

1 **Effective killing of bacteria under blue-light irradiation promoted by green**
2 **synthesized silver nanoparticles loaded on reduced graphene oxide sheets**

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17 **Abstract**

18 Graphene oxide (GO) materials loaded with silver nanoparticles (AgNPs) have drawn
19 considerable attention due to their capacity to efficiently inactivate bacteria through a
20 multifaceted mechanism of action, as well as for presenting a synergetic effect against
21 bacteria when compared to the activity of AgNPs and GO alone. In this investigation,
22 we present an inexpensive and environmentally-friendly method for synthesizing
23 reduced GO sheets coated with silver nanoparticles (AgNPs/r-GO) using a coffee extract
24 solution as a green reducing agent. The physical and chemical properties of the produced
25 materials were extensively characterized by scanning electron microscopy (SEM), field-
26 emission gun transmission electron microscopy (FEG-TEM), ultraviolet and visible
27 absorption (UV-Vis), Raman spectroscopy, X-ray photoelectron spectroscopy (XPS),

28 inductively coupled plasma-optical emission spectroscopy (ICP-OES) and ion release
29 determination. The results demonstrated that AgNPs/r-GO composites were
30 successfully produced, revealing the formation of micrometer-sized r-GO sheets
31 decorated by AgNPs of approximately 70 nm diameter. Finally, bactericidal and
32 photobactericidal effects of the AgNPs/r-GO composites were tested against
33 *Staphylococcus aureus*, in which the results showed that the composites presented
34 antimicrobial and photoantimicrobial activities. Moreover, our results demonstrated for
35 the first time, to our knowledge, that an efficient process of bacterial inactivation can be
36 achieved by using AgNPs/r-GO composites under blue light irradiation as a result of
37 three different bacterial killing processes: (i) chemical effect promoted by Ag⁺ ion
38 release from AgNPs; (ii) photocatalytic activity induced by AgNPs/r-GO composites,
39 enhancing the bacterial photoinactivation due to the excited-Plasmons of the AgNPs
40 when anchored on r-GO; and (iii) photodynamic effect produced by bacterial
41 endogenous photosensitizers under blue-light irradiation. In summary, the present
42 findings demonstrated that AgNPs/r-GO can be obtained by a non-toxic procedure with
43 great potential for biomedical-related applications.

44 Keywords: Green synthesis; Silver nanoparticle; Reduced graphene oxide; Blue light
45 irradiation; Photoinactivation; *Staphylococcus aureus*.

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48

49 1. INTRODUCTION

50 Ag-based nanomaterials have attracted the attention in a wide variety of applications,
51 due to their unique chemical, biological, and physical properties, allowing their use
52 predominantly in health care and related fields [1–6]. Among the Ag-based compounds,
53 silver nanoparticles (AgNPs) are of special interest due to their high surface area and

54 specific Surface Plasmon Resonance (SPR) effect [7,8]. Chemical reduction is the most
55 frequently applied methods for the preparation of AgNPs in the form of stable colloidal
56 solutions in water or organic solvents [9]. However, AgNP production has to address
57 environmental issues and biocompatibility by using “green” methodologies because
58 toxic products such as citrate, borohydride, ascorbate, and H₂ are the most commonly
59 used reducing agents for the synthesis of AgNPs [10]. In this scenario, environmentally
60 friendly plant extracts, such as dried berries [5], seeds [11], leaves [12], and fruits [13]
61 have been proposed as efficient and clean chemical reductants for synthesizing AgNPs.
62 Recently, coffee extract was suggested as a natural reductant for the preparation of
63 AgNPs under room temperature conditions because it contains caffeine and polyphenols
64 in their chemical composition which drives the reduction of metallic Ag ions in water
65 [4,14,15].

66 Among several possible applications of AgNPs, their efficacy to inactivate both
67 Gram-positive and Gram-negative bacteria has been subject to increased attention
68 because AgNPs and Ag ions (Ag⁺) released by AgNPs present a multifaceted
69 mechanism of action against bacteria [16]. This allows AgNPs to efficiently kill
70 antibiotic-resistant bacteria as well as their multifaceted action makes difficult the
71 development of resistance by the bacteria [17]. The emergence of multi-drug resistant
72 bacteria has become one of the major challenges in public health as a consequence of
73 inappropriate and excessive use of antibiotics in clinics, hospitals, and animal and food
74 industries [18–20]. In this scenario, it is necessary to develop new technologies for the
75 treatment of multidrug-resistant bacteria [21–27]. Recent advances have demonstrated
76 that a wide range of nanomaterials can be used as inorganic antimicrobial agents [28].
77 For instance, microbial inactivation can be achieved by using functional nanomaterials

78 composed of silver, zinc, copper and metal oxide nanoparticles due to their unique
79 antibacterial properties [28].

80 The antibacterial effects of AgNPs are mainly attributed to Ag⁺ release from the
81 nanoparticle surface, which can penetrate into bacterial cells and, consequently, damage
82 or even kill the microorganisms by preventing their replication abilities [29,30]. The
83 Ag⁺ bactericidal mechanism is attributed to the combination of two interacting
84 processes: (i) the capacity of the ions to interact with thiol groups in proteins, inducing
85 their inactivation; and (ii) the ions' interaction with bacterial DNA, condensing the DNA
86 and preventing DNA replication [30].

87 Graphene oxide (GO) is formed by carbon sheets that have functional groups of
88 oxygen, leading to a good dispersion in polar solvents, for example in water [31]. This
89 feature enables the deposition of NPs on their surface, resulting in a composite material
90 that can be used in various applications [32–34]. Recent studies have demonstrated that
91 GO can be used as a platform for AgNPs, presenting high mechanical strength, large
92 surface area, fast charge transfer, and good biocompatibility [35]. It has also been
93 demonstrated that GO can present antibacterial properties [6,36] and there may exist a
94 synergism between Ag and GO when AgNPs are incorporated into GO, enhancing the
95 antibacterial properties of the GO/AgNPs composites [30]. Although the antibacterial
96 effect of GO/AgNPs may be higher than that of a single GO or AgNPs, the major
97 mechanism for bacteria-killing is still attributed to the Ag⁺ release [30].

98 Furthermore, in addition to the chemical bactericidal properties, AgNPs can act as
99 photobactericidal agents due to their capacity to absorb light in the visible range,
100 producing reactive oxygen species (ROS) by photodynamic processes [37]. The
101 photosensitizer properties of the AgNPs originate from the existence of the SPR band
102 due to the collective electron oscillations on the nanoparticle surface [7,8], which is

103 usually in the 400 to 490 nm range (blue region) when in a spherical shape. In fact, the
104 photoantimicrobial effect of AgNPs can take place as free electrons can be produced
105 during the SPR induced by the light irradiation, leading to a large amount of ROS and,
106 consequently, killing bacteria [38]. In addition, recent results have also demonstrated
107 that the photoinactivation activity of some nanoparticles can be enhanced when
108 anchored on GO sheets, allowing the free electrons originated from the NPs be rapidly
109 transferred to the surface of GO and then move through the nanosheets, where ROS are
110 produced [28,38–40]. It worth pointing out that this possibility of moving on the GO
111 surface enhances the probability of the free electron finding and interacting with
112 molecular oxygen and thus increasing the photoantimicrobial activity of AgNPs [38].

113 In this paper, we present an inexpensive, environmentally friendly process for
114 synthesizing AgNPs anchored on r-GO sheets by using a coffee extract solution as a
115 green reducing agent at room temperature. Bactericidal and photobactericidal activities
116 under blue-light irradiation of the AgNPs/r-GO composites were tested against
117 *Staphylococcus aureus* strain, revealing that a synergetic antimicrobial effect can be
118 obtained when compared to the results of AgNPs and r-GO. In fact, the present study
119 aims to present, for the first time that an efficient process of bacterial inactivation can
120 be performed using AgNPs/r-GO composites as a consequence of three different
121 bacterial killing mechanisms that can be achieved simultaneously by AgNPs/r-GO
122 under blue-light illumination, such as Ag⁺ ion release (chemical effect induced by
123 AgNPs), enhanced photoinactivation promoted by excited-Plasmons of the AgNPs
124 when anchored on r-GO (photocatalytic activity promoted by AgNPs/r-GO composites),
125 and blue-light photodynamic inactivation caused by bacterial endogenous
126 photosensitizers (photodynamic effect produced by bacterial endogenous
127 photosensitizers).

128 2. MATERIALS AND METHODS

129 **2.1. GO synthesis.** Before the composite synthesis, GO was prepared using the
130 modified Hummers' methods [31]. GO concentration was determined at 0.74 mg/mL (\pm
131 7.8 %) and used as a stock solution for all samples prepared in this work. More details
132 can be accessed in the Supplementary Material.

133

134 **2.2. Preparation and characterization of the coffee extract.** 400 mg of, as obtained,
135 black coffee powder (Brasileiro®, Brazil) was added to 50 mL of distilled water
136 (conductivity of 0.05 $\mu\text{S}\cdot\text{cm}^{-1}$) and heated up to 70°C for 20 min, under magnetic
137 stirring. After cooling to room temperature, the powder was removed using a filter paper
138 and thus the aqueous extract of black coffee was stored at 5-10°C for further
139 experiments. The chemical composition of the coffee extract was studied by high-
140 performance liquid chromatography (HPLC) in a Shimadzu equipment model
141 Prominence 20A with a quaternary pump, automatic sampler, and DAD detector. The
142 chromatographic method was developed and optimized in which the improved
143 conditions were: mobile phase methanol/water (60/40) at pH 3.0, chromatographic
144 column Eclipse C18 150 cm x 4.6 mm, 4.5 μm and a wavelength of 325 nm (caffeine)
145 and 350 nm (caffeic acid), flow of 0.6 mL $\cdot\text{min}^{-1}$, injection volume of 5 μL and oven
146 temperature of 400°C and analysis time of 8 minutes. The presence of caffeine and
147 caffeic acid was proven using a standard through analysis of the UV spectrum in the
148 wavelengths of 325 and 350 nm, respectively.

149

150 **2.3. Green synthesis of AgNPs.** AgNPs were prepared using the procedure reported by
151 Nadagouda and Varma [4] with few modifications. In brief, the AgNPs were produced
152 by adding 2 mL of a 0.1M AgNO_3 (99.5 % of purity) solution to 10 mL of coffee, kept

153 under magnetic agitation at room temperature and ambient pressure for 2h. After
154 preparation, the final solution was stored between 2 – 5°C.

155

156 **2.4. *In situ* synthesis of AgNPs/r-GO nanocomposites.** Two methods were used for
157 the synthesis of the AgNPs/r-GO composites. The first sample (AgNPs/r-GO_{#1}) was
158 prepared as follows: 2 mL of 0.1M AgNO₃ was added to 10 mL of the coffee solution
159 under agitation for 15 minutes. Next, 2 mL of the prepared GO solution was added to
160 the previous mixture. The reaction was maintained under stirring for 2h at room
161 temperature. The second sample (AgNPs/r-GO_{#2}) was prepared by changing the
162 procedure order, i.e., by first mixing and stirring the GO and coffee extract solutions for
163 15 min and then AgNO₃ solution (2 mL at 0.1M) was added and stirred for 2 h at room
164 temperature.

165

166 **2.5. AgNPs, GO and AgNPs/r-GO characterization.** The morphology of GO was
167 studied in a JEOL scanning electron microscope (SEM) model JSM6380-LV and in a
168 FEI field-emission gun transmission electron microscope (FEG-TEM) model Quanta
169 3D operated in the STEM mode. For the collection of images, GO samples were
170 dispersed in ethanol and sonicated for 20 min prior to depositing onto a holey carbon
171 copper grid and drying at room temperature. Morphological and crystalline features of
172 AgNPs and AgNPs/r-GO composites were investigated in a field-emission gun
173 transmission electron microscope (FEG-TEM) model JEM2100 operated at 200 kV. The
174 AgNPs or AgNPs/r-GO aqueous samples were dispersed in ethanol at room temperature
175 and then deposited onto a 400 mesh carbon-coated Cu grid. The histograms of the
176 nanoparticle size distribution, assuming a spherical shape were obtained from
177 measurements of more than 200 particles found in arbitrarily chosen regions of the grid.

178 The histograms of the NPs were fitted considering a normal distribution. Ultraviolet and
179 visible (UV-Vis) spectrophotometry was performed in the 200 - 700 nm range in a
180 PerkinElmer model Lambda 265. X-ray Photoelectron Spectroscopy (XPS) analyses
181 were performed using a conventional XPS spectrometer (Scienta Omicron ESCA+) with
182 a high-performance hemispheric analyser (EAC2000) with monochromatic Al K α ($h\nu$
183 = 1486.6 eV) radiation as the excitation source. The operating pressure during the
184 analysis was 10^{-9} Pa and XPS high-resolution spectra were recorded at constant pass
185 energy of 20 eV with a 0.05 eV per step. Peak positions were corrected by C 1s
186 adventitious carbon set at 284.8 eV using the CasaXPS software package for the
187 treatment of the acquired spectra. Raman spectra at room temperature were recorded
188 using an alpha 300 RA μ -Raman microscope (WITec, Ulm, Germany), in a
189 backscattering geometry with 600 $\text{gr}\cdot\text{mm}^{-1}$ holographic gratings, in the wavenumber
190 range between 100 and 1500 cm^{-1} . An argon ion laser operating at 633 nm was used as
191 an excitation source, being focused on the sample's surface by 20 \times objective (NA =
192 0.25). The Raman peak position was corrected using the reference mode of Si at 521
193 cm^{-1} . Ag concentration in the studied solutions was determined by using an ICP OES
194 iCAP 6300 Duo device (Thermo Fisher Scientific, Bremen, Germany), with an axial
195 and radial view, simultaneous detector CID (Charge Injection Device). Commercial
196 purity argon 99,996% (White Martins-Praxair) was used to purge the optics, plasma
197 generation, and nebulizer and auxiliary gas. All determinations by ICP OES were carried
198 out in plasma axial view under the following operational conditions: 1150 W RF power,
199 12 $\text{L}\cdot\text{min}^{-1}$ plasma gas flow rate, 0.50 $\text{L}\cdot\text{m}^{-1}$ nebulizer gas flow, 50 rpm analysis pump
200 rate, 15 s integration time. The Ag 328.068 nm emission line was used in all ICP OES
201 determinations. The linear dynamic range was between 0.20 – 5.00 $\text{mg}\cdot\text{L}^{-1}$, with $R^2 =$
202 0.9997. The limit of detection (LOD), calculated according to IUPAC's

203 recommendations (3 times the standard deviation of the blank (Sbl, n = 10) divided by
 204 the calibration curve slope (m)), was 0.002 mg L⁻¹ of Ag with a limit of quantification
 205 (LOQ = 10*Sbl/m) of 0.006. Ag⁺ ions liberation from the AgNPs, in distilled water, was
 206 also determined by dialysis experiments [41,42], using dialysis tubing with a molecular
 207 weight cut-off at 12,000 Da – with an approximate exclusion diameter of 2.5 nm –
 208 (Sigma-Aldrich). 5 mL of nanomaterial solution (AgNPs or AgNPs/r-GO_{#1} or AgNPs/r-
 209 GO_{#2}) containing 500 mg L⁻¹ of AgNPs filled the dialysis tubing; then, it was placed in
 210 a beaker containing 45 mL of distilled water, totaling 50 mL. The silver concentration
 211 in the filtrate solution was determined by collecting 5 mL of water from the beaker after
 212 48 h and determining the Ag content in a Thermo iCAP 6300 Duo ICP OES (Thermo
 213 Fisher Scientific). The Ag⁺ concentration was determined considering the Ag content
 214 before ultrafiltration. The rate constant of dissolution (K_d) was determined by using the
 215 dissolution curve model presented in Eq. 1, which is based in a first order kinetics model
 216 and usually used to obtain the Ag dissolution (Ag⁺ ions liberation) rate constant (K_d^{Ag⁺})
 217 [43–45].

$$218 \quad [A_g^+]_t = [A_gNPs]_o (1 - e^{-(K_d^{Ag^+})t}) \quad (1)$$

219
 220 where [A_g⁺]_t represents the concentration of Ag⁺ ions liberation at some point in time (t), after
 221 dissolution has started at an initial concentration of silver nanoparticles of [A_gNPs]_o. The
 222 determination of the reactive oxygen species (ROS) produced by the Ag-containing samples
 223 under blue-light irradiation was performed using a non-fluorescent marker, the 2',7'
 224 *Dichlorofluorescein diacetate* (DCFH-DA) (*Sigma Aldrich*), which is oxidized by interacting
 225 with ROS, forming a highly fluorescent molecule (DCF) [46,47]. Initially, a DCFH-DA stock
 226 solution was prepared in ethanol (5 mM). The DCFH-DA and Ag-containing sample were

227 placed in a quartz cuvette by diluting in distilled water to obtain a final solution containing a
228 concentration of 0.34 mM and 1.5 mg L⁻¹ of DCFH-DA and Ag, respectively. Then, the ROS
229 production was determined in real-time by exciting the samples at 470 nm and collecting the
230 emission between 500 and 600 nm. The first 10 min of ROS production was monitored in dark
231 conditions (chemical reaction), and then blue-light was turned on to determine ROS production
232 under illumination (photochemical reaction), as represented in Fig. S1 of the supplementary
233 materials. The same procedure was carried out with the control groups by testing the GO,
234 coffee and distilled water (H₂O - negative control). Finally, the rate constant of ROS production
235 (k_{ROS}) was estimated by using Eq. 2 as explained in detail in the supplementary material.

$$236 \quad -\frac{d[ROS]}{dt} = k_{ROS} [DCFH : DA][ROS] \quad (2)$$

237

238 **2.6. Bactericidal assay.** The experiments were performed using *Staphylococcus aureus*
239 strain ATCC 25923. The strain was maintained at -70 °C in Brain Heart Infusion (BHI)
240 containing glycerol (20% v/v). For bacterial suspension preparation, 40 μL of the
241 bacterial strain was added in 4 mL of BHI and kept in an oven at 37 °C for 24h. After
242 that, the bacterial solution was prepared to achieve the turbidity standard of 1.0 Mc
243 Farland. Then, 500 μL of the tested materials (AgNPs, GO, AgNPs/r-GO_{#1}, and
244 AgNPs/r-GO_{#2}) were diluted in 500 μL of a saline solution containing the bacterial
245 inoculum. Two control groups were also tested by using the coffee solution and distilled
246 water (H₂O - negative control) in which 500 μL of control solution (coffee or H₂O) was
247 added in 500 μL of a saline solution containing the bacterial inoculum. Consequently,
248 for all prepared samples the final concentration of bacterial solution achieved the
249 turbidity standard of 0.5 Mc Farland (1.5 x 10⁸ UFC.mL⁻¹).

250 The bactericidal assay was performed by adding the prepared sample solutions in an
251 incubator at 37 °C and collecting aliquots after 0.5, 1.0, 3.0, and 6.0 h for testing the
252 antibacterial activity of the samples as a function of the time. For this purpose, 200 µL
253 of each sample was collected and placed into a 96-well microplate; then a serial dilution
254 was performed until a dilution of 1:32. The total bacteria number was determined by the
255 spread plate method, using the Plate Count Agar (PCA) medium (Acumedia, Neogen,
256 Lansing, Michigan, USA) in which the colony-forming units (CFU) were counted 18 h
257 after the incubation at 37 °C.

258

259 **2.7. Photobactericidal assay.** The photobactericidal assay was carried out also using *S.*
260 *aureus* strain ATCC 25923 in which the strain was maintained at -70 °C in Müller
261 Hinton Broth containing glycerol (20% v/v). For bacterial suspension preparation, 40
262 µL of the bacterial strain was added in 4 mL of Brain Heart Infusion broth (BHI) and
263 kept in an oven at 37 °C for 24 h. Then, bacterial concentration was prepared to achieve
264 the turbidity standard 0.5 Mc Farland. After that, the investigated solution (H₂O, Coffee,
265 AgNPs, GO, AgNPs/r-GO_{#1}, and AgNPs/r-GO_{#2}) was diluted in 2 mL of a saline
266 solution containing the bacterial inoculum. The tested concentrations were 0.0 (negative
267 control), 50 ppm of Ag (AgNPs, AgNPs/r-GO_{#1}, and AgNPs/r-GO_{#2}), and 0.23 ppm for
268 GO (the GO concentration in the AgNPs/r-GO_{#1}, and AgNPs/r-GO_{#2} samples). After the
269 addition of tested solutions, the samples were placed in a shaker and agitated at 120 rpm
270 over 30 min. After the solutions incubation, the samples were separated into two groups:
271 one submitted to blue light irradiation (irradiated group) and another kept in the dark
272 (dark control group). 200 µL of each irradiated sample was placed in a 96-well and then
273 illuminated by using a homemade LED device (UFGD, Dourados, MS, Brazil) as a light
274 source. The samples were irradiated at 450 nm with a light intensity of 9.5 mW.cm⁻²

275 during 30, 45, and 90 min, corresponding to energy doses of 17.1, 25.7, and 51.3 J.cm⁻
276 ², respectively. Here it is important to stress that a low light intensity of 9.5 mW.cm⁻²
277 was designed in the present experimental setup to avoid heating the samples
278 (photothermal effect) during the irradiation process. Finally, the samples of both groups
279 (irradiated and non-irradiated) were submitted to a serial dilution until a dilution of 1:32.
280 The total bacteria number was determined by the spread plate method using the Plate
281 Count Agar (PCA) medium, and then the colony-forming units (CFU) were counted 18
282 h after the incubation at 37 °C. All measurements were performed in triplicate, and the
283 statistical analyses were performed, considering the adopted repetitions, and addressing
284 the CFU values obtained for the three light doses and dark control groups.

285

286 **2.8. Morphological evaluation of bacteria by scanning electron microscopy.**

287 Morphology and interaction of bacteria with the nanomaterials were investigated in a
288 scanning electron microscope (SEM, JEOL model JSM-6380LV). The experiments
289 were performed in the irradiated and non-irradiated AgNPs/GO composites containing
290 bacteria, as well as in the control samples (bacteria/water and bacteria/coffee only). All
291 experiments were prepared by dispersing the sample immediately after finishing the
292 bactericidal or photobactericidal assays (approx. 200 µL) into an Eppendorf containing
293 200 µL of a phosphate buffer solution (PBS) at pH 7.0. Then, the samples were
294 centrifuged several times at 3000 rpm for 5 minutes, discarding the supernatant. The
295 centrifugations were performed in PBS (three times), ethanol 70%, 80%, 90%, and
296 absolute ethanol, in this order. Finally, the precipitate was dispersed in absolute ethanol
297 and stored in the refrigerator. Pieces of glass coverslip (1 x 1 cm) were cut and cleaned
298 in water/soup, ethanol and acetone for 20 minutes each process, using a sonicator. The
299 glass substrates were painted with glutaraldehyde and held at ambient conditions

300 overnight for drying to further fix the bacteria/nanocomposites. After depositing onto
301 the glass surface, samples were coated with a thin gold layer using the sputter coater and
302 attached to the SEM sample holders by using conductive carbon tape. Images were taken
303 at the following conditions: 10 kV, spot size 10, and a working distance of 8 mm.

304

305 **2.9. DNA extraction and PCR amplification.** DNA was extracted from 150 μ L *S.*
306 *aureus* cells using the CTAB method as previously described [48]. PCR amplification
307 of a putative transcriptional regulator gene of *Staphylococcus aureus* was performed
308 using the primers Sa0836F (5'-GGCGCTTGTA AAAATTTTCGT-3') and Sa0836R (5'-
309 TGCGCAAAGTTTTATTGAACA-3') and the cycling conditions as previously
310 described [49]. PCR amplification was performed in 25 μ L reactions using a ABI Verity
311 Thermal Cycler (ThermoFisher) for 35 cycles. The reaction mixture consisted of
312 appTAQ RedMix (Appleton Woods Limited, UK), 400 nM of forward and reverse
313 primers and ~100 ng of template DNA. Reaction mixtures with no template DNA were
314 used as a negative control.

315

316 **2.10. Endogenous photosensitizer extraction and identification.** The bacterial extract
317 was obtained by performing the following steps, adapted from Mancini and Imlay
318 (2015) [50]: (i) 100 mL of bacterial cell suspension with an absorbance of 0.4 at 600 nm
319 (A₆₀₀) was prepared; (ii) The bacterial cell suspension was centrifuged at 7000g at 4
320 °C during 10 min; (iii) Bacterial cells in the pellet was washed in 20 mL pre-chilled PBS
321 and then resuspended in 10 mL of the same buffer; (iv) The resuspended solution was
322 adjusted, by adding PBS, to reach again an A₆₀₀ of 0.4 and, then, centrifuged at 7000g
323 at 4 °C for 10 min; (v) The cell pellet was resuspended in 1 mL of ethyl acetate/acetic
324 acid (3:1, v/v); (vi) The cells were lysed by sonication for 2 min on ice; (vii) Finally,

325 the cell debris was removed by centrifuging at 7000g at 4 °C for 10 min and then
326 collecting the supernatant. The obtained fluorescence spectrum of the bacterial extract
327 was determined and compared with the corresponding spectra of the protoporphyrin IX
328 and riboflavin, standard compounds purchased from Sigma-Aldrich that represent the
329 optical feature of porphyrins and flavins, respectively. The fluorescence spectra were
330 collected in the 500 to 750 nm range when excited at 450 nm with aid of a Shimadzu-
331 RF-6000 spectrofluorometer and using a quartz cuvette with four polished faces and an
332 optical path length of 1 cm.

333

334 **3. RESULTS AND DISCUSSION**

335 **3.1. AgNPs, GO and AgNPs/r-GO preparation and characterization**

336 Fig. S2 of Supplementary Information shows SEM and TEM images of GO obtained in
337 this work. It is observed the formation of a two-dimensional material in the form of
338 individual sheets with micrometric dimensions, in agreement with previous results in
339 the literature [31,51,52]. Nevertheless, sheets with lateral sizes ranging from 4 to 700
340 μm were observed, reveling a broad size distribution as can be seen in the histogram
341 presented in Fig. S2c. Fig. S2d shows the Raman spectrum of the GO sample contains
342 two main peaks centered at 1353 and 1598 cm^{-1} , which are attributed to D and G bands,
343 respectively[53–55]. The intensity ratio of these two vibrational bands (I_D/I_G) is
344 commonly used to distinguish the formation of GO and r-GO. The obtained intensity
345 ratio $I_D/I_G = 1.03$ is an assignment of GO formation [56]. After the preparation of the
346 AgNPs in the presence of GO by using the coffee extract solution as reducing agent, D
347 and G bands shifted to approx. 1330 and 1597 cm^{-1} for the composite #1 and 1335 and
348 1594 cm^{-1} for the composite #2 (Fig. S3), respectively. In addition, the intensity ratio
349 I_D/I_G increased to 1.13 and 1.09 for the composites #1 and #2, respectively, which

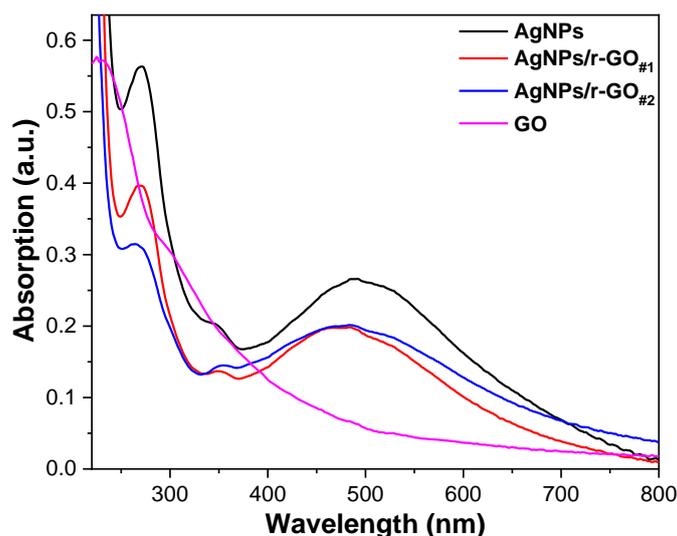
350 represents an increased degree of disorder. The higher I_D/I_G intensity ratio indicates the
351 GO chemical reduction[56,57]. Therefore, GO suffered reduction to r-GO during
352 AgNPs decoration and the composites hereafter are called AgNPs/r-GO. Furthermore,
353 the additional vibrational bands at 242, 816, 945, 1037, 1287, 1375 and 1586 cm^{-1} are
354 ascribed to the surface-enhanced Raman scattering (SERS) by organic molecules
355 present in the coffee solution adsorbed at the surface of AgNPs [58–61]. For instance,
356 the bands at 1287 and 1375 cm^{-1} are originated from the C–N stretching vibrations with
357 contributions from ring bending and ring C–H bending vibrations; the peaks at 1586 and
358 1030 cm^{-1} are attributed to the ring C–C and C–H (with contributions from C–O)
359 stretching vibrational modes[60–62], respectively; and the vibrations at 816 and 945 cm^{-1}
360 are probably due to the presence of carotenoids [59–61,63]. Finally, the vibrational
361 band at 544 cm^{-1} arises from the Si substrate.

362 It is worth noting that r-GO is usually obtained by using highly toxic and hazardous
363 chemicals such as hydrazine, di-methylhydrazine, hydroquinone, sodium borohydride,
364 etc., which introduce several harmful effects on the environment and human health even
365 at trace amounts. Consequently, by-products from the toxic reducing agents may be left
366 behind during the synthesis process, can cause adverse effects and have to be avoided
367 during a medical application or treatment. Therefore, our results show that the coffee
368 extract acts as a green reducing agent for both silver nitrate and GO, resulting in the
369 environmentally friendly production of AgNPs/r-GO composites in a simple and non-
370 toxic reaction set-up with a satisfactory yield. In fact, the reduction of GO by aqueous
371 phytoextracts has been reported before and a mechanism for the reduction has been
372 proposed [64]. As it was also observed for other phytochemicals [65,66], the coffee
373 extract contains phenolic compounds that are easy to get oxidized, which presented
374 sufficient potential to reduce the oxygen-containing groups of GO as well as Ag^+ ions.

375 During the synthesis, reduced silver atoms can interact by physisorption or electrostatic
376 binding [67] with the functional groups present in the high surface area of the GO which
377 function as nucleation sites for NPs' growth and stabilization [68], with several
378 advantages such as avoiding aggregation and facilitating their recovery from the
379 environment by sedimentation [69–72]. Therefore, the presented green method takes
380 benefit from the GO surface as a suitable platform for the deposition of silver ions to
381 form metal nanoparticle composites for bio-related applications using coffee extract as
382 a green reductant.

383 The prepared samples presented different colors by naked eye observation, ranging
384 from transparent brown (coffee extract) to opaque dark brown (AgNPs) and brownish-
385 green (AgNPs/r-GO composites), as can be seen in Fig. S4b of supplementary materials.
386 The UV-Vis absorption spectra of AgNPs and AgNPs/r-GO composites revealed a
387 broad absorption band in the 400 to 700 nm, as presented in Fig. 1. It is well-known that
388 colloidal AgNPs have a characteristic optical absorption band with maximum in the 450
389 - 490 nm range as a result of the SPR, phenomenon induced by the collective electron
390 oscillations at the metal nanoparticle surface [7,8], which can be used to monitor NPs
391 formation as only nanostructured materials present surface Plasmon resonance [73]. Fig.
392 1 also shows that the GO spectrum presented a characteristic absorption peak at around
393 230 nm due to the π - π^* electronic transitions of the C-C aromatic bonds and a shoulder
394 at around 300 nm that can be attributed to n- π^* transitions of C=O bond bands [74].
395 AgNPs sample showed an absorption peak centered at ~490 nm which is assigned to the
396 SPR of AgNPs [4,14,15,75,76]. An additional peak at 270 nm can be seen in the UV-
397 Vis absorption spectrum of AgNPs which was previously attributed to caffeine [77,78].
398 In addition to the caffeine absorption band, a small absorption shoulder appeared at 350
399 nm for all coffee-extract-containing samples that may be attributed to Chlorogenic acids

400 (CGAs) [79]. The presence of caffeine and CGAs in the pure coffee extract used in this
401 work was further confirmed by HPLC (Fig. S4a). A comparison of the UV-Vis
402 absorption spectrum for pure coffee extract and AgNPs can be seen in Supplementary
403 Material (Fig. S5). It is worthy of noting that the SPR peak observed in the spectrum of
404 the AgNPs sample seems to be quite broad, but in fact, this is a result of the overlapping
405 of two distinct contributions, one coming from the broad absorption band of the coffee
406 extract solution with a maximum at 455 nm, and the other from the SPR of AgNPs with
407 a maximum absorption at 490 nm (see Fig. S5 of supporting information). For both
408 AgNPs/r-GO composites, the SPR band originated from the collective electron
409 oscillations at the AgNPs surface was ~15 nm blue-shifted when compared to the pure
410 AgNPs, presenting the absorption bands centered at around 475 nm. In addition, the
411 SPR absorption intensities of the AgNPs/r-GO composites were lower than the free
412 AgNPs absorption, indicating a reduction of the total surface area available for the
413 collective oscillations of the electrons at the AgNPs surface of the composites as a result
414 of the adsorption of the AgNPs on the r-GO surface (i.e., the surface part of the AgNPs
415 in contact with the r-GO surface is not available for the electron oscillation, reducing
416 the total surface area for the occurrence of SPR). Nevertheless, reduction of the SPR
417 absorption related to a size increase of the formed particle and/or a concentration
418 decrease of the AgNPs produced in the presence of the r-GO should not be ruled out and
419 it will be further discussed.



420

421 **Figure 1** - UV-Vis absorption spectra of GO, AgNPs, AgNPs/r-GO_{#1}, and AgNPs/r-GO_{#2}.

422

423 ICP OES analysis was performed to determine the Ag concentration in the colloidal
 424 AgNPs and AgNPs/r-GO composites. The obtained Ag concentration was approx. 1256,
 425 1154 and 1161 mg.L⁻¹ for AgNPs, AgNPs/r-GO_{#1} and AgNPs/r-GO_{#2}, respectively, as
 426 presented in Table S1. The lower concentration of Ag observed for the composites when
 427 compared to the free AgNPs was due to the fact that the reaction volume was increased
 428 during the synthesis of the composite, once 2 mL of GO aqueous solution was
 429 introduced in 12 mL of AgNPs for obtaining 14 mL of the AgNPs decorated GO sheets
 430 solution. Therefore, it should be expected a reduction of around 16% in the
 431 concentration of silver in the colloidal solution of the AgNPs/r-GO composites.
 432 However, the ICP results show that this difference is only about 9%, indicating that the
 433 synthesis yield of Ag ions reduction was higher when in the presence of the GO sheets.
 434 Even though, it is worth pointing out that this reduction of 9% in the AgNPs
 435 concentration observed in the AgNPs/r-GO composites cannot alone explain the
 436 reduction of 30% observed by the SPR absorption measurements, reinforcing that part
 437 of the absorption decrease is a consequence of the adsorption of the AgNPs on the r-GO

438 surface (i.e., the reduction of the total surface area available for the collective
439 oscillations of the electrons at the AgNPs surface).

440 The morphology of the AgNPs and the AgNPs/r-GO composites were investigated
441 by FEG-TEM, as presented in Fig. 2. For AgNPs (Fig. 2a), it is possible to see the
442 formation of nanoparticles with irregular shapes and a mean size of about 77 ± 36 nm,
443 which represents a relatively broad size distribution. Figs. 2b and 2c show that even
444 some isolated nanoparticles could be observed, the AgNPs were preferentially deposited
445 over the r-GO sheets for the AgNPs/r-GO composites. These results confirm the
446 existence of an intrinsic contact between AgNPs and r-GO sheets. It is important to
447 stress that AgNPs produced in both AgNPs/r-GO composites presented similar
448 morphological and size characteristics that include irregular-shaped particles and could
449 not be distinguished by TEM observations. The AgNPs obtained for the AgNPs/r-GO_{#1}
450 presented a mean size of 70 ± 12 nm. For AgNPs/r-GO_{#2}, a very similar size and size
451 distribution could be found, with mean a value of 65 ± 11 nm. This result shows that no
452 matter the order chosen for the chemical synthesis driven deposition of the AgNPs over
453 the r-GO surface, the size and shape of the obtained NPs are almost identical. In
454 addition, the Ag⁺ ions liberation results demonstrated that all Ag-containing samples
455 (AgNPs, AgNPs/r-GO_{#1} and AgNPs/r-GO_{#2}) presented similar Ag⁺ release rate as shown
456 in Table 1. A concentration of 35.9 ± 1.5 , 34.5 ± 1.2 , and 35.6 ± 2.0 mg L⁻¹ was determined
457 for the Ag⁺ released by AgNPs, AgNPs/r-GO_{#1} and AgNPs/r-GO_{#2}, respectively, when
458 Ag-containing samples were kept during 48h in an aqueous solution. Consequently, a
459 rate coefficient of Ag⁺ release ($K_d^{Ag^+}$) of 0.027 ± 0.001 , 0.025 ± 0.001 , and 0.026 ± 0.002 h⁻¹
460 ¹ was determined for the AgNPs, AgNPs/r-GO_{#1} and AgNPs/r-GO_{#2}, respectively. The

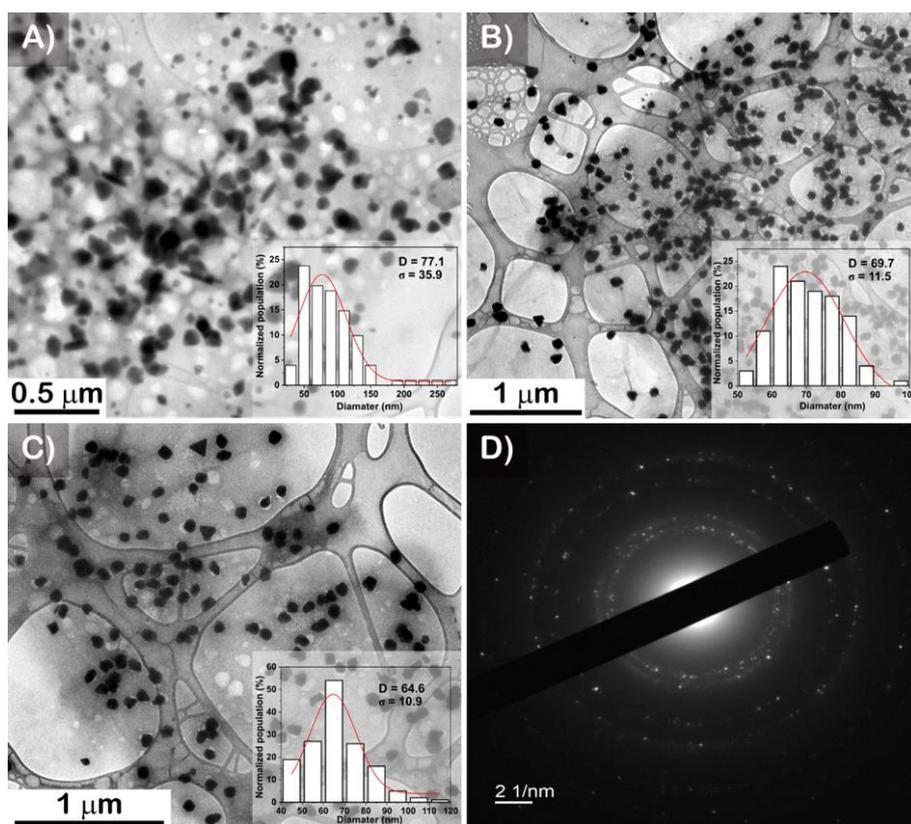
461 $K_d^{Ag^+}$ determination was based in the first-order kinetics model [43] of Eq. 1, which is
 462 presented in more detail in the supplementary materials.

463 Fig. 2d shows a representative selected area electron diffraction (SAED) obtained for
 464 the AgNPs/r-GO_{#1} composite. As a result, diffraction rings with diameters of 2.22, 1.96,
 465 1.38 and 1.17 Å were obtained, which are very close to the interplanar spacing of (111),
 466 (200), (202) and (222) planes of the cubic crystalline phase of silver, space group F m -
 467 3 m and cell parameter equal to 4.126 Å (COD entry 9013048). Similar results were
 468 obtained for AgNPs and AgNPs/r-GO_{#2} composite (not shown) which confirms the
 469 presence of face-centered cubic crystalline silver for all synthesized samples.

470 **Table 1** – Diameter of Ag nanoparticles determined by TEM, hydrodynamic diameter of Ag-containing samples
 471 obtained by DLS, Zeta potential (Zp) in aqueous solution, and rate coefficient of Ag⁺ release ($K_d^{Ag^+}$), respectively.

Sample	AgNPs diameter (nm)	Hydrodynamic diameter (nm)	Zp (mV)	$K_d^{Ag^+}$ (h ⁻¹)
AgNPs	77±36	138 ± 73	- 11.2 ± 6.9	0.027±0.001
AgNPs/r-GO _{#1}	70±12	> 1000	- 25.3 ± 7.2	0.025±0.001
AgNPs/r- GO _{#2}	65±11	> 1000	- 22.3 ± 6.2	0.026±0.002

472



473

474 **Figure 2** – TEM images of the synthesized (a) AgNPs, (b) AgNPs/r-GO#1, and (c) AgNPs/r-GO#2.
 475 Selected area electron diffraction image of the AgNPs/r-GO#1(d).

476

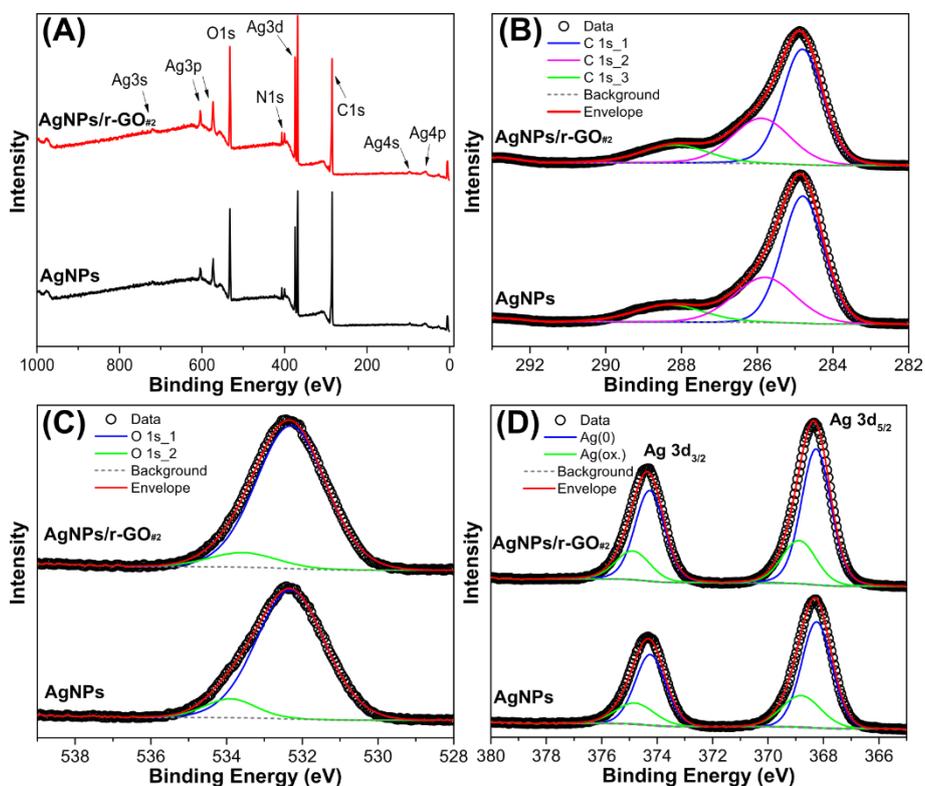
477 DLS (dynamic light scattering) experiments were also performed to determine the
 478 hydrodynamic size of the particles as 138 ± 73 nm, with monomodal size distribution
 479 and a polydispersity index (PDI) of 0.246, indicating that the particles are nearly-
 480 monodispersed. Herein, the size of the AgNPs obtained by DLS is bigger than that
 481 obtained by TEM (Table 1), as expected, since it takes into account the functional groups
 482 that potentially may attach to the surface of the nanoparticles [80]. DLS results for the
 483 AgNPs/r-GO composites revealed the presence of micro-sized aggregates due to r-GO
 484 presence and, therefore, it was not possible to determine with precision the exact size of
 485 the AgNPs in the composites.

486 Zeta potential measurements were applied to study the surface charge of the AgNPs
 487 and the AgNPs/r-GO composites. Considering only the coffee extract solution the

488 obtained Zeta potential was -27.6 ± 5.5 mV. When the AgNPs were synthesized in the
489 coffee extract solution, the Zeta potential negatively decreased to -11.2 ± 6.9 mV,
490 indicating that the AgNPs may contribute with a positive or less negative surface charge
491 for the colloidal solution. However, the Zeta potential value negatively increased to $-$
492 25.3 ± 7.2 mV and -22.3 ± 6.2 mV for the AgNPs/r-GO_{#1} and AgNPs/r-GO_{#2}
493 composites, respectively, revealing different surface charge properties when compared
494 with the free AgNPs.

495 Fig. 3 shows XPS results for AgNPs and a representative AgNPs/r-GO_{#2} composite.
496 The survey spectrum showed in Fig. 3a confirms that no other elements are present in
497 the surface composition of samples rather than C, O, N, and Ag. It is important to note
498 that the N contribution comes from the coffee. Survey spectra were used for the
499 quantification of the sample surface chemical composition (see Table S2). The high-
500 resolution C 1s spectra presented a main peak that was attributed to adventitious carbon
501 (C-C sp²) and used to calibrate the energy at 284.8 eV. Fig. 3b shows high-resolution
502 spectra of C 1s regions, where three peaks centred at 284.8 eV, 285.90 eV and 288.05
503 eV were detected and assigned to the C-C, C=C (284.8 eV), C-O, C=O (285.9 eV) and
504 O-C=O (288.1 eV) bonds [54,55,81–83]. It is important to highlight that the C 1s XPS
505 spectra of AgNPs and AgNPs/r-GO_{#2} are almost identical and could not be used to
506 distinguish GO contribution. Fig. 3c presents the O 1s spectra which contains two peaks;
507 one main contribution at 532.3 eV that is attributed to O-(C=O^{*})-C (aliphatic), and the
508 other located at 533.9 eV that may be attributed to C-OH in an aromatic environment
509 [84]. In addition, Ag 3d spectra of the free AgNPs and AgNPs/r-GO_{#2} samples were
510 very similar, presenting two peaks centred at 368.3 and 374.3 eV that corresponds to Ag
511 3d_{5/2} and Ag 3d_{3/2}, respectively, as shown in Fig. 3d. For the fitting components, the
512 spin-orbit doublet energy separation and area ratio was set at 6.0 eV and 2:3,

513 respectively, and the full-width at half maximum (fwhm) values were constrained to
 514 coincide for the same doublets and restrained to values between 1 and 2. Moreover, for
 515 the correct fitting of these spectra, two contributions had to be taken into account (green
 516 and blue lines in Fig. 3c), one with an Ag 3d_{5/2} peak located at 368.3 eV, corresponding
 517 to metallic silver, and other with an Ag 3d_{5/2} peak located at 368.8 eV, assigned to
 518 oxidized silver [85]. All peak position values and atomic percentages obtained by the
 519 XPS analysis can be seen in Table S2.



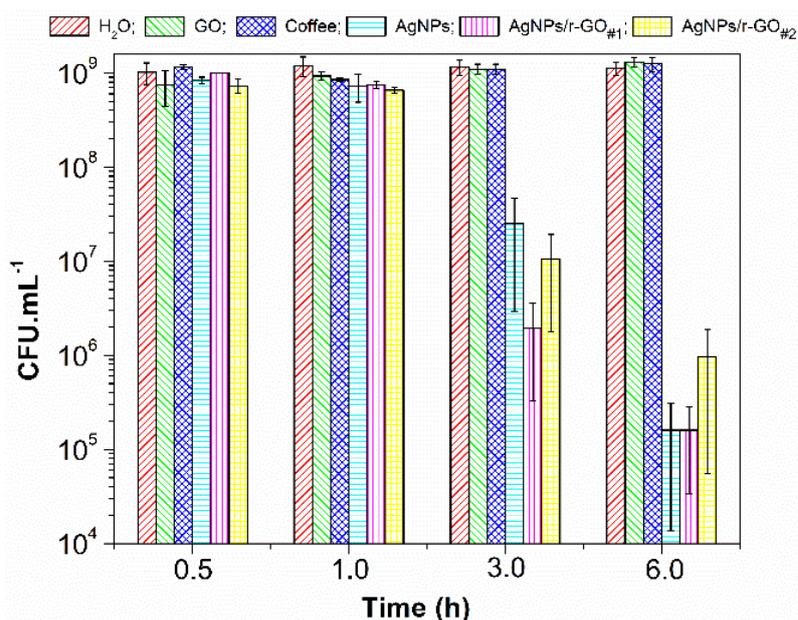
520
 521 **Figure 3** - XPS spectra of the AgNPs and AgNPs/GO_{#2} samples: a) Survey; b) C 1s; c) O 1s and d) Ag
 522 3d regions.

523
 524 **3.2. Antibacterial activity.** The antibacterial activities of the tested samples against *S. aureus*
 525 are presented in Fig. 4. The results revealed that GO sheets were not able to avoid the bacterial
 526 growth during 6 h of interaction with the bacteria, presenting a similar response observed for
 527 water and coffee extract samples (control solutions) as can be seen in Fig. S6 in the
 528 supplementary materials. Therefore, our results indicate that the prepared GO sheets were not

529 able to induce physical damage to the bacterial cell walls, which could promote the formation
530 of pores in the cell walls and, consequently, cell death caused by an osmotic imbalance [86].
531 This assumption was confirmed by SEM results which demonstrated that the bacterial cells
532 remained intact after interacting with the GO sheets as presented in Figure S9 of the
533 supplementary material. The SEM images indicate that the bacteria were wrapped by the GO
534 sheets during the sample preparation procedure. However, it is important to note that the
535 bacterial cell walls have preserved their original rounded shape as observed prior to the
536 interaction with GO. Although recent works have shown that GO can present different
537 mechanisms of action against bacteria, such as oxidative stress induction, protein dysfunction,
538 and transcriptional arrest [87,88], the GO antibacterial activity is mainly due to its capacity to
539 kill bacteria by destroying the cell membrane, acting as a “knife” [89,90]. This GO feature is
540 due to the unique two-dimensional (2D) shape, presenting sharp corners and edge protrusions
541 that can easily destroy the bacterial cell walls and membranes [89]. However, it is worth to
542 stress that the cell damage induced by GO is not only shape-dependent but is also dependent
543 on the size of the GO sheet (i.e., dependent on the sheet area). For instance, Perreault et al. [91]
544 have demonstrated that the antimicrobial activity of GO surface coatings against *Escherichia*
545 *coli* decreased 4-fold after 3h of interaction between GO and bacteria when GO sheet area
546 increased from 0.01 to 0.65 μm^2 . Additionally, their results also revealed that GO sheets with
547 area of 0.65 μm^2 presented similar results to the control group, i.e., the largest tested GO sheet
548 did not show antibacterial activity[91]. Furthermore, Akhavan and Ghaderi [90] have shown
549 that GO nanosheets were very effective in killing both Gram-positive and Gram-negative
550 bacteria by damaging the cell membrane of the bacteria as a result of direct contact of the
551 bacteria with the extremely sharp edges of the GO during 2h. In addition, they also observed
552 that Gram-positive bacteria, *S. aureus*, was less resistant to the cell membrane damage caused
553 by the nano-GO than Gram-negative bacteria, *E. coli*, due to the lacking the outer membrane

554 of Gram-positive bacteria when compared to Gram-negative [90]. Based on that, we believe
 555 that the lack of bacterial toxicity of the GO sheets applied in the present study, even after 6h of
 556 contact with bacteria, may be related to their size because the tested GO presents a much higher
 557 sheet area ($> 9 \mu\text{m}^2$).

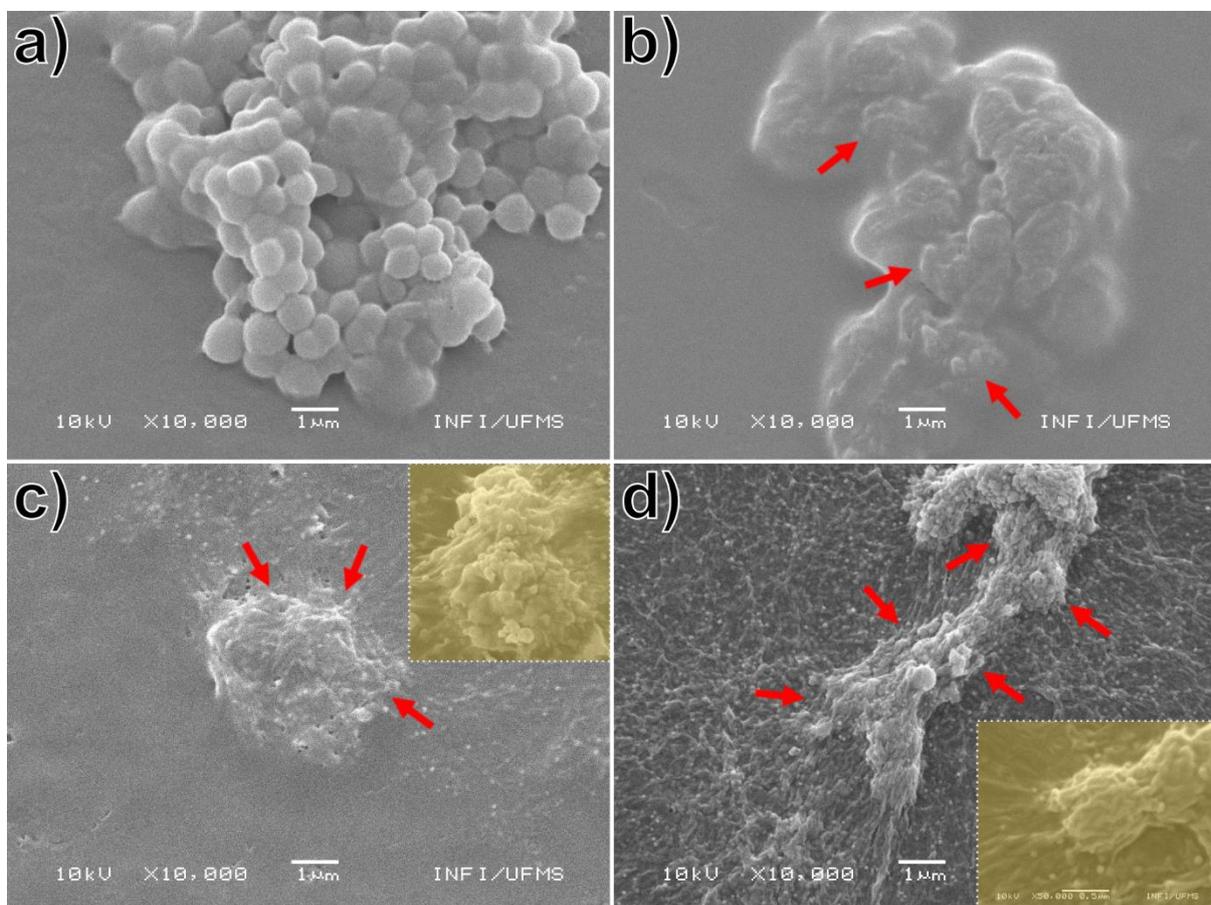
558 Nevertheless, it is important to stress that, in addition to their size, the antibacterial activity
 559 of graphene family nanomaterials (GFNs) has been demonstrated to be also dependent on
 560 oxygen content of the sheets [92], where more oxidative content can generate more ROS and,
 561 consequently, can promote higher bactericidal effect. Hence, a low antimicrobial capacity
 562 related to oxidative stress induction is expected from r-GO due to their low content of
 563 functionalized oxygen-containing groups when compared with other graphene oxide
 564 nanomaterials.



574 **Figure 4** - CFU mean values (\pm SD) of *S. aureus* after 0.5, 1.0, 3.0, and 6.0 h of interaction with Ag-free
 575 (H_2O , GO, Coffee) and Ag-containing (AgNPs, AgNPs/r-GO_{#1}, and AgNPs/r-GO_{#2}) samples.

577 Differently, free AgNPs and r-GO sheets decorated with AgNPs were very effective against
 578 *S. aureus*. A reduction of approximately 2 logs in the bacterial count was promoted by AgNPs,
 579 AgNPs/r-GO_{#1}, and AgNPs/r-GO_{#2} after 3h of interaction between the Ag-based

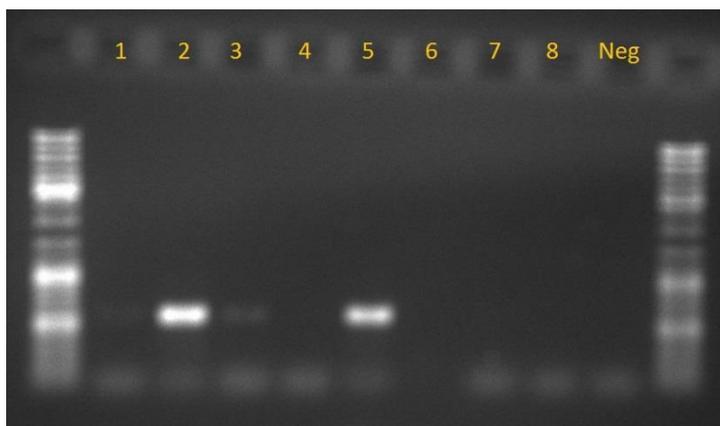
580 nanomaterials and bacteria. Although the obtained results presented in Fig. 4 possibly
581 indicate an improvement trend of the antibacterial activity of the AgNPs/r-GO_{#1}
582 composite when compared with free AgNPs after 3h of interaction, no significant
583 difference was observed after 6h in which all AgNPs-based materials induced a bacterial
584 inhibition growth over 99.9% (*i.e.*, over 3 logs). The SEM results demonstrated that the
585 antibacterial effect promoted by the Ag-containing nanomaterials was primarily due to
586 a disruption of the integrity of the cell membranes as can be seen observed in Fig. 5.
587



588 **Figure 5** - SEM images of *S. aureus* after 3.0 h of interaction with coffee extract (a), AgNPs (b), AgNPs/r-
589 GO_{#1} (c), and AgNPs/r-GO_{#2} (d) samples. Red arrows indicate cell wall parts which are partially or
590 completely damaged. Insets show AgNPs attached to the surface of the bacterial cells.

591

592 In addition, PCR amplification of the transcriptional regulation gene in *S. aureus*
593 indicated that there was no DNA damage with *S. aureus* cells after 6 h of interaction in
594 the dark with coffee (Lane 2), and GO (Lane 3) (Fig 6). However, DNA damage was
595 observed with cells with AgNPs (Lane 4), and AgNPs/GO#2 (Lane 6).



596

597 **Figure 6** - Amplification of transcriptional regulation gene of *S. aureus*. Lanes (1) *S. aureus* – control; *S.*
598 *aureus* after 6h of interaction with: (2) coffee, (3) GO, (4) AgNPs, (5) AgNPs/GO#1, and (6)
599 AgNPs/GO#2; (7) *S. aureus* after 45 min of interaction with AgNPs under blue-light irradiation; (8) only
600 *S. aureus* under blue-light illumination for 90 min; (Neg) PCR Control. GeneRuler DNA ladder
601 (ThermoScientific).

602

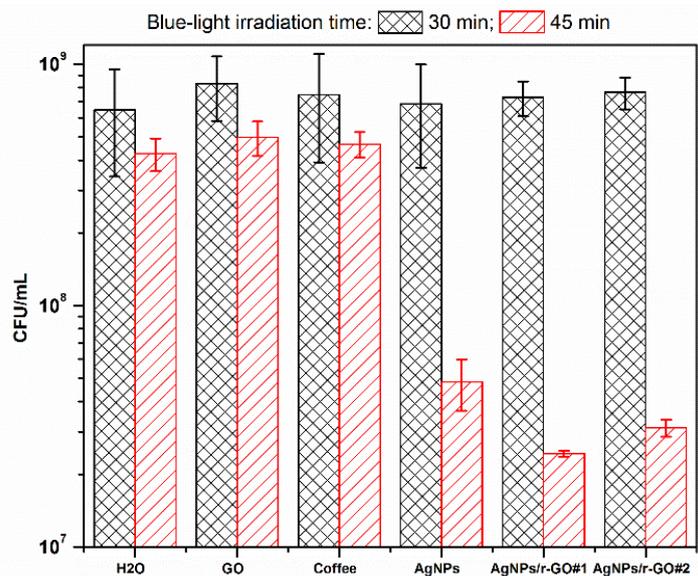
603 These results suggest that Ag⁺ liberation played a key role in bacterial toxicity as a
604 similar Ag⁺ release percentage was determined for All AgNPs-based tested materials as
605 shown in Table 1 and it is well established that the antibacterial activity of AgNPs is mainly
606 due to the Ag⁺ liberation from nanoparticle surface [29,30]. Consequently, these results
607 demonstrated that the AgNPs anchored on r-GO sheets may preserve their antibacterial
608 properties. Prasad et al. [17] have reported a synergetic effect of AgNPs and r-GO
609 against Gram-positive and Gram-negative bacteria, caused by the combined effect of
610 the membranolytic and oxidative activity of r-GO with the free radical formation of
611 AgNPs. They suggest that, in addition to the individual effects of the r-GO and AgNPs,

612 the synergic effect can be derived from the mechanical interaction between the sharp
613 edges of r-GO sheets, which disrupts the cell membrane, and facilitates the transport of
614 Ag⁺ ions across the cell membrane [17]. Das et al. [93] have also demonstrated that the
615 AgNPs/GO composites presented a considerable synergetic effect on membrane leakage
616 of reducing sugars and proteins of Gram-positive bacteria. Against *S. aureus*, for instance,
617 the synergetic effect of AgNPs/GO enhanced the sugar and protein leakage up to 65.15%
618 and 137% after 8 h of incubation, respectively compared to GO nanosheets. When
619 compared with AgNPs, they have shown that AgNPs/GO promoted an enhancement of
620 32.93% and 27.95% of the sugar and protein leakage, respectively.[93] Differently to
621 the previous studies, our prepared AgNPs/r-GO composites presented an antibacterial
622 activity only due to the AgNPs toxicity against *S. aureus* as r-GO did not present
623 antibacterial action and, consequently, no synergetic effect was observed. It should be
624 noted that Liu et al. [67] have observed that the antibacterial activity AgNPs was
625 enhanced when anchored on GO sheets, even when GO did not present any bactericidal
626 effect. However, this observation was explained as a result of the avoiding of AgNPs
627 aggregation promoted by the GO sheets, increasing the antibacterial activity of the
628 nanoparticles due to the higher surface area to interact with bacteria [67]. Consequently,
629 our results also indicated that the free AgNPs were well dispersed as similar inactivation
630 was observed for all Ag-containing samples and no direct antimicrobial activity can be
631 attributed to r-GO sheets as previously discussed.

632

633 **3.3. Photodynamic antibacterial activity.** The photobactericidal assays of the AgNPs-
634 based materials were carried out by choosing an experimental set up to avoid the
635 bactericidal activity (chemical effect) of AgNPs. As reported in the previous section, no
636 antimicrobial effect was induced by Ag-based nanomaterials during the first hour. Based

637 on that, the photobactericidal experiments were carried out under blue light irradiation
 638 by evaluating the antimicrobial photodynamic inactivation (aPDI) effect of the Ag-
 639 containing nanomaterials on bacteria using a reduced concentration of AgNPs (10 times
 640 lower than the used in the antibacterial activity, i.e., the presented in the previous
 641 section) during up to 90 min of interaction. The aPDI of the tested samples against *S.*
 642 *aureus* is presented in Fig. 7, revealing that no photoantibacterial activity was induced
 643 by the Ag-based samples during the first 30 min of irradiation. However, a clear
 644 bacterial photodynamic inactivation was observed for all Ag-based materials after 45
 645 min of illumination, which was promoted exclusively by the AgNPs light absorption as
 646 no bacterial inactivation was induced either for the control samples (coffee and GO
 647 sheets) or for the light (H_2O sample) as presented in Fig. S7 in the supplementary
 648 materials. These results also showed that, differently to the chemical effect, an
 649 enhancement of the photoinactivation action was induced by AgNPs when anchored on
 650 r-GO. Although small, a statistically significant reduction of bacterial growth was
 651 determined, where the photoinactivation induced by AgNPs, AgNPs/GO#1 and
 652 AgNPs/GO#2 achieved a bacterial growth reduction of 88.6, 94.3 and 92.7%,
 653 respectively, as presented in Fig. 7.



654

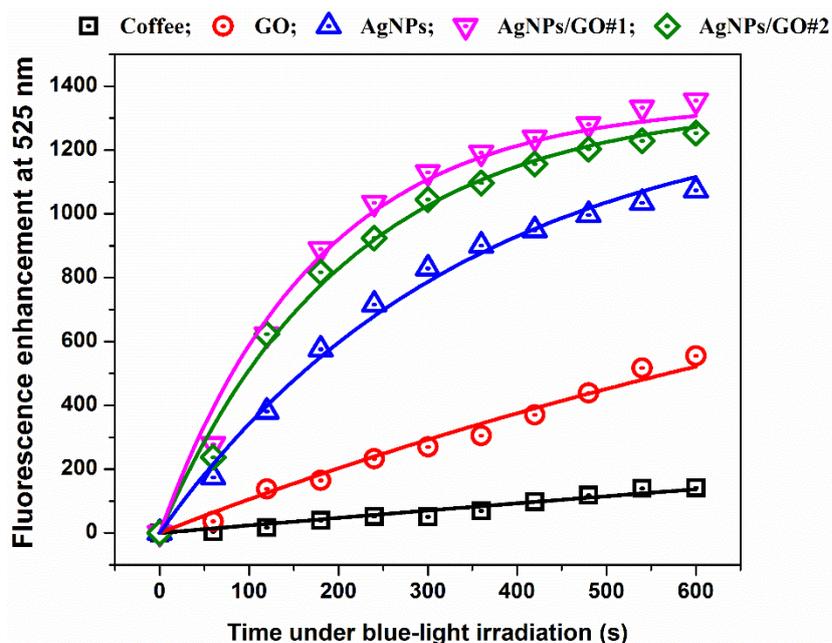
655 **Figure 7** - CFU mean values (\pm SD) of *S. aureus* after 30 and 45 min of interaction with Ag-free (H₂O,
656 GO, Coffee) and Ag-containing (AgNPs, AgNPs/r-GO_{#1}, and AgNPs/r-GO_{#2}) samples under blue light
657 irradiation at 9.5 mW.cm⁻².

658

659 The photodynamic effect induced by AgNPs shows that AgNPs acted as
660 photosensitizers due to their SPR absorption band, where the Plasmon-excited states of
661 AgNPs were able to transfer energy and/or charge (i.e., electron) to molecular oxygen
662 located close to the NPs' surface, and then generating singlet oxygen by energy transfer
663 and/or oxygen radicals by charge transfer (such as superoxide, hydrogen peroxide,
664 hydroxyl radical), causing the bacterial death by oxidative stress induction [94,95].
665 Recent investigations have proved that metal NPs, especially gold and silver NPs, can
666 be efficient photosensitizers for photodynamic therapy because the photons can produce
667 free electrons from the SPR during the light irradiation, which can promote the ROS
668 production [95–97]. The synergetic effect observed for the AgNPs/r-GO composites can
669 be explained by the enhancement of the oxidative stress induction promoted by an
670 additional channel to generate oxygen radicals as the Plasmon-excited AgNPs may also
671 transfer electrons to the surface of the r-GO, facilitating a long-range interfacial charge
672 transfer process due to the good conductivity of the r-GO and, consequently, increasing
673 the probability of ROS production because the photo-transferred electron can migrate
674 to different parts of the r-GO sheet prior to finding an oxygen to react [38,40,98–100].
675 Xie et al [38,101] have recently shown that the photocatalytic performance of AgNPs
676 can be enhanced under 660 nm light irradiation once AgNPs bind to GO. They have
677 demonstrated that the amount of ROS generation was increased because the excited-
678 plasmon electrons can be rapidly transferred to the surface of GO sheets where ROS are
679 generated, enhancing the photocatalytic activity of the AgNPs/GO composite due to the
680 high conductivity of GO [38]. Although they showed that AgNPs/GO can promote a

681 rapid and efficient photoinactivation of *S. aureus*, killing almost all bacteria after 20 min
682 of 660 nm red laser irradiation at 180 mW, this experimental irradiation setup also
683 promoted an elevation of the temperature up to 42°C, which reflects that the
684 photobactericidal activity of the AgNPs/GO was also influenced by a small
685 photothermal effect. However, our findings reveal that AgNPs/r-GO composites can
686 also exhibit a rapid and highly effective photodynamic antibacterial activity under a low
687 dose of blue light irradiation (i.e., illuminating during 45 min at 9.5 mW.cm⁻²). Both
688 AgNPs/r-GO composites caused a bacterial growth reduction greater than 92% after 45
689 min of irradiation, exclusively due to the photodynamic action of AgNPs.

690 The capability of ROS generation by the Ag-based nanomaterials under blue-light
691 irradiation is presented in Fig. 8, demonstrating the higher efficiency of ROS production
692 by the AgNPs/r-GO composites. The apparent rate constant of ROS production (k_{ROS})
693 under blue-light illumination was obtained by using Eq. S5 to fitting the experimental
694 results shown in Figure 8 (see details in the supplementary material). A k_{ROS} value of
695 0.54±0.02, 2.43±0.07, 8.77±0.20, 17.18±0.71, and 14.26±0.43 was determined to
696 coffee, GO, AgNPs, AgNPs/GO_{#1}, and AgNPs/GO_{#2}, respectively. These results are in
697 accordance with the aPDI results, confirming the AgNPs/GO_{#1} presents the highest
698 photo-oxidative activity. Our findings also revealed that the photoantibacterial effect
699 induced by the Ag-containing samples was mainly due to the bacterial cell membrane
700 damage, as can be seen in Fig. S10 of the supplementary material [40,98–103]. The PCR
701 results also revealed that AgNPs-containing sample promoted DNA damage in *S. aureus*
702 cells after 45 min of interaction under blue-light irradiation (Lane 7) (Fig 6).



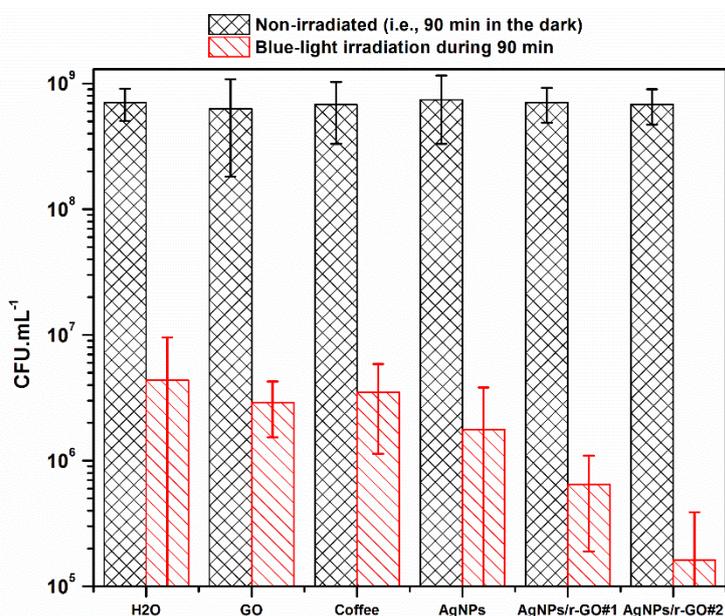
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704 **Figure 8** - Fluorescence emission promoted by the ROS production under blue-light illumination as a
 705 function of the time.

706

707 Although not statistically different, Fig. 7 also reveals a trend of reduction in the
 708 bacterial growth for the Ag-free samples (H₂O, GO, and coffee), possibly induced solely
 709 by blue-light irradiation as similar results were obtained for the three samples. In fact,
 710 several studies have demonstrated that *S. aureus* strains are susceptible to be
 711 photoinactivated directly by blue-light due to photo-excitation of endogenous
 712 intracellular molecules, which act as endogenous photosensitizers under blue-light
 713 irradiation [104–106]. Our results also confirmed that *S. aureus* can be directly
 714 photoinactivated by the blue-light irradiation under our experimental setup when
 715 exposed to a higher dose of irradiation (Fig. S8a). A bacterial growth reduction of ~ 99.4
 716 % (higher than 2 logs) was observed for the H₂O, GO, and coffee samples under 51.3
 717 J.cm⁻² as presented in Fig. 9. However, it is important to stress that Fig. 9 also shows
 718 that AgNPs/r-GO composites induced a bacterial growth reduction greater than 3 logs
 719 (higher than 99.9 %), revealing the combined effect promoted by the photobactericidal

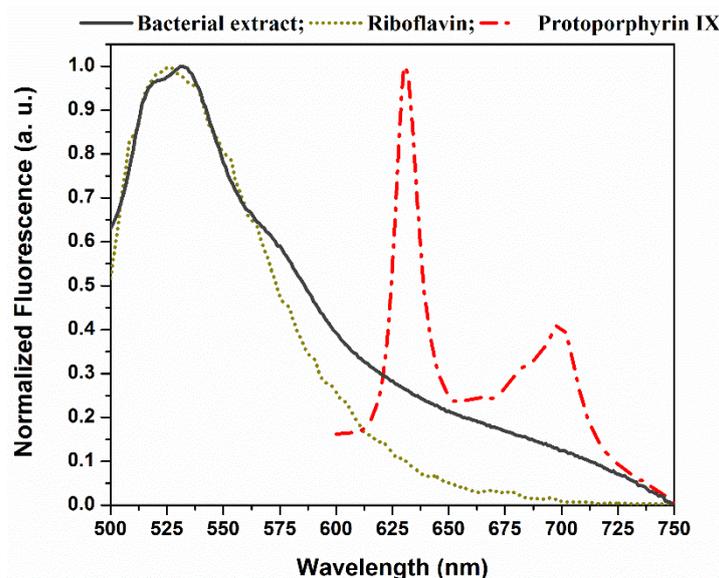
720 effect of blue-light irradiation and the photodynamic action caused by AgNPs/r-GO
721 composites.



722
723 **Figure 9** - CFU mean values (\pm SD) of *S. aureus* after 90 min of interaction with Ag-free (H₂O, GO,
724 Coffee) and Ag-containing (AgNPs, AgNPs/r-GO#₁, and AgNPs/r-GO#₂) samples when kept in the dark
725 and under blue light irradiation at 9.5 mW.cm⁻².

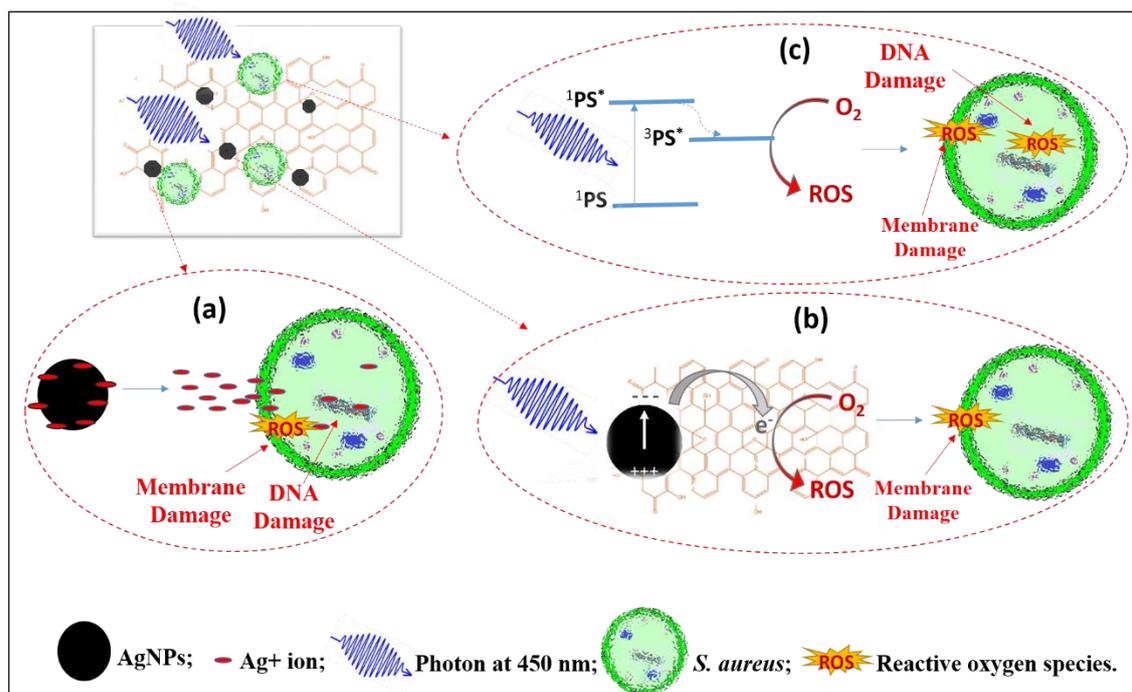
726 Although several studies have reported that porphyrins are the main endogenous
727 photosensitizers to photoinactivate *S. aureus* strains under blue-light irradiation [104–106], our
728 findings revealed that flavins are the key endogenous intracellular photosensitizers under 450
729 nm illumination. As can be seen in Fig. 10, the bacterial extract has a broad fluorescence band
730 in the 500 to 750 nm range with a maximum at around 530 nm due to the emission of the
731 endogenous flavins and porphyrins extracted from bacterial cells. Fig. 10 also shows the
732 fluorescence spectra of protoporphyrin IX and riboflavin when excited at 450 nm, which
733 presents the typical emission spectra of porphyrins and flavins in the red (with maxima 630 nm
734 and 695 nm) and green (with a maximum at 530 nm), respectively. By comparing the spectra
735 profiles presented in Fig. 10, our data show that despite the presence of porphyrins and flavins
736 in the bacterial extract, the flavins are the main endogenous photosensitizer present in the
737 bacterial extract obtained from *S. aureus* strain. In addition to the spectral shape, the results

738 also demonstrated that the fluorescence intensity of porphyrins (with emission in the 625 to
739 750 nm range) was very low, representing less than 80% of the bacterial extract emission. Our
740 results are in accordance with similar findings presented by Plavskii and collaborators (2018)
741 [107], which recently demonstrated that the presence of porphyrins was found in trace amounts
742 in *S. aureus* extracts and also observed a maximum fluorescence band in the range of at around
743 525 nm due to the presence of flavin compounds. Finally, it is important to stress that the main
744 role played by flavins as endogenous photosensitizers is also because they present a maximum
745 of absorption at around 450 nm, with a good overlap with the used photoactivation blue-light
746 (with a maximum at 450 nm), as shown in Fig. S12 of the supplementary material, while the
747 absorption bands of porphyrins have almost no overlap with this excitation light. Recent studies
748 have demonstrated that the direct photoinactivation of bacteria by visible light strongly depends
749 on the light wavelength, where the antibacterial effect promoted by blue light in the spectral
750 range of 450–470 nm is mainly attributed to flavins, while porphyrins are mainly
751 photoactivated by blue-light in the 400 to 430 nm range [108–110]. Lastly, our findings also
752 demonstrated that the antibacterial effect of the blue-light photoactivated endogenous
753 photosensitizers was primarily due to the disruption of the bacterial cell wall (Fig. S11) as well
754 as the oxidation of intracellular DNA (Line 8) (Fig. 6).”



755
 756 **Figure 10** - Fluorescence spectra of bacterial extract (solid line), riboflavin (dotted line), and
 757 protoporphyrin IX (dotted-dashed line) when excited at 450 nm.
 758

759 In fact, our findings demonstrated that the green synthesized silver nanoparticles
 760 loaded on reduced graphene oxide sheets were effective on killing *S. aureus* under blue-
 761 light irradiation (@450 nm), promoted by three different and simultaneous bacterial
 762 killing mechanisms: (a) Ag^+ ion release; (b) enhanced photoinactivation promoted by
 763 excited-Plasmons of the AgNPs when anchored on r-GO; and (c) blue-light
 764 photodynamic inactivation caused by bacterial endogenous photosensitizers, as is
 765 schematically represented in Fig. 11. Finally, it is important to state that despite recent
 766 studies have demonstrated that GO can promote an antibacterial effect induced by a
 767 photothermal process under red and infrared light irradiation [100,111], no heating was
 768 observed during the sample illumination in the present work. This result is in accordance
 769 with Plavskii et al. [107], which demonstrated that even using higher light doses, the
 770 photobactericidal effect promoted by the blue-light presented a photochemical but not a
 771 photothermal nature.



772

773 **Figure 11** - Schematic diagram of antibacterial mechanisms induced by AgNPs/r-GO composites. (a)
 774 Ag⁺ ion release; (b) enhanced photoinactivation induce by excited-plasmons of the AgNPs loaded on r-
 775 GO; and (c) blue-light antimicrobial photodynamic inactivation promoted by endogenous
 776 photosensitizers.

777

778 4. Conclusions

779 AgNPs/r-GO composites were prepared by an environmentally-friendly, simple,
 780 inexpensive and non-toxic reaction set-up with a satisfactory yield of > 70% for silver
 781 reduction. Our green method has the advantage that the r-GO surface acts as a suitable
 782 platform for deposition of AgNPs to form composites for bio-related applications, using
 783 coffee extract as a green reductant for both Ag⁺ ions and GO reduction. AgNPs with a
 784 mean diameter of about 70 nm were obtained for all Ag-containing samples (i.e., free
 785 AgNPs and AgNPs anchored on the r-GO surface). The chemical characterization
 786 showed that the silver was obtained in the metallic form with little oxidation at the
 787 surface as evidenced by SAED and XPS. In addition, AgNPs were intimately linked to

788 the r-GO surface, with a negative Zeta potential that increased in modulus after the
789 AgNPs/r-GO composite formation. The results also demonstrated that all Ag-containing
790 samples (AgNPs, AgNPs/r-GO_{#1} and AgNPs/r-GO_{#2}) presented similar Ag⁺ release rates
791 of approx. 0.026 h⁻¹ that reflected in an excellent antibacterial effect against *S. aureus*.
792 A reduction of approximately 2 logs in the bacterial counts was promoted for Ag-
793 containing samples after 3h of interaction with the bacteria, and a bacterial inhibition
794 growth over 99.9% after 6h was obtained with no significant difference among the
795 samples. In addition, a clear antibacterial photodynamic inactivation was observed for
796 all Ag-based materials after 45 min of blue light irradiation (at 20.3 J.cm⁻²) when
797 compared with the Ag-free samples (H₂O, GO, and coffee), which a statistically
798 significant bacterial growth reduction of 88.6, 94.3 and 92.7% was observed for AgNPs,
799 AgNPs/GO_{#1} and AgNPs/GO_{#2}, respectively. In addition, the photodynamic
800 experiments also revealed that blue light irradiation was able to induce a
801 photoantibacterial effect through photoactivation of endogenous photosensitizers; a
802 bacterial growth reduction of ~ 99.4 % was determined for the Ag-free samples when
803 irradiated at 51.3 J.cm⁻². In summary, the present findings demonstrate that an efficient
804 process of bacterial inactivation can be achieved using green synthesized AgNPs/r-GO
805 compounds as a consequence of the Ag⁺ ion release (chemical antibacterial effect) and
806 the enhanced photoinactivation promoted by excited-Plasmons of the AgNPs when
807 anchored on rGO in association with the blue-light photodynamic inactivation caused
808 by bacterial endogenous photosensitizers (photodynamic antibacterial effects).

809

810 **Conflicts of interest**

811 There are no conflicts to declare.

812

813 **Statement of contributions**

814 C.S.A. Caires performed the bactericidal and photobactericidal experiments; L.A.S. Farias and
815 L.E. Gomes contributed to the development of the AgNPs-r-GO composites, UV-Vis and DLS
816 measurements; B.P. Pinto and D.C.B. Alves helped with the graphene oxide preparation and
817 Raman characterization; D.A. Gonçalves and V.A. Nascimento carried out ICP-OES
818 characterization and ion release experiments; L.F. Zagonel made the microscopy analyzes; I.
819 Colbeck and C. Whitby analyzed the results and review the manuscript; A.R.L. Caires and H.
820 Wender conceived this research, analyzed the results, wrote the manuscript and supervised the
821 entire project. All authors have given approval to the final version of the manuscript.

822

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