

1 **The impact of cold plasma on the phenolic composition and biogenic amine content of** 2 **red wine**

3 Iwona Niedźwiedź¹, Justyna Płotka-Wasyłka², Ireneusz Kapusta³, Vasil Simeonov⁴, Anna
4 Stój¹, Adam Waśko¹, Joanna Pawłat⁵, Magdalena Polak-Berecka^{1*}

5
6 ¹Department of Microbiology, Biotechnology and Human Nutrition, University of Life
7 Sciences in Lublin, 8 Skromna Street, 20-704 Lublin, Poland

8 ²Department of Analytical Chemistry, Faculty of Chemistry, Gdańsk University of
9 Technology, 11/12 Narutowicza Street, 80-233 Gdańsk, Poland;

10 ³Department of Food Technology and Human Nutrition, College of Natural Science, Rzeszów
11 University, 4 Zelwerowicza Street, 35-601 Rzeszów, Poland

12 ⁴Faculty of Chemistry and Pharmacy, University of Sofia, 1 James Bourchier Blvd., 1126
13 Sofia, Bulgaria;

14 ⁵Faculty of Electrical Engineering and Computer Science, Lublin University of Technology,
15 38A Nadbystrzycka Street, 20-618 Lublin, Poland

16
17 *Corresponding authors: Magdalena Polak-Berecka magdalena.polak-berecka@up.lublin.pl

18

19 **Abstract**

20 The effect of cold plasma (CP) on phenolic compound (PC) and biogenic amine (BA)
21 contents of red wine was investigated for the first time. The influence of CP was compared
22 with the effects of a wine preservation using potassium metabisulfite and a combined method.
23 The PC profile was determined by UPLC-PDA-MS/MS while BAs using DLLME-GC-MS.
24 Chemometric analysis also was used. The content of PCs was 3.1% higher in the sample
25 preserved by CP treatment (5 min, helium/nitrogen) compared to a sample preserved by the
26 addition of potassium metabisulfite (100 mg/L). On a positive note, CP treatment reduced the
27 concentration of BAs in the wine samples. The lowest BA contents were recorded after 10
28 min of cold plasma (helium/oxygen) treatment with the addition of potassium metabisulfite
29 (1120.85 µg/L). The results may promote interest in CP as a potential alternative method for
30 the preservation of wine and other alcoholic beverages.

31

32 **Keywords:** cold plasma; phenolic compounds; biogenic amines; chemometric analysis; wine
33 preservation; red wine

34

35 **1. Introduction**

36 Wine is an alcoholic beverage, the tradition of production and consumption of which
37 has been known around the world for centuries (Gajek et al. 2021). The recent climatic
38 changes have brought about alterations in the geographical distribution of areas used for
39 viticulture. As a consequence of global warming, a significant increase in the area of
40 vineyards and wine production has been observed across Central and Eastern Europe,
41 including Poland (Kozmiński et al. 2020). Wine is produced by fermentation of sugars
42 contained in fruit using naturally occurring microorganisms or starter cultures. This product is
43 a complex matrix consisting of water, alcohol, carbohydrates, organic acids, polyphenols,
44 minerals and aromatic substances (Robles et al. 2019).

45 One of the most abundant and important groups of compounds found in wines are
46 polyphenols. They are responsible for the color (anthocyanins), taste (tannins), and aroma of
47 wines. Additionally, they show antioxidant activity, which makes them beneficial in the
48 prevention of cardiovascular diseases and other chronic medical conditions (Snopek et al.
49 2018). The polyphenol content of wine depends on the grapevine strain and the grape variety,
50 the winemaking technology, the aging processes and the wine preservation methods used. Red
51 wines are characterized by a higher content of polyphenolic compounds (PCs) compared to
52 white wines, and thus show a higher antioxidant activity (Robles et al. 2019). Due to the
53 growing consumer awareness of the health benefits associated with the consumption of
54 polyphenol-rich products as well as the knowledge of the impact of these compounds on the
55 final quality of a product, wine producers are looking for solutions that would minimize the
56 loss of polyphenols during the entire winemaking process.

57 Besides health-promoting phenolic compounds, wines also contain biogenic amines
58 (BAs), which may have a negative impact on human health. They are nitrogenous compounds
59 that are mainly formed by the decarboxylation of amino acids, which in wine is the result of
60 the activity of microbes such as yeast or lactic acid bacteria (LAB) (Smit and Maret du Toit,
61 2012). The content of biogenic amines depends mainly on the concentration of amino acid
62 precursors in a product's matrix, but also on pH as well as alcohol and sulfur dioxide
63 contents, which directly affect the growth of microorganisms (Papageorgiou et al. 2018). In
64 addition, the presence of amino acid precursors is influenced by the grape variety, the
65 geographical region, vinification methods, and the aging process (Płotka-Wasyłka et al.

66 2018a). The biogenic amines most commonly found in wines include histamine (HIS),
67 cadaverine (CAD), tyramine (TYR), 2-phenylethylamine (2-PE), putrescine (PUT), and
68 tryptemine (TRP) (Esposito et al. 2019). High concentrations of biogenic amines in the final
69 product may cause undesirable physiological effects in the consumer, such as headaches,
70 nausea or tachycardia (Naila et al. 2010).

71 In order to prevent the negative effects of microorganisms on the quality of wine,
72 methods of eliminating the undesirable microbes have been developed. Although classic
73 thermal methods of food preservation still play a very important role in food technology, they
74 are not suitable for vinification processes as they can negatively affect the unique taste, color
75 and flavor of wine (Niu et al. 2019). Instead, sulfur dioxide, which has decontaminating and
76 antioxidant properties, is commonly added to wine to remove unwanted microorganisms.
77 However, despite its positive effects, it can cause allergic reactions in some consumers, which
78 is why the World Health Organization (WHO) has introduced restrictions on its use. This has
79 contributed to an increased search for new strategies to minimize or even replace SO₂
80 (Cordero-Bueso et al. 2019), but the problem of biogenic amines still remains unsolved.
81 Therefore, scientists are looking for effective non-thermal preservation methods which allow
82 to remove undesirable microorganisms without significantly affecting the final stability of the
83 product (Puligundla et al. 2018).

84 Cold plasma is one of the most recent non-thermal methods used in sterilization
85 processes. Numerous scientific publications confirm its effective antimicrobial activity, which
86 is connected with the influence of reactive compounds, atoms in the excited and basic state,
87 and UV photons on microbial cells (Bourke et al. 2017). Reactive compounds are produced
88 by subjecting a working gas to various electrical discharges such as barrier discharge and
89 corona discharge. Importantly, in the context of cold plasma applications in the food industry,
90 the temperature of the free electrons in the working gas is lower than that of the other
91 particles, which directly results in a slight increase in process temperature (Niedźwiedź et al.
92 2019). However, there is limited information in the literature regarding the impact of cold
93 plasma on the final quality of alcoholic beverages, which means this problem is worth delving
94 into.

95 The objective of the present study was to investigate the effect of a new wine
96 preservation method using cold plasma on the phenolic composition and biogenic amine
97 content of red wine. An additional objective was to compare the effect of preserving wine
98 samples using the traditional method (addition of potassium metabisulfite at 30 mg/L or

99 100mg/L) and a combined method (cold plasma and the addition of potassium metabisulfite at
100 30 mg/L) with the effect of cold plasma alone. Wine sample storage was also considered in
101 the study. In addition, chemometric analysis was conducted to discover specific relationships
102 between the different wine preservation methods and the content of bioamines and selected
103 phenolic compounds.

104 **2. Materials and methods**

105 **2.1 Chemicals and materials**

106 All reference materials used in the determination of the biogenic amines such as tryptamine
107 hydrochloride, putrescine dihydrochloride, histamine dihydrochloride, tyramine
108 hydrochloride, cadaverine hydrochloride and 2-phenylethylamine hydrochloride, as well as
109 hexylamine (internal standard, IS), were purchased from Sigma-Aldrich (St. Louis, MO,
110 USA). The derivatization reagent (isobutyl chloroformate) was purchased from Sigma-
111 Aldrich. Ultrapure water was obtained from a Milli-Q water purification system (Millipore,
112 Bedford, MA, USA). Stock solutions of BAs and IS (both at 1 mg/mL) were prepared daily in
113 ultrapure water and stored at +4°C in silanized screw-capped vials with solid PTFE-lined caps
114 (Supelco, Bellefonte, PA). Methanol, used as a dispersive solvent, was a high purity grade
115 solvent purchased from Fluka. High purity grade chloroform, applied as an extractive solvent,
116 was obtained from Sigma. 0.1 M HCl was supplied by Fluka. Other chemicals were of an
117 analytical grade.

118 Analytical standards for phenolic profile determination such as cyanidin-3-O-glucoside,
119 delphinidin-3-O-glucoside, isorhamnetin-3-O-glucoside, kaempferol-3-O-glucoside, malvidin-
120 3-O-glucoside, myricetin-3-O-glucoside, peonidin-3-O-glucoside, petunidin-3-O-glucoside,
121 quercetin-3-O-glucoside, quercetin-4'-O-glucoside, quercetin-3-O-rutinoside, (+)-catechin, (-
122)-epicatechin, (-)-epicatechin-3-gallate, procyanidin A1 and A2, trans-resveratrol, and trans-
123 piceid were purchased from Extrasynthese (Lyon, France). Caftaric acid, caffeic acid, coumaric
124 acid, gallic acid, caftaric acid, ferulic acid, protocatechuic acid, and p-coumaric acid were
125 purchased from PhytoLab (Vestenbergsgreuth, Germany). Formic acid (LC-MS grade) was
126 purchased from Fischer Scientific (Schwerte, Germany). Acetonitrile was purchased from
127 POCH (Gliwice, Poland).

128

129 **2.2 Wine samples**

130 The red wine used in this study was produced at Dom Bliskowice Winery (Poland, Lublin
 131 Province) from grapes of Regent and Rondo (1:1) varieties harvested in October 2019. The
 132 wine was subjected to different preservation processes (control sample – not preserved; cold
 133 plasma treatment; addition of 30 mg/L potassium metabisulfite; addition of 30 mg/L
 134 potassium metabisulfite combined with cold plasma treatment; and addition of 100 mg/L
 135 potassium metabisulfite). The samples were then analyzed immediately after preservation and
 136 also after three months of storage (15°C, limited light) (Table 1).

137 Table 1. Characterization of samples and sample coding

Sample	Preservation method	Cold plasma exposure time	Gas used for preservation	Storage
1	no preservation	0	No	No
2	cold plasma	2	He / O ₂	No
3	cold plasma	5	He / O ₂	No
4	cold plasma	10	He / O ₂	No
5	cold plasma	2	He / N ₂	No
6	cold plasma	5	He / N ₂	No
7	cold plasma	10	He / N ₂	No
8	30mg/L potassium metabisulfite	0	No	No
9	cold plasma and 30mg/L potassium metabisulfite	2	He / O ₂	No
10	cold plasma and 30mg/L potassium metabisulfite	5	He / O ₂	No
11	cold plasma and 30mg/L potassium metabisulfite	10	He / O ₂	No
12	cold plasma and 30mg/L potassium metabisulfite	2	He / N ₂	No
13	cold plasma and 30mg/L potassium metabisulfite	5	He / N ₂	No
14	cold plasma and 30mg/L potassium metabisulfite	10	He / N ₂	No
15	100 mg/L potassium metabisulfate	0	No	No

16	no preservation	0	No	Yes
17	cold plasma	2	He / O ₂	Yes
18	cold plasma	5	He / O ₂	Yes
19	cold plasma	10	He / O ₂	Yes
20	cold plasma	2	He / N ₂	Yes
21	cold plasma	5	He / N ₂	Yes
22	cold plasma	10	He / N ₂	Yes
23	30 mg/L potassium metabisulfite	0	No	Yes
24	cold plasma and 30 mg/L potassium metabisulfite	2	He / O ₂	Yes
25	cold plasma and 30 mg/L potassium metabisulfite	5	He / O ₂	Yes
26	cold plasma and 30 mg/L potassium metabisulfite	10	He / O ₂	Yes
27	cold plasma and 30 mg/L potassium metabisulfite	2	He / N ₂	Yes
28	cold plasma and 30 mg/L potassium metabisulfite	5	He / N ₂	Yes
29	cold plasma and 30 mg/L potassium metabisulfite	10	He / N ₂	Yes
30	100 mg/L potassium metabisulfate	0	No	Yes

138

139 2.3 Cold plasma treatment of wine

140 Wine samples were exposed to cold plasma for 2, 5 and 10 min. Mixtures of helium and
 141 nitrogen or helium and oxygen were used as the working gas. The samples were treated using
 142 a DBD (Dielectric Barrier Discharge) plasma jet reactor. The volume of 50 ml of wine was
 143 poured to a sterilized glass container and placed on a magnetic stirrer. To ensure homogenous
 144 exposure to plasma treatment, samples were stirred with a PTFE stir bar placed inside the
 145 sample. The DBD reactor consisted of a 1.4 mm internal diameter ceramic gas tube. Two
 146 metal electrodes were located as follows: a ring-shaped high voltage electrode was positioned
 147 10 mm from the end of the jet and A flat, copper PCB laminated electrode was used as the
 148 ground. The latter electrode was placed on the magnetic stirrer, just beneath the sample
 149 container. The distance between the end of the reactor's tube and the surface of the liquid was

150 2 mm. The flow rates of the substrate gas mixtures were 96 L/h of helium with 1.8 L/h of
151 oxygen or nitrogen admixtures. The flow rates were adjusted by gas flow controllers
152 (Automatic Works “ROTAMETR”, Gliwice, Poland). A schematic view of the experimental
153 set-up is presented in Fig. 1. The mean power of the power supply was 6 W. For both gas
154 mixtures, the sine-like voltage signals were quite similar, with a subtle difference in the
155 maximum voltage, which was slightly higher in the case of the helium and oxygen mixture
156 and ranged 8.3 kV.

157 A K-type thermocouple connected to a DT-847U meter was used to measure the temperature
158 of the sample after plasma treatment. In the course of the experiment, the maximum registered
159 temperature of the sample did not exceed 32°C, so the treatment can be considered a cold one.

160 **2.4. Determination of polyphenolic compounds**

161 The protocole reported by Kapusta et al. (2018) was used to determine polyphenolic
162 compounds in the wine samples. The qualitative and quantitative determination of the
163 phenolic compound profile was performed using ultra-performance reverse-phase liquid
164 chromatography (UPLC-PDA-MS/MS). The UPLC-PDA-MS/MS Waters ACQUITY system
165 (Waters, Milford, MA, USA) used consisted of a sample manager, a binary pump manager, a
166 column manager, a photodiode array (PDA) detector, and a tandem quadrupole mass
167 spectrometer (TQD) with electrospray ionization (ESI). A BEH C18 column (100 mm × 2.1
168 mm i.d., 1.7 µm, Waters) was used to separate the compounds. Wine samples were filtered
169 before the analysis through a 0.45-µm Millipore filter and then injected onto the
170 chromatographic column. The injected sample volume was 5 µL. The experiment was
171 conducted in duplicate. Waters MassLynx software v.4.1 was used to collect and analyze the
172 results. The results obtained are expressed in mg/L.

173 **2.5 GC-MS determination of biogenic amine content**

174 The protocole reported by Płotka-Wasyłka et al. (2018b) was used to determine biogenic
175 amines (BAs) in the wine samples. Isolation of analytes was carried out simultaneously with
176 their derivatization. The selected analytes were determined qualitatively and quantitatively
177 using gas chromatography combined with mass spectrometry (GC-MS). A gas
178 chromatography (GC) 7890A (Agilent Technologies, Santa Clara, CA, USA) system was
179 interfaced with an inert mass selective detector (5975C, Agilent Technologies) with an
180 electron impact ionization chamber (EI). A ZB-5MS capillary column (30 m × 0.25 mm I.D.,
181 0.25 µm) supplied by Zebron Phenomenex was used for chromatographic separation. The

182 injection was performed in the splitless mode at 230°C. The interface was set at 250°C. The
183 injected sample volume was 2 µl. Helium was the carrier gas with a constant pressure of 30
184 psi. The oven temperature program was as follows: 50°C held for 1 min, ramped to 280°C at
185 15°C /min and held for 9 min (total run time was 25.3 min). The analysis was carried out in
186 the selected ion monitoring (SIM) mode. The MS parameters were set as follows: EI
187 ionization with 70 eV energy; ion source temperature, 250 °C. All the ion fragments with
188 their relative intensities at the specific retention times were considered as a valid confirmation
189 criterion and were used to identify the selected BAs. An Agilent ChemStation was used for
190 data collection and GC-MS control.

191 The optimized method was evaluated using the following validation parameters: linearity,
192 precision, sensitivity and accuracy in accordance to quality assurance protocol. Linearity was
193 examined by application of 10 different concentrations. Hexylamine was used as internal
194 standard. Limits of detection (LODs) and limits of quantification (LOQs) were calculated to
195 estimate the sensitivity of the methodology. Both LODs and LOQs were calculated
196 from spiked samples ($n=3$) and the minimum detectable analyte amount with a signal-to-noise
197 ratio of 3 and 10, respectively, was established. The intra-day (RSD_I) and inter-day (RSD_R)
198 precision were determined by the application of five replicates of wine samples spiked at two
199 levels (0.10 and 0.25 mg/L). In addition to validation parameters, recovery rates were
200 estimated using the ratio of the peak areas of the spiked samples of known concentration of
201 biogenic amines to those of spiked water solution ($n=3$). The matrix effect (ME) of the
202 optimized method was also evaluated by application the procedure described by Matuszewski
203 et al. (Matuszewski, Constanzer, & Chavez-Eng, 2003). The ME was examined
204 at a concentration level of 0.25 mg/L, and calculated by comparing the mean peak area
205 of the analyte standards in the water solution (a, $n=3$) with the mean peak area of an analyte
206 spiked postextraction (b, $n=3$). The following Equation was used:

$$207 \quad ME [\%] = \frac{b}{a} \times 100\% \quad (\text{Equation 1})$$

208 The MEs, were ranged from 79% and 99%. In general, ME has no impact on the qualitative
209 and quantitative results of this method and can be omitted. Additionally, it was proven that it
210 is justified to use an internal standard (IS) for calibration. Information on determined
211 validation parameters and average recoveries (%) obtained with the optimized method in
212 spiked wine samples are given in Table 1SI (Supporting Information).

213

214 **2.6. Chemometric analysis**

215 In the present study, multivariate statistical data mining was used to discover the
216 specific correlations between the different wine preservation methods and determine the
217 content of bioamines and selected phenolic compounds. The following chemometric methods
218 were used for intelligent data analysis: cluster analysis (hierarchical and non-hierarchical or
219 K-means clustering), two-way joining analysis, principal component analysis, and factor
220 analysis. The analysis were performed using STATISTICA 8.0 software.

221 **3. Results and Discussion**

222 **3.1. Polyphenolic content**

223 Red wine is a rich source of phenolic compounds that exert beneficial effects on the
224 human health due to their antioxidant properties. Many studies have been conducted which
225 indicate that the profile of phenolic compounds in a wine depends on the geographical
226 location of the vineyard, the type of grapes, the method of production and preservation, and
227 storage time (Manns et al. 2013; Stój et al. 2020). To evaluate the effect of the preservation
228 method and storage time on the phenolic compound content of red wine samples, UPLC-
229 PDA-MS/MS was used. A total of 54 compounds were determined in the studied samples by
230 UPLC: 24 anthocyanins, 7 flavonols, 12 flavon-3-ols, 7 phenolic acids, and 4 stilbenes
231 (Supplementary Material – Table S.1). The Retention times, molecular ion masses and the
232 basic MS2 fragments of the individual phenolic compounds are presented in Supplementary
233 Material - Table S.2. The contents of selected phenolic compounds detected in our red wine
234 samples are shown in Table 2.

235 The most abundant group were anthocyanins, especially malvidin 3-O-glucoside-5-O-
236 glucoside, malvidin 3-O-glucoside and delphinidin 3-O-glucoside, a profile that is
237 characteristic of Rondo variety wines (Stój et al. 2020; Kapusta et al. 2018). Anthocyanins are
238 responsible for the hue and color stability of wine and are indicative of its final quality. The
239 basic structure of anthocyanins is their aglycone part (Khoo et al. 2017). In the examined
240 wine, derivatives of five aglycones were determined: delphinidin, malvidin, petunidin, peonidin
241 and cyanidin. Anthocyanins are unstable compounds that can undergo reversible
242 transformations in aqueous environments due to pH changes, thus affecting the color of the
243 product. In addition, these compounds may degrade during processing when exposed to
244 various factors, such as temperature, oxygen, or light (He et al. 2012; Yue et al. 2021). This is
245 consistent with our results, which indicated that the storage process as well as the preservation

246 method used affected the final anthocyanin concentration. Analyzing the influence of the
247 storage proces, we noted a 8.23 to 47.51 % reduction in the subtotal levels of these
248 compounds in each of the tested samples compared to samples which had not been stored.
249 Additionally, a lower decrease in the content of diglycoside anthocyanins was observed,
250 which indicates that they exhibit a higher stability than monoglycoside anthocyanins (Table
251 S.1). This observation is confirmed by numerous scientific reports (He et al. 2012; Kim et al.
252 2010). The most stable molecule with the lowest level of reduction in all samples was
253 cyanidin-3-O-glucoside-5-O-glucoside. By contrast, cyanidin-3-O-glucoside was the most
254 susceptible to degradation, which was directly related to its structure. Malvidin-3-O-glucoside
255 and peonidin-3-O-glucoside do not have hydroxyl groups in the ortho position, which makes
256 them relatively more resistant to oxidation than cyanidin-3-O-glucoside (He et al.2012). Our
257 results indicate that the content of each anthocyanin in both non-stored and stored samples
258 was also dependent on the preservation method applied. In the present study, three
259 preservation methods were used: cold plasma (variable process conditions), addition of
260 potassium metabisulfite (30 mg/L or 100mg/L) and a method combining the use of cold
261 plasma with the addition of potassium metabisulfite at 30 mg/L. In wine production, the
262 standard method of wine preservation is sulfurization (Christofi et al. 2020). In the wine
263 samples analyzed immediately after the addition of potassium metabisulfite (Table S.1 –
264 samples no. 8 and 15), we observed a slight increase in the total content of anthocyanins
265 compared to the control sample (no. 1). Moreover, the sample with the addition of 100 mg/L
266 potassium metabisulfite had the highest content of anthocyanins (836.32 mg/L) compared to
267 the other samples (580.36–811.73 mg/L). Sulfur compounds are used in vinification as
268 antimicrobial and antioxidant agents. Furthermore, the addition of sulfur dioxide is thought to
269 prevent enzymatic and non-enzymatic oxidation of wines (Esparza 2020). In our study,
270 however, the total content of anthocyanins after the three-month storage period in samples
271 subjected to sulfurization (Table S.1– samples 23 and 30) was similar to the control sample
272 (sample 16); only the addition of 100 mg/L potassium metabisulfite caused a decrease in the
273 content of these compounds by 5.77%. These results indicate that the application of potassium
274 metabisulfite has a minimal effect on the reduction of the anthocyanin content. Despite their
275 good preservative properties, sulfur compounds can have negative effects on consumer health
276 causing allergic reactions in some consumers. Therefore, alternative wine preservation
277 methods or combined methods are being sought to reduce the sulfate doses used (Christofi et
278 al.2020). One of the new methods of food preservation, which we tested in this study, is cold
279 plasma. To the best of our knowledge, there is no research so far regarding the effect of cold

280 plasma treatment on the content of phenolic compounds in red wine samples in comparison
281 with the effect of this method combined with potassium metabisulfite. In our experiment, we
282 evaluated the impact of cold plasma treatment time (2, 5, 10 min) and the type of working gas
283 used (helium/oxygen and helium/nitrogen) on the profile of phenolic compounds in red wine
284 samples. Additionally, we tested the effect of cold plasma treatment combined with potassium
285 metabisulfite (30 mg/L) treatment. Our results showed that both the duration of the process
286 and the type of gas used contributed to a change in the content of individual compounds. The
287 analysis of the level of anthocyanins in unstored samples indicated that the application of cold
288 plasma for 10 min with the mixture of helium/oxygen as the working gas resulted in the
289 highest reduction in the total anthocyanin content compared to the control (Table S.1). To
290 date, there are few reports in the literature explaining the mechanism of action of cold plasma
291 on food products (Alves Filho et al. 2020; Gavahian et al. 2018). However, cold plasma
292 generation is accompanied by light emission, cavitation processes, shock wave generation and
293 free radical generation, which directly contributes to the degradation of many organic
294 compounds including phenolic compounds (He et al. 2012). On the other hand, in wine
295 samples exposed to cold plasma with helium/nitrogen as the working gas, an increase in
296 anthocyanin concentration was observed, which was the larger the longer the samples were
297 exposed to treatment. The total anthocyanin content after 2, 5, and 10 min was, respectively,
298 707.23, 747.74, and 755.25 mg/L. Also, higher anthocyanin concentrations were recorded in
299 the samples exposed to cold plasma with the addition of potassium metabisulfate compared to
300 the same samples exposed to cold plasma alone (Table S.1). This was probably related to the
301 protective effect of sulfate on anthocyanins discussed earlier in this section. We also observed
302 a similar relationship related to the working gas used. Again, wine samples exposed to cold
303 plasma generated using a mixture of helium and oxygen showed a higher reduction in the
304 anthocyanin content compared to samples using a mixture of helium and nitrogen as the
305 working gas. The disparities in the effect of the individual gases on anthocyanin stability were
306 probably due to the fact that the different gases produced different reactive compounds during
307 plasma generation. When oxygen is used in the working gas mixture, the plasma stream may
308 contain hydrogen peroxide, hydroxyl radical, peroxy anion or singlet oxygen, all of which
309 can cause significant degradation of anthocyanins (Arjunan et al. 2015). Since red wine is a
310 complex matrix and undergoes various chemical processes, the effects of different
311 preservation methods on phenolic compounds after three months of storage were also
312 analyzed. Interesting results were observed in most of the samples exposed to 5 min of cold
313 plasma. A higher content of some anthocyanins was noted compared to samples that were

314 plasma-treated for only 2 min (Table 2). In addition, the decrease in the anthocyanin content
315 compared to the sample preserved by the same method but not stored was also lower than
316 after a 2-min exposure to cold plasma. For example, for a 5-min cold plasma treatment with
317 helium/nitrogen as the working gas, the total anthocyanin content before storage was 747.74
318 mg/L and dropped after storage by 11.57 % to 661.23 mg/L. By contrast, a 2-min cold plasma
319 treatment resulted in a 30.27 % reduction in anthocyanins compared to the non-stored sample
320 (Table S.1). Moreover, higher anthocyanin contents were observed in the samples subjected to
321 5 min of cold plasma treatment without potassium metabisulfite, which was an inverse
322 relationship to that observed in the samples before storage. This may indicate that cold
323 plasma, despite the initial degradation of anthocyanins, produces a better overall preservation
324 effect than the mixed method. In addition, when samples with the same exposition time were
325 compared, the anthocyanin content in samples exposed to cold plasma generated using the
326 helium/nitrogen gas mixture was similar to that of the control sample and the sample with
327 30mg/L potassium metabisulfite, and 4.34 % higher than that of the sample with 100 mg/L
328 potassium metabisulfite.

329 The contents of phenolic acids such as gallic acid, protocatechuic acid, caftaric acid,
330 cutaric acid, caffeic acid, coumaric acid and ferulic acid were also determined in the studied
331 wine. Gallic acid was the most abundant of those compounds at concentrations from 9.52
332 mg/L to 11.86 mg/L. In the samples before storage, the highest total content of phenolic acids
333 was noted after a 2-min exposure to cold plasma – 24.68 mg/L (helium/nitrogen), a value that
334 was 8.25% higher compared to the control sample (Table S.1). A study conducted on white
335 wine by Lukić et al. (2019) also reported a slight increase in the content of some phenolic
336 acids as a result of cold plasma exposure. Cold plasma also had a beneficial effect on the
337 content of hydroxycinnamic acids in pomegranate juice (Herceg et al. 2016). Acids belonging
338 to this group are characterized by a higher stability, which probably translates into their lower
339 reactivity with the radicals formed during cold plasma generation.

340 In contrast to anthocyanins, the content of phenolic acids increased after storage in most
341 samples (Table S.1). Interesting results were observed for the content of protocatechuic acid.
342 In each sample after storage, the content of this acid increased compared to the non-stored
343 samples. However, cold plasma treatment (10 min, helium/nitrogen) resulted in a substantial,
344 up-to-4-fold increase in the content of this compound compared to non-stored samples (0.84
345 mg/L). The lowest content of this compound was observed in samples with 100mg/L
346 potassium metabisulfite (0.19 mg/L) (Table 2). The contents of other acids showed a similar

347 trend. Based on the literature data and our own results on the anthocyanin content, we can
 348 assume that such a large increase in protocatechuic acid in samples exposed to cold plasma
 349 was related to a decrease in the anthocyanin content. Under cold plasma treatment,
 350 anthocyanins degrade to phenolic acids, and the main products of their decomposition are
 351 protocatechuic, vanillic, syringic, and p-coumaric acids (Yang et al. 2018). Garofulić et al
 352 (2015), who evaluated the effect of cold plasma treatment on the contents of anthocyanins and
 353 phenolic acids in cherry juice, suggested that plasma acting on the food matrix for a short time
 354 caused the dissociation of agglomerates or particles, leading to an increase in the content of
 355 phenolic compounds.

356 In another experiment, we used ultraperformance chromatography to determine flavanols,
 357 flavan-3-ols, and stilbenes in the examined red wine samples. The content of flavanols in the
 358 wine was low and their total content ranged from 3.74 mg/L to 2.52 mg/L. The highest
 359 concentration was recorded in the non-stored control sample, while the lowest concentration
 360 was recorded after storage in the sample preserved by cold plasma (10 min, helium/nitrogen
 361 working gas) with the addition of potassium metabisulfite. The most abundant flavan-3-
 362 ols were (+)-catechin at 25.67 mg/L (sample no. 5) and procyanidin B1 at 10.46 mg/L (sample
 363 no. 12). *Cis* - and *trans*-resveratrol were also determined in the studied wine samples. The
 364 content of *cis*-resveratrol in the samples before and after storage was practically the same. A
 365 slight increase in its content was observed after storage in the sample exposed to cold plasma
 366 (10 min, helium/oxygen). An inverse correlation was noted for *trans*-resveratrol (Table S.1).

367 Table 2. Contents of selected phenolic compounds in red wine samples determined by UPLC-
 368 PDA-MS/MS (n=2)

Sample no.*	3gM (mg/L)	3gD (mg/L)	3gC (mg/L)	3kGM (mg/L)	3kGPet (mg/L)	3kGPeo (mg/L)	PCA (mg/L)
1	191.76 ±	82.38 ±	2.96 ±	45.67 ±	18.99 ±	4.94 ± 0.26	0.16 ±
	3.02	5.62	0.01	1.13	1.84		0.00
2	142.6 ±	49.26 ±	1.91 ± 0.01	27.87 ±	13.35 ±	2.92 ± 0.26	0.2 ±
	3.02	5.60		1.07	1.75		0.00
3	153.32 ±	50.93 ±	2.11 ± 0.01	31.25 ±	15.38 ±	3.22 ± 0.28	0.22 ±
	3.24	5.79		1.19	2.02		0.00
4	126.35 ±	39.49 ±	1.67 ± 0.01	23.74 ±	11.36 ±	2.48 ± 0.22	0.2 ±
	2.67	4.49		0.91	1.49		0.00

5	157.68 ± 3.34	55.64 ± 6.33	2.03 ± 0.01	33.75 ± 1.29	16.33 ± 2.15	3.32 ± 0.29	0.2 ± 0.00
6	166.42 ± 3.52	57.24 ± 6.51	2.07 ± 0.01	34.97 ± 1.34	16.4 ± 2.15	3.61 ± 0.32	0.21 ± 0.00
7	170.08 ± 3.60	58.03 ± 6.60	2.07 ± 0.01	35.98 ± 1.38	17.17 ± 2.26	3.63 ± 0.32	0.21 ± 0.00
8	182.88 ± 3.87	64.70 ± 7.36	2.44 ± 0.01	39.71 ± 1.52	19.23 ± 2.53	4.03 ± 0.35	0.17 ± 0.00
9	177.2 ± 3.75	64.19 ± 7.30	2.25 ± 0.01	37.73 ± 1.44	18.94 ± 2.49	3.89 ± 0.34	0.2 ± 0.00
10	170.57 ± 3.61	58.29 ± 6.63	2.2 ± 0.01	37.34 ± 1.43	17.98 ± 2.36	3.70 ± 0.33	0.22 ± 0.00
11	150.23 ± 9.16	57.69 ± 9.27	1.91 ± 0.05	30.75 ± 3.14	11.63 ± 0.89	2.99 ± 0.24	0.17 ± 0.01
12	178.48 ± 10.88	75.63 ± 12.16	2.41 ± 0.06	39.46 ± 4.03	15.64 ± 1.19	3.80 ± 0.31	0.18 ± 0.01
13	166.59 ± 10.16	72.04 ± 11.58	2.23 ± 0.05	38.68 ± 3.95	15.28 ± 1.16	3.63 ± 0.30	0.18 ± 0.01
14	171.68 ± 10.47	69.42 ± 11.16	2.08 ± 0.05	38.43 ± 3.93	14.93 ± 1.14	3.66 ± 0.30	0.19 ± 0.01
15	190.82 ± 11.63	64.7 ± 13.17	2.43 ± 0.06	43.86 ± 4.48	17.36 ± 1.32	3.96 ± 0.32	0.13 ± 0.01
16	149.42 ± 9.11	61.47 ± 9.88	2.12 ± 0.05	30.64 ± 3.13	12.09 ± 0.92	2.94 ± 0.24	0.32 ± 0.02
17	106.81 ± 6.51	15.13 ± 2.43	0.41 ± 0.01	18.55 ± 1.90	7.43 ± 0.57	2.03 ± 0.17	0.79 ± 0.06
18	121.59 ± 7.41	40.16 ± 6.46	1.45 ± 0.04	22.42 ± 2.29	8.69 ± 0.66	2.27 ± 0.19	0.7 ± 0.05
19	54.59 ± 3.33	14.78 ± 2.38	0.52 ± 0.01	6.96 ± 0.71	3.05 ± 0.23	1.07 ± 0.09	0.8 ± 0.06
20	101.6 ± 6.19	11.50 ± 1.85	0.34 ± 0.01	17.1 ± 1.75	6.32 ± 0.48	1.88 ± 0.15	0.78 ± 0.06
21	138.68 ±	53.03 ±	1.67 ± 0.10	26.58 ±	13.18 ±	2.59 ± 0.01	0.73 ±

	2.00	6.97		0.43	2.12		0.02
22	79.88 ± 1.15	12.89 ± 1.69	0.39 ± 0.04	11.36 ± 0.18	5.78 ± 0.93	1.44 ± 0.01	0.84 ± 0.02
23	143.55 ± 2.07	61.70 ± 8.11	2.28 ± 0.14	28.27 ± 0.46	14.36 ± 2.31	2.83 ± 0.01	0.25 ± 0.01
24	92.75 ± 1.34	7.81 ± 1.03	0.25 ± 0.02	14.19 ± 0.23	7.29 ± 1.17	1.63 ± 0.01	0.81 ± 0.02
25	97.01 ± 1.40	11.90 ± 1.56	0.33 ± 0.02	15.12 ± 0.25	7.74 ± 1.24	1.71 ± 0.01	0.79 ± 0.02
26	76.38 ± 1.10	19.42 ± 2.55	0.67 ± 0.04	11.26 ± 0.18	5.9 ± 0.95	1.4 ± 0.01	0.80 ± 0.02
27	84.70 ± 1.22	9.37 ± 1.23	0.28 ± 0.02	12.73 ± 0.21	6.49 ± 1.04	1.52 ± 0.01	0.84 ± 0.02
28	100.49 ± 1.45	23.42 ± 3.08	0.67 ± 0.04	16.68 ± 0.27	8.91 ± 1.43	1.83 ± 0.01	0.83 ± 0.02
29	97.29 ± 1.40	34.25 ± 4.50	1.18 ± 0.07	17.31 ± 0.28	8.86 ± 1.42	1.92 ± 0.01	0.74 ± 0.02
30	132.67 ± 1.91	57.73 ± 7.58	2.07 ± 0.13	26.45 ± 0.43	13.35 ± 2.15	2.7 ± 0.01	0.19 ± 0.00

369 3gM – malvidin 3-O-glucoside; 3gD – delphinidin 3-O-glucoside; 3gC – cyanidin 3-O-
370 glucoside; 3kGM – malvidin 3-O-(600-O-coumaryl)-glucoside; 3kGPet – petunidin 3-O-(600-
371 O-coumaryl)-glucoside; 3kGPeo – peonidin 3-O-(60 0-O-coumaryl)-glucoside; PCA –
372 protocatechuic acid

373 * the coding of the samples is shown in Table 1

374 3.2 Biogenic amine content

375 DLLME-GC-MS was applied to determine the concentrations of biogenic amines in
376 the red wine samples analyzed. The results are presented in Table 3. Six biogenic amines were
377 identified: TRP, PUT, HIS, TYR, CAD and 2-PE, with histamine having the highest
378 concentrations in all samples. This finding corresponds with the results reported by other
379 researchers who indicate that histamine is the most abundant biogenic amine in wines (Plotka
380 et al. 2018). High concentrations of histamine in a product can cause negative health effects in
381 the consumer, so it is important to use methods that will reduce the content of this compound
382 in the food matrix (Esposito et al. 2019). In our experiment, the highest HIS content was
383 found in the unpreserved control sample (before storage: 818 ± 34 µg/L; after storage: 821 ±

384 30 µg/L). A significantly lower content of this compound was observed in the sample that had
 385 been exposed to cold plasma for 10 min using a helium/oxygen mixture as the working gas
 386 (584 ± 34 µg/L) in combination with the addition of 30 mg/L potassium metabisulfite. Also
 387 after three months of storage, the HIS content of this sample did not change significantly (586
 388 ± 33 µg/L). When the effect of the wine preservation method on the content of other biogenic
 389 amines was analyzed, in all cases the 10-min application of cold plasma (helium/oxygen as
 390 working gas) with 30 mg/L potassium metabisulfite resulted in the highest reduction in the
 391 level of these compounds. Moreover, this effect persisted after storage. To date, the literature
 392 provides no information on or explanation of the effect of cold plasma on the content of
 393 biogenic amines in wine. However, because the formation of these compounds depends
 394 mainly on the microorganisms present in the food matrix (Restuccia et al. 2018), it can be
 395 assumed that cold plasma, which has a well-proven biocidal activity against unwanted
 396 microorganisms, indirectly contributes to the reduction of biogenic amines in food products
 397 (Bourke et al. 2017; Lu et al. 2014). Our results also showed that the efficiency of cold
 398 plasma in reducing biogenic amines in wine samples was affected by the duration of treatment
 399 and the type of working gas used. Increasing the duration of the process to 10 min and the use
 400 of a mixture of helium and oxygen as the working gas favourably affected the elimination of
 401 these compounds from the product matrix. The influence of the duration of the process as well
 402 as the type of gases used on the sterilizing efficiency of cold plasma has also been
 403 demonstrated by other authors. Hou et al. (2019), who sterilized blueberry juice using cold
 404 plasma for 2, 4 and 6 min, recorded the highest reduction in *Bacillus* spp. populations after the
 405 time of 6 min. Also our previous study on the effects of cold plasma on *Lentilactobacillus*
 406 *hilgardii* cells showed that increasing the duration of the process as well as using a mixture of
 407 helium and oxygen as the working gas resulted in higher cell reduction than using a mixture
 408 of helium and nitrogen (Niedźwiedź et al. 2020).

409 Table 3. Concentrations of selected biogenic amines determined in wine samples by DLLME-
 410 GC-MS; $n=3$

411

Sample no.*	TRP (µg/L)	PUT (µg/L)	HIS (µg/L)	TYR (µg/L)	CAD (µg/L)	2-PE (µg/L)
1	4.089 ± 0.012	489 ± 25	818 ± 34	27.74 ± 0.16	58.73 ± 0.15	18.70 ± 0.054
2	3.670 ± 0.011	475 ± 24	799 ± 31	27.58 ± 0.17	54.15 ± 0.12	18.68 ± 0.049
3	3.578 ± 0.008	455 ± 25	734 ± 37	27.34 ± 0.17	52.21 ± 0.12	18.73 ± 0.047

4	3.551 ± 0.009	449 ± 23	732 ± 36	26.43 ± 0.13	52.01 ± 0.14	18.63 ± 0.050
5	3.662 ± 0.010	471 ± 22	784 ± 29	27.51 ± 0.18	53.94 ± 0.13	18.71 ± 0.048
6	3.589 ± 0.008	466 ± 27	741 ± 33	27.44 ± 0.16	52.27 ± 0.11	18.75 ± 0.044
7	3.540 ± 0.010	457 ± 22	742 ± 34	26.78 ± 0.17	52.22 ± 0.13	18.66 ± 0.051
8	2.918 ± 0.008	344 ± 25	654 ± 34	<LOD	48.29 ± 0.16	23.74± 0.044
9	2.705 ± 0.011	324 ± 23	627 ± 38	<LOD	44.54 ± 0.14	23.77± 0.047
10	2.678 ± 0.013	299 ± 20	622 ± 33	<LOD	39.79 ± 0.12	23.68± 0.050
11	1.972 ± 0.006	278 ± 19	584 ± 34	<LOD	38.09 ± 0.14	23.76± 0.048
12	2.802 ± 0.014	348 ± 24	654 ± 38	<LOD	43.87 ± 0.16	23.72± 0.051
13	2.732 ± 0.016	320 ± 21	641 ± 32	<LOD	40.17 ± 0.13	23.63± 0.047
14	2.052 ± 0.008	291 ± 19	601 ± 36	<LOD	37.89 ± 0.11	23.69± 0.052
15	3.878 ± 0.013	466 ± 23	773 ± 30	<LOD	52.42 ± 0.17	25.88± 0.054
16	4.086 ± 0.011	490 ± 24	821 ± 30	27.71 ± 0.15	58.66 ± 0.18	18.78 ± 0.044
17	3.674 ± 0.010	479 ± 22	794 ± 29	27.66 ± 0.16	54.05 ± 0.14	18.75 ± 0.043
18	3.581 ± 0.012	457 ± 24	739 ± 35	27.91 ± 0.14	52.18 ± 0.13	18.79 ± 0.051
19	3.560 ± 0.010	449 ± 21	732 ± 33	26.38 ± 0.12	52.09 ± 0.18	18.60 ± 0.044
20	3.669 ± 0.010	476 ± 26	789 ± 31	27.79 ± 0.21	53.99 ± 0.15	18.77 ± 0.044
21	3.593 ± 0.013	471 ± 23	748 ± 27	27.49 ± 0.18	52.30 ± 0.17	18.70 ± 0.038
22	3.547 ± 0.011	457 ± 20	739 ± 31	26.85 ± 0.15	52.28 ± 0.10	18.71 ± 0.047
23	2.915 ± 0.009	349 ± 24	658 ± 33	<LOD	48.33 ± 0.16	23.81± 0.056
24	2.711 ± 0.013	332 ± 21	629 ± 38	<LOD	44.50 ± 0.19	23.84± 0.031
25	2.684 ± 0.012	309 ± 24	617 ± 31	<LOD	39.83 ± 0.10	23.77± 0.062
26	1.979 ± 0.011	279 ± 19	586 ± 33	<LOD	38.04 ± 0.14	23.85± 0.045
27	2.811 ± 0.017	353 ± 22	659 ± 36	<LOD	43.95 ± 0.11	23.77± 0.044
28	2.729 ± 0.014	320 ± 19	646 ± 31	<LOD	40.20 ± 0.17	23.56± 0.039

29	2.058 ± 0.009	289 ± 21	613 ± 35	<LOD	37.84 ± 0.15	23.71± 0.057
30	3.874 ± 0.012	469 ± 25	773 ± 34	<LOD	52.47 ± 0.20	25.93± 0.061

412 TRP – tryptamine, PUT – putrescine, HIS – histamine, TYR – tyramine, CAD – cadaverine,
413 2-PE – 2-phenylethylamine

414 * the coding of the samples is shown in Table 1.

415 3.3 Chemometric analysis

416 The major goal of multivariate statistical data mining was to reveal hidden specific relations
417 between differently treated (different preservation conditions) wine samples (a total of 30
418 cases) characterized by 13 chemical variables (bioamines and phenolic compounds). Another
419 important task was to find similarity patterns depending on the storage conditions and, beyond
420 that, to identify specific chemical descriptors responsible for the classification of the different
421 wine samples.

422 The following chemometric methods were used in the intelligent data analysis:

- 423 • Cluster analysis (hierarchical and non-hierarchical or K-means clustering);
- 424 • Two-way joining;
- 425 • Principal components analysis and factor analysis.

426 Hierarchical clustering was performed on standardized input data (z-normalization), with
427 squared Euclidean distance as a similarity measure, using Ward's method of linkage and
428 Sneath's significance test. Fig. 2 A1 shows a hierarchical clustering dendrogram of the 13
429 chemical variables. Three major clusters were identified at Sneath's significance level of
430 1/3Dmax:

431 C1: 3gM, 3kGM, 3kGPeo, 3kGPet, 3gD, 3gC – phenolic cluster;

432 C2: HIS, PUT, TRP, CAD, TYR – amine cluster;

433 C3: 2PE, PCA – mixed cluster.

434 The hierarchical clustering of the chemical variables identified three patterns of similarity
435 which could be conditionally determined as phenolic, amine and mixed clusters. There was a
436 good separation between the phenolic and the amine variables, which indicated that both
437 groups of variables had a separate impact on the quality of the different wine samples which
438 was unrelated to the preservation or storage conditions. Fig. 2 A2 shows a hierarchical

439 dendrogram linking 30 wine samples (with different preservation and storage conditions).
440 Three major clusters of cases were formed (under the same clustering conditions):

441 C1: 17, 19, 20, 22, 24, 25, 26, 27, 28, 29 – samples after storage and preservation by plasma
442 and by plasma in combination with potassium metabisulfite;

443 C2: 8, 9, 10, 11, 12, 13, 14, 23 – samples before storage with preservation by plasma and
444 potassium metabisulfite;

445 C3: 1, 2, 3, 4, 5, 6, 7, 15, 16, 18, 21, 30 – samples before storage with plasma preservation.

446 Cluster 1 mainly included samples after storage preserved by plasma and plasma plus
447 potassium metabisulfite. Cluster 2 chiefly consisted of samples before storage but preserved
448 by plasma or by potassium metabisulfite. Cluster 3 aggregated 12 plasma-preserved samples
449 before storage. The clustering of the wine samples showed separation into patterns which
450 differed in the treatment and storage conditions.

451 K-means clustering is a non-supervised clustering method in which clusters are not
452 formed spontaneously but according to a preliminary hypothesis regarding the possible
453 number of clusters. This a priori segmentation is based on an algorithm which selects
454 centroids in the dataset under a predefined distance measure. The results of K-means
455 clustering for the formation of 3 clusters of variables and 3 clusters of cases were identical to
456 those obtained by hierarchical clustering. The members of the non-hierarchical clusters were
457 the same. This is illustrated in Table 3 in Supplementary Materials (S.3) which shows cluster
458 membership data for cases and variables along with the respective distances between the
459 members in each identified cluster. It was important to reveal the role of the chemical
460 variables as specific descriptors for each of the identified clusters. Fig. 3A presents the
461 average values of each chemical variable for each cluster. The cluster which included plasma-
462 preserved samples before storage (C1 in the plot below) was characterized by the highest
463 levels of amines, moderate (rather high) levels of phenolic compounds and low levels of 2-
464 PE and PCA. The cluster with samples before storage, preserved by plasma and potassium
465 metabisulfite (C2 in the plot below) was characterized by the lowest levels of amines, the
466 highest levels of phenolic compounds, the highest level of 2-PE, and the lowest level of PCA.
467 The cluster with samples stored after preservation by plasma and by plasma in combination
468 with potassium metabisulfite (C3 in the plot below) was characterized by moderate levels of
469 amines, the lowest levels of phenolic compounds, moderate levels of 2-PE and the highest
470 levels of PCA. It is readily seen that the storage conditions led to changes in the levels of all

471 the chemical variables, which additionally depended on the preservation treatment used. In
472 general, the levels of phenolic compounds fell after storage, whereas levels of amines were
473 high before storage and plasma preservation but decreased substantially following
474 preservation with potassium metabisulfite or after storage.

475 The relationship between the chemical variables and the wine samples is shown
476 additionally in the plot of the results of two-way joining cluster analysis, in which variables
477 and cases are in respective correspondence (Fig. 3B).

478 The plot confirms the conclusions above about the determination of specific chemical
479 descriptors for the wine sample clusters.

480 Both chemometric methods are very similar and their basic task is to find hidden
481 factors (principal components or factors) responsible for the structure of the data matrix.
482 Additionally, they are typical projection methods and, as such, lead to a dimensionality
483 reduction of the system under consideration. In the working algorithm, the data matrix is
484 decomposed into a factor loading matrix and a factor score matrix, the former presenting the
485 newly defined special directions in the variables space, and the latter – the new coordinates of
486 the objects. Both of these matrices need to be correctly interpreted in order to find specific
487 relationships between objects and variables. In our dataset, two latent factors were responsible
488 for the data structure. The first of them, which explained 51.3 % of the total variance of the
489 system, could be tentatively named the “phenolic factor”, and the second factor, with 40.5 %
490 of explained variance could be called the “amine factor”. This is largely consistent with the
491 results of cluster analysis. Table 4 (Supplementary Materials S.4), in which statistically
492 significant loadings are given in bold, shows that the variables 2-PE and PCA are reversely
493 correlated to the rest of the significant factor loadings with regard to factor 1 and factor 2, and
494 this specificity corresponds to the formation of the mixed cluster in cluster analysis. An
495 interpretation of the data in the loadings table leads to the conclusion that the data structure is
496 dependent on two latent relationships between the variables – a relationship between phenolic
497 compounds as a similarity group and a relationship between biogenic amines as another
498 similarity pattern. The graphical plot of the factor loadings in Fig. 2B clearly illustrates these
499 relationships. Both clusters of variables are well-defined, and the more specific role of 2-PE
500 as opposite to the amine group and PCA as opposite to the phenolic group is indicated. The
501 factor scores plot illustrates the formation of three patterns of similarity between the wine
502 samples. It matches the hierarchical and K-means clusters of wine samples almost perfectly.



503

504 4. Conclusion

505 In this study, for the first time, the effect of cold plasma on the content of phenolic
506 compounds and biogenic amines in red wine was evaluated with respect to storage time. In
507 addition, the effect of cold plasma was compared with the traditional method of preservation
508 (addition of 30 mg/L and 100 mg/L of potassium metabisulfite) and a combined method (cold
509 plasma with 30 mg/L of potassium metabisulfite). In general, cold plasma treatment caused a
510 decrease in the total content of phenolic compounds in the wine samples subjected to three
511 months of storage. However, the application of cold plasma for 5 min with helium/nitrogen as
512 the working gas reduced the content of these compounds by only 2.85 % compared to the
513 control. Moreover, the content of phenolic compounds was 3.1% higher in the sample
514 preserved by this method compared to the sample preserved by the addition of potassium
515 metabisulfite at a dose of 100 mg/L. Additionally, cold plasma increased the content of
516 phenolic acids in the studied samples. Importantly, the use of cold plasma resulted in a
517 reduction of biogenic amines, which can cause adverse health reactions in the consumer. The
518 highest degree of reduction was observed in the samples exposed to 10 min of cold plasma
519 (helium/oxygen). Our results indicate that the influence of the storage process as well as the
520 preservation method on the phenolic profile and the content of biogenic amines is not
521 unambiguous and depends mainly on the chemical properties of the individual compounds.
522 However, the reported effects of cold plasma and cold plasma combined with the addition of
523 potassium metabisulfite on the analyzed compounds allow us to assume that in the future
524 these methods can be successfully used to reduce the use of SO₂ in winemaking.

525 To conclude, cold plasma may become an alternative method for the preservation of wine or
526 other alcoholic beverages in the future, ensuring adequate product safety and preserving the
527 pro-health values of these products. However, further research is needed to optimize the
528 process conditions of cold plasma treatment.

529 CRediT authorship contribution statement

530

531 **Iwona Niedźwiedź:** Conceptualization, Project administration, Investigation, Methodology,
532 Validation, Writing – original draft, Visualization. **Justyna Płotka-Wasyłka:** Methodology,
533 Software, Validation, Resources, Writing – original draft, Writing – review & editing.
534 **Ireneusz Kapusta:** Methodology, Software. **Vasil Simeonov:** Methodology, Software,



535 Writing – original draft, Writing – review & editing. **Anna Stój:** Resources, Validation.
536 **Adam Waśko:** Conceptualization, Writing – review & editing. **Joanna Pawlat:** Resources,
537 Writing – original draft, Visualization **Magdalena Polak-Berecka:** Supervision,
538 Conceptualization, Project administration, Writing – review & editing
539

540 References

- 541 Alves Filho, E. G., de Brito, E. S., & Rodrigues, S. (2020). Effects of cold plasma
542 processing in food components. In *Advances in Cold Plasma Applications for Food Safety*
543 *and Preservation* (pp. 253-268). Academic Press. [https://doi.org/10.1016/B978-0-12-](https://doi.org/10.1016/B978-0-12-814921-8.00008-6)
544 [814921-8.00008-6](https://doi.org/10.1016/B978-0-12-814921-8.00008-6).
- 545 Arjunan, K. P., Sharma, V. K., & Ptasińska, S. (2015). Effects of atmospheric pressure
546 plasmas on isolated and cellular DNA—a review. *International Journal of Molecular*
547 *Sciences, 16*(2), 2971-3016. <https://doi.org/10.3390/ijms16022971>.
- 548 Bourke, P., Ziuzina, D., Han, L., Cullen, P. J., & Gilmore, B. F. (2017). Microbiological
549 interactions with cold plasma. *Journal of Applied Microbiology, 123*(2), 308-324.
550 <https://doi.org/10.1111/jam.13429>.
- 551 Christofi, S., Malliaris, D., Katsaros, G., Panagou, E., & Kallithraka, S. (2020). Limit SO₂
552 content of wines by applying High Hydrostatic Pressure. *Innovative Food Science &*
553 *Emerging Technologies, 62*, 102342. <https://doi.org/10.1016/j.ifset.2020.102342>.
- 554 Cordero-Bueso, G., Moraga, J., Ríos-Carrasco, M., Ruiz-Muñoz, M., Cantoral, J. M.
555 (2019). Bacteriophages as an Up-and-Coming Alternative to the Use of Sulfur Dioxide in
556 Winemaking. *Frontiers in Microbiology, 10*. <https://doi.org/10.3389/fmicb.2019.02931>.
- 557 Esparza, I., Martínez-Inda, B., Cimminelli, M. J., Jimeno-Mendoza, M. C., Moler, J. A.,
558 Jiménez-Moreno, N., & Ancín-Azpilicueta, C. (2020). Reducing SO₂ doses in red wines
559 by using grape stem extracts as antioxidants. *Biomolecules, 10*(10), 1369.
560 <https://doi.org/10.3390/biom10101369>.
- 561 Esposito, F., Montuori, P., Schettino, M., Velotto, S., Stasi, T., Romano, R., & Cirillo, T.
562 (2019). Level of biogenic amines in red and white wines, dietary exposure, and histamine-
563 mediated symptoms upon wine ingestion. *Molecules, 24*(19), 3629.
564 <https://doi.org/10.3390/molecules24193629>.

- 565 Gajek, M., Pawlaczyk, A., & Szykowska-Jozwik, M. I. (2021). Multi-Elemental
566 Analysis of Wine Samples in Relation to Their Type, Origin, and Grape Variety.
567 *Molecules*, 26(1), 214. <https://doi.org/10.3390/molecules26010214>.
- 568 Garofulić, I. E., Jambrak, A. R., Milošević, S., Dragović-Uzelac, V., Zorić, Z., & Herceg,
569 Z. (2015). The effect of gas phase plasma treatment on the anthocyanin and phenolic acid
570 content of sour cherry Marasca (*Prunus cerasus* var. Marasca) juice. *LWT-Food Science*
571 *and Technology*, 62(1), 894-900. <https://doi.org/10.1016/j.lwt.2014.08.036>.
- 572 Gavahian, M., Chu, Y. H., Khaneghah, A. M., Barba, F. J., & Misra, N. N. (2018). A
573 critical analysis of the cold plasma induced lipid oxidation in foods. *Trends in Food*
574 *Science & Technology*, 77, 32-41. <https://doi.org/10.1016/j.tifs.2018.04.009>.
- 575 He, F., Liang, N. N., Mu, L., Pan, Q. H., Wang, J., Reeves, M. J., & Duan, C. Q. (2012).
576 Anthocyanins and their variation in red wines I. Monomeric anthocyanins and their color
577 expression. *Molecules*, 17(2), 1571-1601.. <https://doi.org/10.3390/molecules17021571>.
- 578 Herceg, Z., Kovačević, D. B., Kljusurić, J. G., Jambrak, A. R., Zorić, Z., & Dragović-
579 Uzelac, V. (2016). Gas phase plasma impact on phenolic compounds in pomegranate
580 juice. *Food Chemistry*, 190, 665-672. <https://doi.org/10.1016/j.foodchem.2015.05.135>.
- 581 Hou, Y., Wang, R., Gan, Z., Shao, T., Zhang, X., He, M., & Sun, A. (2019). Effect of cold
582 plasma on blueberry juice quality. *Food Chemistry*, 290, 79-86.
583 <https://doi.org/10.1016/j.foodchem.2019.03.123>.
- 584 Kapusta, I., Cebulak, T., & Oszmiański, J. (2018). Characterization of polish wines
585 produced from the interspecific hybrid grapes grown in south-east Poland. *European Food*
586 *Research and Technology*, 244(3), 441-455. <https://doi.org/10.1007/s00217-017-2972-5>.
- 587 Khoo, H. E., Azlan, A., Tang, S. T., & Lim, S. M. (2017). Anthocyanidins and
588 anthocyanins: colored pigments as food, pharmaceutical ingredients, and the potential
589 health benefits. *Food & Nutrition Research*, 61(1), 1361779.
590 <https://doi.org/10.1080/16546628.2017.1361779>.
- 591 Kim, M., Yoon, S. H., Jung, M., & Choe, E. (2010). Stability of meoru (*Vitis coignetiea*)
592 anthocyanins under photochemically produced singlet oxygen by riboflavin. *New*
593 *Biotechnology*, 27(4), 435-439. <https://doi.org/10.1016/j.nbt.2010.01.003>.

- 594 Koźmiński, C., Mąkosza, A., Michalska, B., & Nidzgorska-Lencewicz, J. (2020). Thermal
595 Conditions for Viticulture in Poland. *Sustainability*, 12(14), 5665.
596 <https://doi.org/10.3390/su12145665>.
- 597 Lu, H., Patil, S., Keener, K. M., Cullen, P. J., & Bourke, P. (2014). Bacterial inactivation
598 by high- voltage atmospheric cold plasma: influence of process parameters and effects on
599 cell leakage and DNA. *Journal of Applied Microbiology*, 116(4), 784-794.
600 <https://doi.org/10.1111/jam.12426>.
- 601 Lukić, K., Vukušić, T., Tomašević, M., Ćurko, N., Gracin, L., & Ganić, K. K. (2019). The
602 impact of high voltage electrical discharge plasma on the chromatic characteristics and
603 phenolic composition of red and white wines. *Innovative Food Science & Emerging
604 Technologies*, 53, 70-77. <https://doi.org/10.1016/j.ifset.2017.11.004>.
- 605 Manns, D. C., Coquard Lenerz, C. T., & Mansfield, A. K. (2013). Impact of processing
606 parameters on the phenolic profile of wines produced from hybrid red grapes Maréchal
607 Foch, Corot noir, and Marquette. *Journal of Food Science*, 78(5), C696-C702.
608 <https://doi.org/10.1111/1750-3841.12108>.
- 609 Matuszewski, B. K., Constanzer, M. L., & Chavez-Eng, C. M. (2003). Strategies for the
610 Assessment of Matrix Effect in Quantitative Bioanalytical Methods Based on
611 HPLC–MS/MS. *Analytical Chemistry*, 75(13), 3019–3030.
612 <https://doi.org/10.1021/AC020361S>
- 613 Naila, A., Flint, S., Fletcher, G., Bremer, P., & Meerdink, G. (2010). Control of biogenic
614 amines in food—existing and emerging approaches. *Journal of Food Science*, 75(7),
615 R139-R150. <https://doi.org/10.1111/j.1750-3841.2010.01774.x>.
- 616 Niedźwiedź, I., Juzwa, W., Skrzypiec, K., Skrzypek, T., Waško, A., Kwiatkowski, M., ...
617 & Polak-Berecka, M. (2020). Morphological and physiological changes in
618 *Lentilactobacillus hilgardii* cells after cold plasma treatment. *Scientific Reports*, 10(1), 1-
619 14. <https://doi.org/10.1038/s41598-020-76053-x>.
- 620 Niedźwiedź, I., Waško, A., Pawłat, J., Polak-Berecka, M. (2019). The state of research on
621 antimicrobial activity of cold plasma. *Polish Journal of Microbiology*, 68(2), 153-164.
622 <https://doi.org/10.33073/pjm-2019-028>.
- 623 Niu, D., Wang, L. H., Zeng, X. A., Wen, Q. H., Brennan, C. S., Tang, Z. S., Wang, M. S.
624 (2019). Effect of ethanol adaption on the inactivation of *Acetobacter* sp. by pulsed electric

625 fields. *Innovative Food Science & Emerging Technologies*, 52, 25 – 33.
626 <https://doi.org/10.1016/j.ifset.2018.11.009>.

627 Papageorgiou, M., Lambropoulou, D., Morrison, C., Kłodzińska, E., Namieśnik, J.,
628 Płotka-Wasyłka, J. (2018) Literature update of analytical methods for biogenic amines
629 determination in food and beverages. *TrAC Trends in Analytical Chemistry*, 98, 128-142.
630 <https://doi.org/10.1016/j.trac.2017.11.001>.

631 Płotka-Wasyłka, J., Simeonov, V., & Namieśnik, J. (2018a). Impact of selected
632 parameters of the fermentation process of wine and wine itself on the biogenic amines
633 content: Evaluation by application of chemometric tools. *Microchemical Journal*, 142,
634 187-194. <https://doi.org/10.1016/j.microc.2018.06.038>.

635 Płotka-Wasyłka, J., Simeonov, V., & Namieśnik, J. (2018b). Evaluation of the impact of
636 storage conditions on the biogenic amines profile in opened wine bottles. *Molecules*,
637 23(5), 1130. <https://doi.org/10.1016/j.jfca.2017.07.042>

638 Puligundla, P., Pyun, Y. R., Mok, C. (2018). Pulsed electric field (PEF) technology for
639 microbial inactivation in low-alcohol red wine. *Food Science and Biotechnology*, 27(6),
640 1691-1696. <https://doi.org/10.1007/s10068-018-0422-1>.

641 Restuccia, D., Loizzo, M. R., & Spizzirri, U. G. (2018). Accumulation of biogenic amines
642 in wine: role of alcoholic and malolactic fermentation. *Fermentation*, 4(1), 6.
643 <https://doi.org/10.3390/fermentation4010006>.

644 Robles, A. D., Fabjanowicz, M., Płotka-Wasyłka, J., & Konieczka, P. (2019). Organic
645 acids and polyphenols determination in Polish wines by ultrasound-assisted solvent
646 extraction of porous membrane-packed liquid samples. *Molecules*, 24(23), 4376.
647 <https://doi.org/10.3390/molecules24234376>.

648 Smit, A. Y., Engelbrecht, L., & Du Toit, M. (2012). Managing your wine fermentation to
649 reduce the risk of biogenic amine formation. *Frontiers in Microbiology*, 3, 76.
650 <https://doi.org/10.3389/fmicb.2012.00076>.

651 Snopek, L., Mlcek, J., Sochorova, L., Baron, M., Hlavacova, I., Jurikova, T., ... & Sochor,
652 J. (2018). Contribution of red wine consumption to human health protection. *Molecules*,
653 23(7), 1684. <https://doi.org/10.3390/molecules23071684>.

654 Stój, A., Kapusta, I., & Domagała, D. (2020). Classification of red wines produced from
655 Zweigelt and Rondo grape varieties based on the analysis of phenolic compounds by

656 UPLC-PDA-MS/MS. *Molecules*, 25(6), 1342.
657 <https://doi.org/10.3390/molecules25061342>.

658 Yang, P., Yuan, C., Wang, H., Han, F., Liu, Y., Wang, L., & Liu, Y. (2018). Stability of
659 anthocyanins and their degradation products from cabernet sauvignon red wine under
660 gastrointestinal pH and temperature conditions. *Molecules*, 23(2), 354.
661 <https://doi.org/10.3390/molecules23020354>.

662 Yue, X. F., Jing, S. S., Ni, X. F., Zhang, K. K., Fang, Y. L., Zhang, Z. W., & Ju, Y. L.
663 (2021). Anthocyanin and Phenolic Acids Contents Influence the Color Stability and
664 Antioxidant Capacity of Wine Treated With Mannoprotein. *Frontiers in Nutrition*, 8, 335.
665 <https://doi.org/10.3389/fnut.2021.691784>.

666 Figure Captions

667 Figure 1. A. Experimental set-up for plasma treatment of wine: 1– plasma jet reactor; 2 –
668 sample in a glass container; 3 – magnetic stirrer; 4 – high voltage power supply; 5 – gas
669 flow controller. B. Voltage signal between electrodes for the selected gas mixtures.

670 Figure 2. A. Hierarchical dendrogram. 1) clustering of 13 chemical variables 2) –
671 clustering of wine samples. B. 1) Plot of factor loadings. 2) Plot of factor scores. 3gM –
672 malvidin 3-O-glucoside; 3gD – delphinidin 3-O-glucoside; 3gC – cyanidin 3-O-glucoside;
673 3kGM – malvidin 3-O-(600-O-coumaryl)-glucoside; 3kGPet – petunidin 3-O-(600-O-
674 coumaryl)-glucoside; 3kGPeo – peonidin 3-O-(60 0-O-coumaryl)-glucoside; PCA –
675 protocatechuic acid; TRP – tryptamine, PUT – putrescine, HIS – histamine, TYR –
676 tyramine, CAD – cadaverine, 2-PE – 2-phenylethylamine.

677 Figure 3. A. Plot of means for each variable for each identified cluster B. Correspondence
678 between wine samples and chemical variables. . 3gM – malvidin 3-O-glucoside; 3gD –
679 delphinidin 3-O-glucoside; 3gC – cyanidin 3-O-glucoside; 3kGM – malvidin 3-O-(600-O-
680 coumaryl)-glucoside; 3kGPet – petunidin 3-O-(600-O-coumaryl)-glucoside; 3kGPeo –
681 peonidin 3-O-(60 0-O-coumaryl)-glucoside; PCA – protocatechuic acid; TRP –
682 tryptamine, PUT – putrescine, HIS – histamine, TYR – tyramine, CAD – cadaverine, 2-
683 PE – 2-phenylethylamine.

684