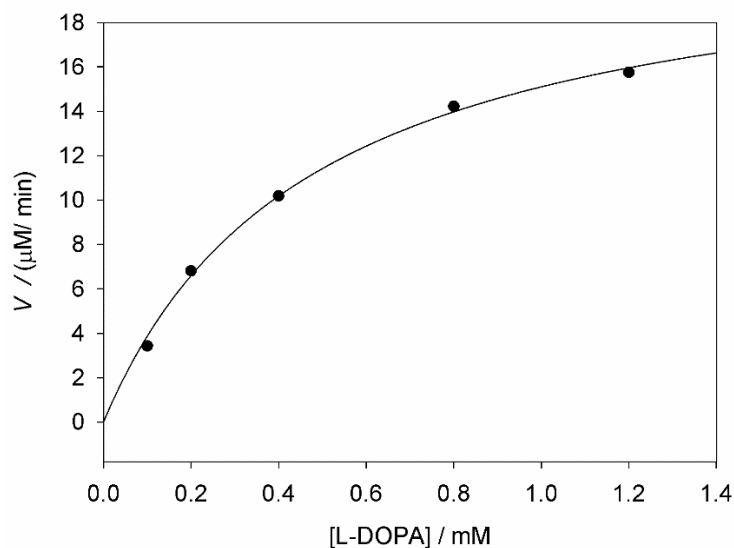


Figure S4. Example of plot of Initial rates of oxygen consumption during tyrosinase catalyzed oxidation of L-dopa and the corresponding non-linear fitting to Michaelis-Menten kinetics (data from Table S1).

Identical kinetic data collection and treatment was applied when using L-tyrosine as the substrate.

In this case the measured rate of O₂ consumption was divided by 1.5 to match with the rate of dopachrome (DC) formation, to account for the stoichiometric ratio of 1:1.5 of DC to O₂ for monophenolase reaction, as determined in matched kinetic measurements via the oxygen sensor and UV-Vis spectrophotometry (see main manuscript). No conversion was necessary for diphenolase reaction since the stoichiometric ratio DC to O₂ is 1:1.

For kinetic measurements in the presence of an inhibitor (Glabridin or Kojic acid), identical procedure was followed both for monophenolase and diphenolase reactions, using different concentrations of the inhibitor, for each set of measurements at different substrate concentration.

In data treatment with equation $y = \frac{ax}{b+x}$, y , x , a and b represent V , $[S]$, V_{\max}^{app} and K_m^{app} respectively, where the last two are, respectively, the apparent V_{\max} and K_m at each concentration of the inhibitor.

Table S2. Michaelis-Menten kinetics parameters measured both by UV-Vis spectrophotometry and by oximetry during uninhibited mushroom tyrosinase reaction at 30°C, pH=6.8.

activity	substrate	dopachrome formation		oxygen consumption	
		K_m (mM)	V_{max} ($\mu\text{M}/\text{min}$)	K_m (mM)	V_{max} ($\mu\text{M}/\text{min}$)
monophenolase	L-tyrosine	0.18±0.01	9.01±0.12	0.17±0.02	8.45±0.62
diphenolase	L-DOPA	0.26 ±0.02	25.80±0.53	0.24±0.02	24.18±0.96

Given the higher rate of the diphenolase reaction, the V_{max} of this process was calculated at the beginning of the process (between $t=0$ and $t=3$ min), while monophenolase activity was evaluated between 3 and 15 min, to skip the initial lag phase.

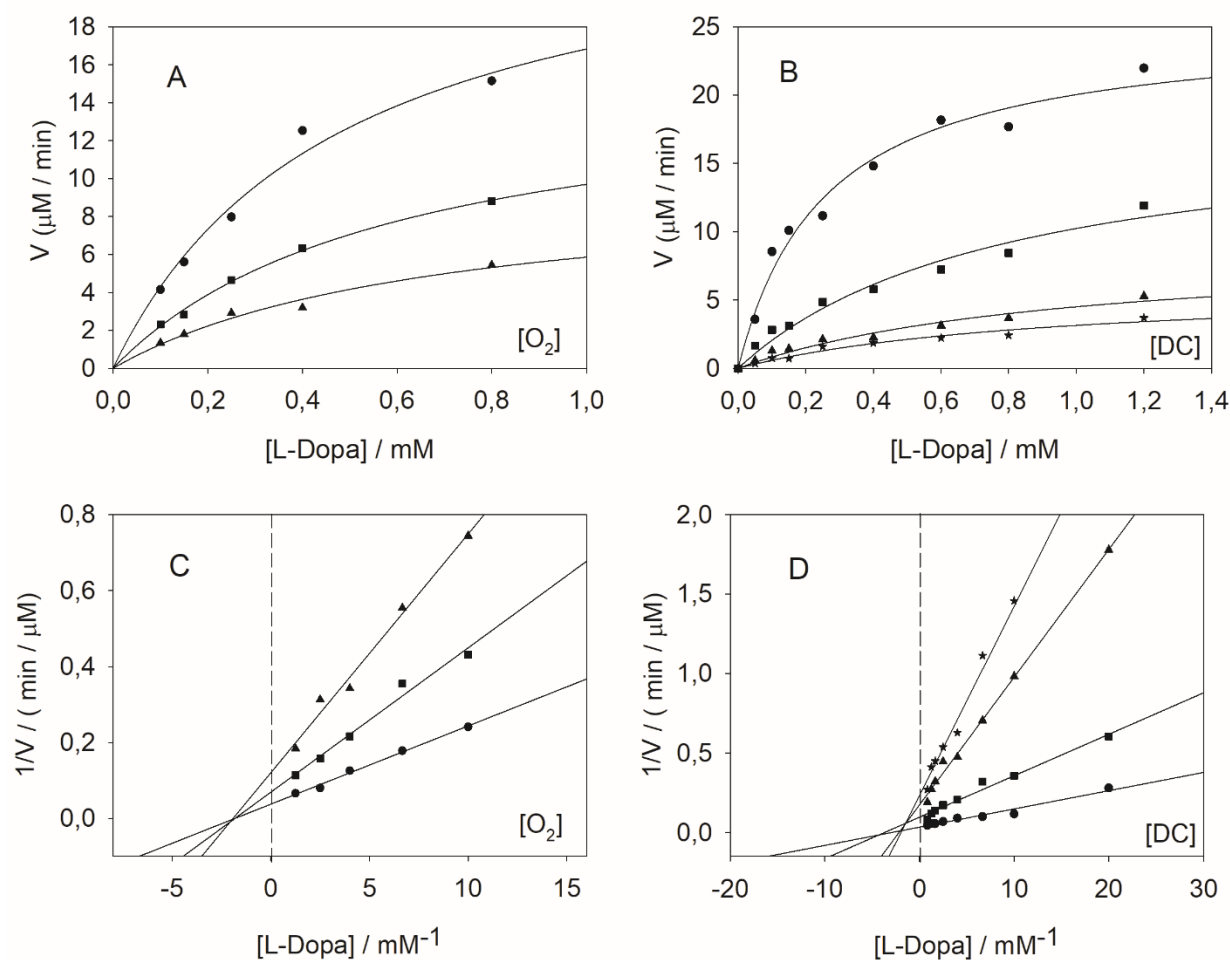


Figure S5. Non-linear fittings (A and B) of Michaelis-Menten kinetics for kojic acid inhibition of diphenolase tyrosinase activity and (C and D) the corresponding Lineweaver–Burk linear fittings. Data were obtained both by oximetry (A, C) and UV-Vis spectrophotometry (B, D): (A, C) kojic acid concentrations: ●-0 μM , ■- 20 μM , ▲-50 μM ; (B, D) kojic acid concentrations: ●-0 μM , ■- 20 μM , ▲-50 μM , ★-100 μM . Enzyme concentration for substrate L-dopa was 3.85 U/ml, all experiments were conducted at pH 6.8 and 30°C. The rate of reaction V was evaluated from the initial portion (between $t=0$ and $t=2$ min) of the plot in each experiment.

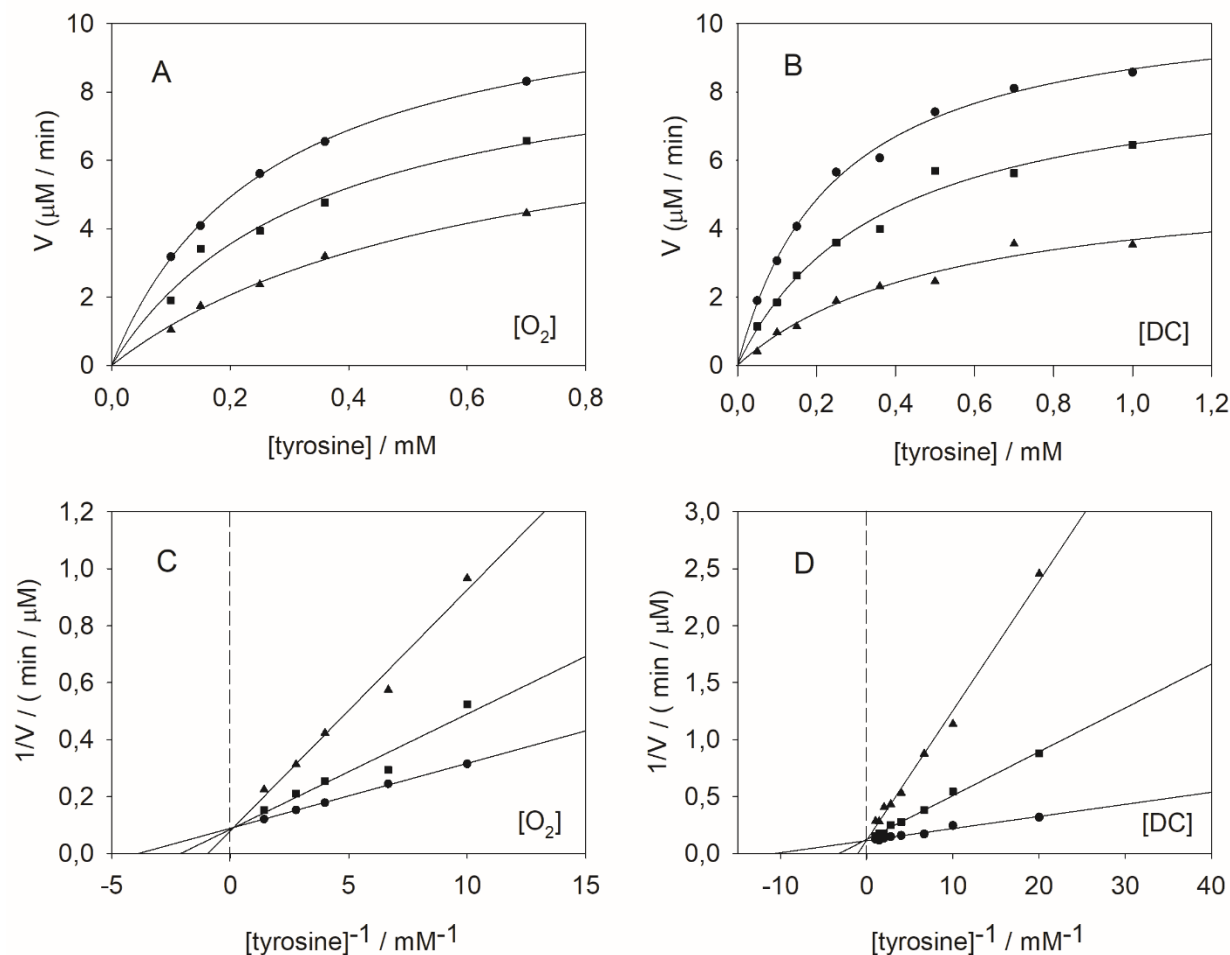


Figure S6. Non-linear fittings (A and B) of Michaelis-Menten kinetics for kojic acid inhibition of monophenolase tyrosinase activity and (C and D) the corresponding Lineweaver–Burk linear fittings. Data were obtained both by oximetry (A, C) and UV-Vis spectrophotometry (B, D): (A, C) kojic acid concentrations: ●-0 nM, ■- 16 μM, ▲-25 μM; (B,D) kojic acid concentrations: ●- 0 μM, ■- 10 μM, ▲- 30 μM. Enzyme concentration for substrate L-Tyrosine was 7.7 U/ml, all experiments were conducted at pH 6.8 and 30°C. The V of monophenolase activity was evaluated between 5 and 15 min.

Table S3. Kinetic parameters of tyrosinase activity inhibition by kojic acid at 30°C (pH= 6.8). Kinetics data were obtained by spectrophotometric monitoring of dopachrome (DC) or by real-time oxygen sensing (using the same procedure as for glabridin).

A. Kinetic parameters of tyrosinase diphenolase activity inhibition by kojic acid.								
	Dopachrome (DC) formation				Oxygen (O ₂) consumption			Average
[kojic acid] (μM)	0	20	50	100	0	20	50	
V_{\max} or V_{\max}^{app} (μM/min)	30.66 ± 1.74	13.2 ± 2.76	7.38 ± 1.8	5.07 ± 0.12	23.82 ± 3.6	13.62 ± 0.96	8.28 ± 1.34	
K_m or K_m^{app} (mM)	0.26 ±0.05	0.34 ±0.02	0.47 ±0.04	0.53 ±0.03	0.28 ±0.01	0.45 ±0.07	0.52 ±0.02	
$\alpha = (K_m^{\text{app}} \times \alpha') / K_m$		2.98	7.42	12.26		2.77	5.35	
$\alpha' = V_{\max} / V_{\max}^{\text{app}}$		2.32	4.17	6.04		1.73	2.88	
$K_I = [I] / (\alpha - 1)$ (μM)		10.08	7.79	8.89		11.30	11.50	9.91 ±1.42
$K_I = [I] / (\alpha' - 1)$ (μM)		15.12	15.79	19.85		27.48	26.62	20.97 ±5.23
B. Kinetic parameters of tyrosinase monophenolase activity inhibition by kojic acid.								
	Dopachrome (DC) formation			Oxygen (O ₂) consumption ^a			Average	
[kojic acid] (μM)	0	16	25	0	10	30		
V_{\max} or V_{\max}^{app} (μM/min)	8.94 ± 0.42	8.4 ± 0.66	7.98 ± 0.66	8.04 ± 0.96	7.5 ± 0.78	7.2 ± 0.48		
K_m or K_m^{app} (mM)	0.18 ± 0.02	0.36 ± 0.06	0.75 ± 0.12	0.26 ± 0.01	0.48 ± 0.09	1.07 ± 0.09		
$\alpha = (K_m^{\text{app}} \times \alpha') / K_m$		2.31	3.56		1.98	3.62		
$\alpha' = V_{\max} / V_{\max}^{\text{app}}$		1.06	1.12		1.07	1.12		
$K_I = [I] / (\alpha - 1)$ (μM)		12.25	9.78		10.17	11.45	10.91 ± 0.99	
$K_I = [I] / (\alpha' - 1)$ (μM)		266.67	208.33		142.85	250.00	216.96 ± 55.16	

Note: V_{\max} or V_{\max}^{app} refer to not inhibited and inhibited assays, respectively, and K_m or K_m^{app} refer to not inhibited and inhibited assays, respectively. Data were obtained both by UV-vis spectrophotometry and by oximetry method. V_{\max} or V_{\max}^{app} were calibrated by using the stoichiometry ratios 1.5 for O₂/DC for monophenolase reaction and 1.0 O₂/DC for diphenolase.

Table S4. IC₅₀ values calculated for mushroom tyrosinase inhibition by glabridin (at 30°C) at different concentrations of L-tyrosine and L-dopa substrates, both by spectrophotometric monitoring of dopachrome (at 475 nm) and by real-time oxygen sensing.

From UV-Vis. monitoring at 475 nm (diphenolase)							
[L-dopa] (mM)	0.05	0.10	0.20	0.40	0.80	1.00	1.20
IC ₅₀ (nM)	80.9	81.6	96.4	114.0	229.7	255.1	292.6
Error (±std.dev.)	±0.5	±3.5	±8.9	±10.1	±9.9	±8.4	±12.6
From real-time O₂ sensing (diphenolase)							
[L-dopa] (mM)	0.05	0.10	0.20	0.40	0.80	1.00	1.20
IC ₅₀ (nM)	69.8	78.4	108.3	152.4	201.1	259.0	295.7
Error (±std.dev.)	±0.6	±4.1	±10.5	±3.7	±3.3	±15.7	±33.4
Averaged between O₂ sensing and UV-Vis (diphenolase)							
[L-dopa] (mM)	0.05	0.10	0.20	0.40	0.80	1.00	1.20
IC ₅₀ (nM)	75.4	80.0	102.3	133.2	220.9	257.0	294.2
Error (±std.dev.)	±5.6	±4.1	±11.4	±20.6	±11.5	±12.7	±25.3
From UV-Vis. monitoring at 475 nm (monophenolase)							
[L-tyrosine] (mM)	0.05	0.10	0.16	0.25	0.32	0.40	1.00
IC ₅₀ (nM)	16.50	21.0	22.8	29.3	31.6	38.4	84.0
Error (±std.dev.)	±0.2	±0.8	±2.4	±2.4	±4.1	±3.9	±6.9
From real-time O₂ sensing (monophenolase)							
[L-tyrosine] (mM)	0.05	0.10	0.16	0.25	0.32	0.40	1.00
IC ₅₀ (nM)	17.4	20.0	23.0	25.9	35.2	38.5	75.0
Error (±std.dev.)	±0.2	±0.9	±4.9	±1.6	±4.3	±2.8	±7.1
Averaged between O₂ sensing and UV-Vis (monophenolase)							
[L-tyrosine] (mM)	0.05	0.10	0.16	0.25	0.32	0.40	1.00
IC ₅₀ (nM)	16.9	20.5	22.9	27.6	33.4	38.5	79.5
Error (±std.dev.)	±0.5	±1.0	±3.9	±2.7	±4.6	±3.4	±8.3

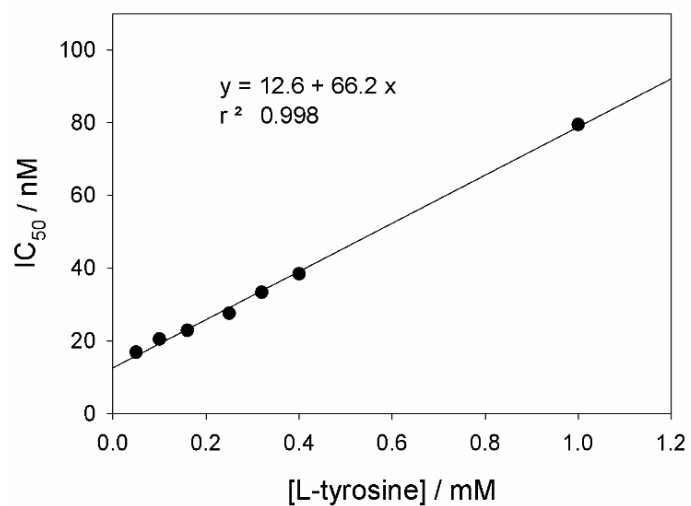


Figure S7. Dependency on the concentration of substrate of IC₅₀ for glabridin in the inhibition of monophenolase activity of mushroom tyrosinase at 30°C (pH= 6.8), averaged between spectrophotometric monitoring of dopachrome and real-time O₂ sensing (data from Table S3).

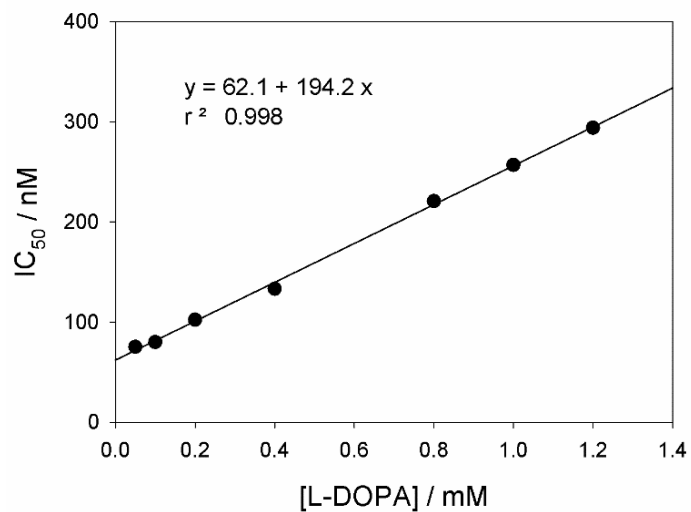


Figure S8. Dependency on the concentration of substrate of IC₅₀ for glabridin in the inhibition of diphenolase activities of mushroom tyrosinase at 30°C (pH= 6.8), averaged between spectrophotometric monitoring of dopachrome and real-time O₂ sensing (data from Table S3).

Table S5. IC₅₀ values calculated for mushroom tyrosinase inhibition by kojic acid (at 30°C; pH=6.8) at different concentrations of L-tyrosine and L-dopa substrates.

[L-dopa] (mM)	0.1	0.15	0.40	0.60	0.80	1.00	1.20
IC ₅₀ (μM)	9.4	8.3	12.1	12.5	15.8	17.0	19.9
Error (±std.dev.)	±2.1	±1.0	±2.7	±1.9	±2.6	±3.4	±3.9
[L-tyrosine] (mM)	0.05	0.10	0.15	0.25	0.36	0.7	1.00
IC ₅₀ (μM)	15.5	17.9	19.4	20.2	23.0	27.9	32.8
Error (±std.dev.)	±3.5	±2.9	±3.8	±2.4	±5.2	±4.4	±6.5

The IC₅₀ were determined from combined data by averaging UV-Vis and O₂ uptake experiments.

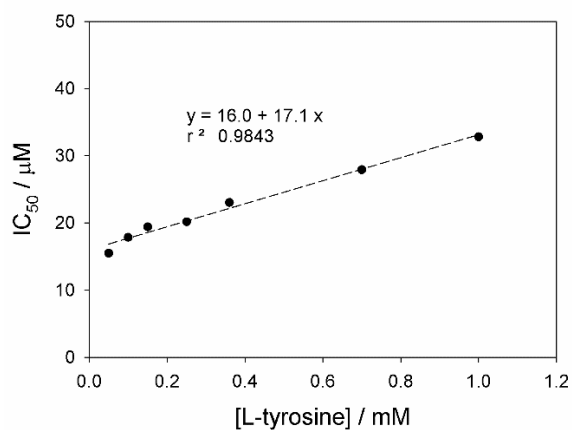


Figure S9. Plot of IC₅₀ vs the concentration of substrate (L-Tyrosine) for monophenolase inhibition of mushroom tyrosinase by Kojic acid at 30°C (data from Table S4).

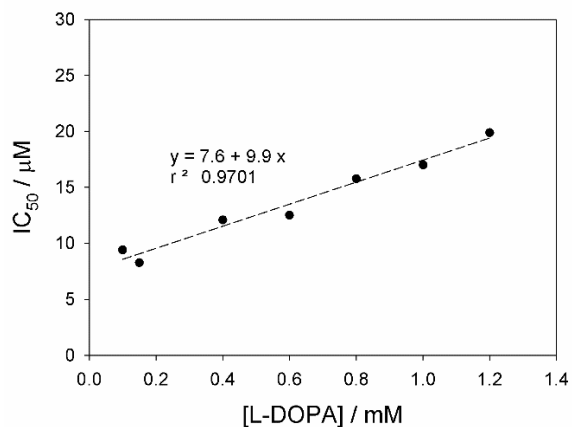


Figure S10. Plot of IC₅₀ vs the concentration of substrate (L-DOPA) for diphenolase inhibition of mushroom tyrosinase by Kojic acid at 30°C (data from Table S4).

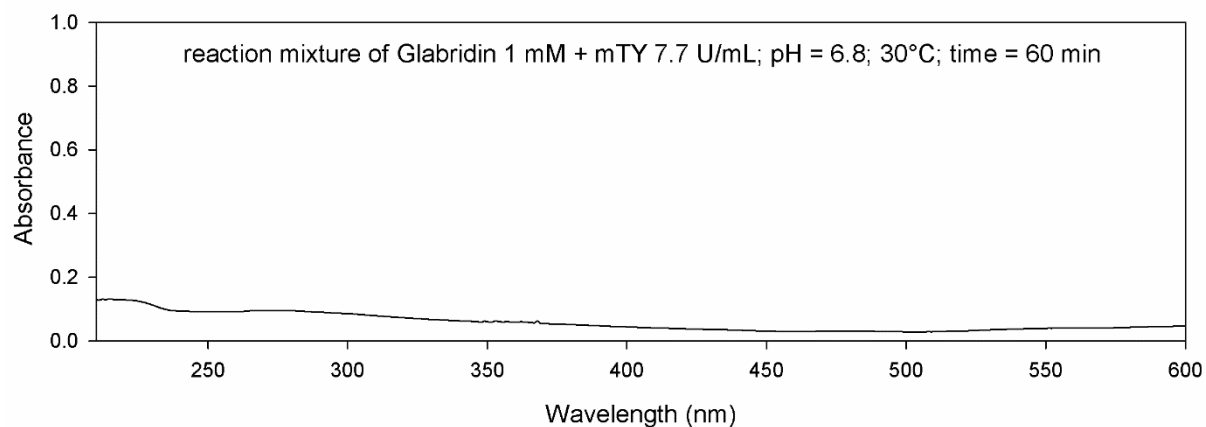


Figure S11. UV-Vis. difference spectrum obtained by subtracting from the spectrum of the reaction mixture composed by mushroom tyrosinase (7.7.U/mL) and 1 mM glabridin incubated at 30° for 1 hour (pH=6.8), the spectrum of glabridin at the same concentration in the same medium. No change or development of significant absorption suggests the absence of transformation of glabridin by the enzyme.

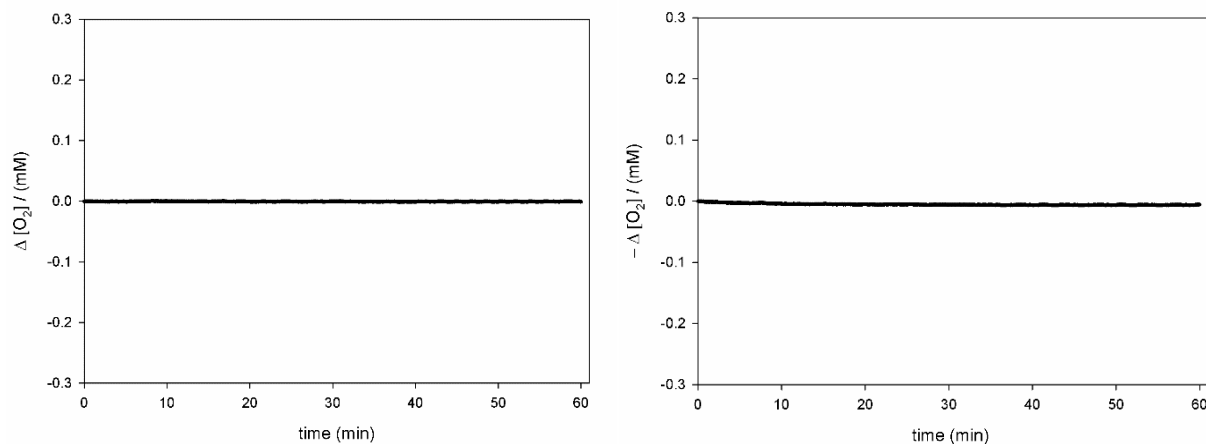


Figure S12. Oxygen consumption recorded by incubating mushroom tyrosinase (7.7.U/mL) with 200 nM glabridin (left panel) and 1 mM glabridin (right panel) at 30° for 1 hour (pH=6.8), in the absence of other substrates. No detectable oxygen consumption indicates no transformation of glabridin by the enzyme.