

1     **An analytical hierarchy process for selection of the optimal procedure for resveratrol**  
2                                    **determination in wine samples**

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8     **Abstract**

9     The study shows the application of analytical hierarchy process (AHP) in ranking the analytical procedures, that  
10    are applied for resveratrol determination in wine samples. 19 different analytical methodologies are described by  
11    metrological, economic and environmental criteria, that are further divided into 10 subcriteria. Before AHP  
12    application , the amount of input data is decreased with cluster analysis. The first run of AHP is aimed to rank  
13    the clustered analytical procedures, while the second analysis is performed to select the best procedure from the  
14    cluster with the highest rank obtained in the first AHP run. The procedure based on a direct sample injection to  
15    high performance liquid chromatography with UV detection is the most beneficial one. AHP is excellent tool for  
16    the assessment and the selection of the most appropriate analytical procedure from several available. The choice  
17    of MCDA method is dictated by the fact, that so far, no examples of the usage of a given method for the  
18    selection of the optimal analytical procedure have been found in the literature.

19

20    **Keywords:** wine samples analysis; multi-criteriadecision analysis; AHP; sample preparation

21

22     **1. Introduction**

23    Without a doubt, the relationship between diet and health has developed an intense research in bioactive  
24    compounds in foods. Among food and beverages products, wine seems to be an essential component and may be  
25    partially responsible for health-promoting properties. Wine, especially the red variety, has been studied

26 extensively over many years. It is well known, that moderate consumption of red wine, is associated with several  
27 potential health benefits, such as lower risk of cardiovascular or neurological diseases and anti-cancer properties  
28 [1].

29 The most significant and beneficial health properties of wine consumption are related to compounds with high  
30 antioxidant capacity like polyphenols, including trans-resveratrol [1].

31 Resveratrol is a phenolic compound, occurring naturally in over-ground part of plants, mainly in seeds, skin and  
32 leaves. It is synthesized from phenylalanine through the shikimic pathway and three key enzymes are involved in  
33 this pathway: coenzyme A ligase, phenylalanine ammonium lyase, and stilbene synthase. The biosynthesis of  
34 these enzymes can be induced by stress, thus resveratrol is a phytoalexin synthesized by grapes after exposure to  
35 biotic or abiotic stress [1]. Therefore, it can be stated, that resveratrol is produced in grapes as self-protection  
36 against toxins and it can be found within the skins [2]. The persistence of the grape skins during the fermentation  
37 process impacts on the resveratrol content in final products, meaning wines. The concentration of this compound  
38 is lower in white wine than in red wine, due to the fact, that skins are removed earlier during production of the  
39 white wines [3].

40 Resveratrol has recently been the subject of intensive investigation. This is mainly due to being reported as a  
41 potent antioxidant, anticancer, anti-inflammatory and chemoprotective agent. Moreover, this compound is  
42 associated with increased longevity, and cardiovascular protective effects, due to its ability to reduce platelet  
43 aggregation, modulate lipid metabolism, and inhibit oxidation of low density lipoprotein, [4, 5]. The increased  
44 awareness of the trans-resveratrol beneficial impact on human health and the challenges associated with its low  
45 and variable abundance in samples characterized by complex matrix composition, have driven the need to  
46 develop rapid and reliable methods for resveratrol analysis in wine and related samples. Many analytical  
47 procedures have been developed for determination of resveratrol in wine, which are based on the application of  
48 gas chromatography (GC), high performance liquid chromatography (HPLC) and capillary electrophoresis (CE)  
49 [6, 7, 8, 9]. Pre-concentration step is often required, because resveratrol occurs at low concentration level as well  
50 as, because wine is characterized by complex matrix composition. However, several direct methods are also  
51 reported. Taking into consideration separation and determination technique, derivatization process is often  
52 required to:

- 53 • increase volatility and thermal stability of analytes, improve resolution as well as detection parameters  
54 when the gas chromatography is applied;

- 55 • improve sensitivity and separation properties when the liquid chromatography is utilized;
- 56 • give charge to a specific components, while using electrophoresis [10].

57 Some articles report application of combination of analyte pre-concentration, extraction and derivatization, what  
58 is in accordance with green analytical chemistry, which arise from the principles of sustainable development [3].

59 Although, there is a large number of reports in the literature, which show the results of the determination of  
60 resveratrol compound in the wine industry, there is a lack of critical comparisons of developed methodologies,  
61 not only in terms of the parameters of the analytical merits achieved, but also in terms of their green character. It  
62 is clear, that analytical procedure for resveratrol determination should meet green analytical chemistry  
63 requirements. The large number of available procedures requires the application of dedicated tools for systematic  
64 procedure selection within complex criteria and many alternatives [3].

65 The approach, that gives the possibility to assess the analytical procedures taking into account their  
66 environmental impact is Multicriteria Decision Analysis (MCDA). The group of MCDA tools may be applied to  
67 select the most preferred procedure and/or rank the remaining ones [11, 12]. MCDA is used to select the most  
68 appropriate procedure to determine aldrin in water samples, with green analytical chemistry principles taken into  
69 consideration in another study [11]. The ranking of analytical procedures is obtained with Preference Ranking  
70 Organization METHod for Enrichment of Evaluations (PROMETHEE). In different study, with this MCDA  
71 technique completely different weighting criteria are applied to investigate the influence of metrological,  
72 economic and environmental factors on the final ranking results [12]. Another MCDA tool - Technique for  
73 Order of Preference by Similarity to Ideal Solution (TOPSIS) is used for the assessment of analytical procedures,  
74 that are applied for the determination of ibuprofen in wastewater samples [13]. It should be emphasized that  
75 MCDA and chemometrics/multivariate statistics have different jargons. The equivalents of variables and objects  
76 known in chemometrics, in MCDA are criteria and alternatives.

77 This study aims to present the selection of analytical procedure for resveratrol determination in wine samples,  
78 from 19 available procedures, according to different decision making criteria. *Analytical Hierarchy*  
79 *Process(AHP)* as MCDA algorithm is applied for data analysis and its applicability is discussed. The choice of  
80 method is dictated by the fact, that so far, no examples of the usage of given method for the selection of the  
81 optimal analytical procedure have been found in the literature.

## 82 2. Materials and methods

83 **2.1. AHP technique**

84 The AHP is a multicriteria decision analysis technique that was developed by Saaty [14]. It is mainly  
 85 used to aid solving complex decision making problems. In this methodology, the problem is structured in a  
 86 hierarchy of different levels constituting of the main goal, criteria, sub-criteria and alternatives. This structure  
 87 organizes the components of the problem from the most general, placed in the upper part of the hierarchy, to the  
 88 more detailed, located in the lower part. Elements from different levels are compared in pairs. It allows to assess  
 89 relative preference with respect to each of the elements at the next and higher level.  
 90 The intensity of preference between two elements is established on the basis of Saaty's Fundamental Scale [15].  
 91 A linear and bipolar scale consists of nine possible numeric values. Description of each degrees of a scale are  
 92 presented in Table 1.

93 **Table 1** Pair-wise comparison scale [16, 17]

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed

94 According to the given data, the degree of advantage of one element over another is determined. Value 1 means,  
 95 that element A is of the same importance as B. On the other hand, 9 means total advantage A over B or vice  
 96 versa. Odd steps are usually used. However, if it is not possible to make such an assessment by the decision  
 97 maker, then even degrees (intermediate values) as 2, 4, 6, 8 are used. The determination of the advantage of one  
 98 of the elements is based on the so-called axiom of reciprocity, that is a reverse system. If the responder considers,  
 99 that object A has a very strong advantage over object B ( $A = 7B$ ), then B will be 7 times weaker than A ( $1/7A =$   
 100 B).

101 As it was mentioned previously, AHP considers a set of evaluation criteria, and a set of alternative  
 102 options among, which the best resolution is chosen. The best option is not that one, that optimizes each single  
 103 criterion, but rather that one, which achieves the most suitable trade-off among the different criteria. It is

104 important to note, that AHP allows to make a good decision, even if some of the criteria are contrasting.  
105 Generally obtaining each scale's value is possible due to results from a questionnaire, that is designed to obtain  
106 Saaty's Scale values.

107 In this step experts experience and knowledge may be required to be used, as well as stakeholders`  
108 opinions.

109 More detailed description of AHP theory is available in references [18, 19]. The procedure is also  
110 described by Lin and Yang [20]. According to them, AHP algorithm can be briefly described in several simple  
111 steps as follows [18, 19, 20]:

112 1. Defining the problem, determining the goal of analysis and building the hierarchical structure model

113 First of all, the main aim of the analysis should be defined. Criteria or sub-criteria as well as alternatives should  
114 be also determined. Later, all the information should be put in hierarchy structural skeleton of AHP model. The  
115 number of hierarchies (levels) depends on the complexity of the problem that is analyzed. However, they are  
116 structured from the top with a goal, by criteria and sub-criteria on an intermediate levels, till the alternatives,  
117 which are putted on the lowest level of hierarchy. In other words, they are presenting a range of information  
118 from general to more detailed one. Hierarchy system allows to determine the influence possessed by the function  
119 among elements, as well as their impact on the entire system. It is the first step, and the most important at the  
120 same time. The quality of performance affects the correctness of results, especially the consistency between  
121 pair-wise comparisons of elements.

122 2. Establishing a pair-wise comparison matrix of the criteria

123 In this step, the elements of a particular level are compared pair-wise, with respect to  
124 a specific element in the upper level. The purpose of such analysis is to derive the degree of relative importance  
125 amongst elements. In this way, it can be judged, which element is preferred and how much more it is preferred  
126 over another. First, criteria are compared pair-wise with respect to the goal, then sub-criteria (if they are defined)  
127 are compared pair-wise with respect to the criteria, and finally alternatives are compared with respect to the each  
128 sub-criteria or criteria. The priorities of the corresponding elements are possible to compute, thanks to an  
129 assessment, which uses 9-point scale proposed by Saaty [16]. It allows to transform the verbal judgments into  
130 numerical quantities representing the values. Given results may be presented in the form of judgmental matrix. It  
131 is worth to notice, that it is mostly applicable when each hierarchy does not contain more than seven elements.

132 Otherwise, these elements should be clustered and divided into an additional hierarchy (for example by inclusion  
133 of sub-criteria). Comparison of two elements may be mathematically presented as:

134

$$135 \quad A_{i,j} = \frac{W_i}{W_j} i, j = 1, 2, 3, \dots, n \quad (1)$$

136

137 where  $A_{i,j}$  denotes the weight exchange value of the pair-wise comparison of element  $e_i$  and  $e_j$ , and  $W_i$  and  $W_j$   
138 denote the relative weights amongst elements.

139

140 3. Derivation of the eigenvector and maximum eigenvalue (normalization of the pair-wise comparison  
141 matrix)

142 Based on the comparison matrix, the eigenvector is derived. It describes the degree of relative importance  
143 amongst the elements. In addition, at the same time, the maximum eigenvalue can be derived. This value may be  
144 used to determine the strength of consistency amongst comparisons, and further may be used as a reference  
145 index. The method of derivation is performed according to the equilibrium:

146

$$147 \quad AW = nW \quad (2)$$

148

149 Priorities of criteria can be estimated by finding the principal eigenvector  $W$  (normalized vector) of the matrix  $A$   
150 [19, 21]. The maximum eigenvalue  $\lambda_{max}$  equals the number of order. It may be presented as follows:

151

$$152 \quad AW = \lambda_{max}W \quad (3)$$

153

154 By normalized solution, the relative weight  $W_i$ ,  $W_i = 1, 2, 3, \dots, n$ , can be derived. By the Perron-Forbenius  
155 rule, the following relative weight can be derived:

156

$$157 \quad \lambda_{max} = \left(\frac{1}{n}\right) \left(\frac{w_1}{w_1} + \frac{w_2}{w_2} + \dots + \frac{w_n}{w_n}\right) \quad (4)$$

$$158 \quad W^* = AW \quad (5)$$

159

160 4. Determination of the consistency of the pair-wise (consistency index and consistency ratio)

161 If matrix A is a consistent matrix, then the maximum eigenvalue of A should equal to its number of order.  
 162 However, in practice the pair-wise comparison matrix cannot achieve complete consistency. This difference of  
 163 value between  $\lambda_{max}$  and  $n$  can be used to judge the degree of consistency.

164 Consistency index (CI) may be calculated as follows:

$$166 \quad CI = \frac{\lambda_{max}}{(n-1)} \quad (6)$$

167  
 168 If the consistency index  $\leq 0.1$ , it means, that the consistency level is satisfactory.

169 To check the correctness of comparisons, consistency ratio (CR) is also designated. It is calculated to determine  
 170 inconsistencies in the evaluation. It measures how consistent the judgments have been relative to large samples  
 171 of purely random judgments. It is determined in accordance with equation:

$$173 \quad CR = \frac{CI}{RI} \quad (7)$$

174  
 175 If the consistency ratio  $\leq 0.1$ , it means, that the evaluation within the matrix is acceptable. Instead if CR is more  
 176 than 0.1 the judgments are untrustworthy, because they are too close for comfort to randomness and the  
 177 assessment is valueless or must be repeated.

178 For each comparison matrix, a corresponding random index (RI) is used. It is an index of randomly generated  
 179 reciprocal matrix from the 9-point scale, with reciprocals forced. Its value for computation is presented in Table  
 180 2.

181 **Table 2** The average consistencies of random matrices [22]

Size	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

182  
 183 5. Evaluation of alternatives according to the priorities identified  
 184 According to identified priorities (criteria, sub-criteria, and their weights), the most suitable alternative is chosen.  
 185 The optimum solution is an answer for decision problem.

186  
 187 **2.2. AHP analysis using Super Decision Software**

188            Actually, most of study cases are complex, so there are lots of different criteria and alternatives. Thus,  
 189 calculations without software support may be time-consuming and labor-intensive, in addition it is easy to make  
 190 a mistake. That is why, MCDA algorithms are very often used as a commercial computer software. Furthermore,  
 191 some of the parameters may be calculated automatically, so the number of actions is minimized. Performing the  
 192 analyses with the software creates more clear form of presentation. In this case, Super Decisions software was  
 193 selected to be applied. It was developed by Thomas Saaty [23], who is also the developer of AHP tool. It  
 194 implements the Analytical Hierarchy Process for decision making with dependence and feedback. It allows to  
 195 perform hierarchy structure, including several levels. In the Super Decisions software a decision model is made  
 196 up of clusters, nodes and links. Clusters are groups of nodes, which are logically related factors of the decision  
 197 [24]. Connections are made among nodes to define comparison groups. If nodes are connected then links  
 198 automatically appear between their clusters.

199            It is also possible to put values of elements` weighting in it. The decision-making process automatically  
 200 involves the calculation of inconsistency. It is useful for identifying possible errors in judgments as well as  
 201 actual inconsistencies. In case of a negative outcome, the software marks the problematic elements and  
 202 recommends required changes.

### 203            **2.3. Criteria**

204            To structure the hierarchy model properly, the criteria and alternatives are required to be determined. The  
 205 criteria such as parameters, indicators, etc. should be determined in relation, to which the decision-making  
 206 variants will be assessed with the main goal in mind. The selection of the best analytical procedure for  
 207 resveratrol determination is a complicated decision making process. This evaluation should be compatible with  
 208 sustainable development concept [25]. In other words, in this case, there should be a balance between the  
 209 environment, the economy and the technical aspect. According to this assumptions, 3 main groups of criteria are  
 210 established: environmental, metrological and economic. To each set of criteria, some sub-criteria are assigned.  
 211 The division of measured parameters is presented in Table 3.

212            **Table 3** Criteria and sub-criteria for evaluation in case study of resveratrol determination

<b>Criterion</b>	<b>Sub-criterion</b>	<b>The description</b>
Environmental	Amount of wastes	Amount of waste generated during sample analysis expressed in grams.
	Procedure steps	Number of steps performed in each procedure.
	Reagent toxicity	Toxicity – weighted amount of solvents.
Metrological	LOQ	Limit of Quantitation
	RSD	Relative Standard Deviation



Economic	Amount of sample	The amount of sample needed to perform analysis, expressed in mL
	Energy consumption	Energy consumed by the equipment used during analysis.
	Number of other analytes	The amount of other analytes than trans-resveratrol determined with the analytical procedure.
	Reagents price	The price of solvents, derivatization agents and other reagents expressed in Euro.
	Sample throughput	The amount of samples that can be analysed with analytical instrument in one hour.

213 It is worth to notice, that in AHP algorithm each sub-criteria may be used only once. Thus, it is possible to put  
 214 chosen sub-criteria in one of the groups: environmental or metrological or economic. In addition, such amount of  
 215 evaluation parameters is a significant problem. As it was mentioned before, each hierarchy should not contain  
 216 more than seven elements. Hence, it influenced further division of all the parameters into groups.

#### 217 *2.4. The alternatives: analytical procedures*

218 One of the types of input data to AHP algorithm is the set of alternatives - proposed solutions for analyte  
 219 determination. Alternative is a way to achieve the solution of the main goal stated in the decision problem. In  
 220 the presented case, they are alternatives, which constitute to the possible options – analytical procedures for  
 221 resveratrol determination. The data is collected by searching the scientific databases (ACS, RSC, ScienceDirect,  
 222 Springerlink, Wiley). The required information qualified later as the sub-criteria (Table 3) is extracted from  
 223 articles or standard procedures. Most of the criteria are assessed with the values, that are directly taken from the  
 224 literature data. The 19 fully described procedures are taken into consideration. The analytical procedures include  
 225 analysis that are based on various sample preparation, separation and detection techniques. Information on the  
 226 alternatives for reaching the main goal of MCDA assessment are presented in Table 4. If full data on analytical  
 227 procedure is not available in a reference paper, such analytical procedure is not included in the assessment.  
 228 However, there are methods to deal with such a problem, like application of simple linear models, maximum  
 229 likelihood or multiple imputation models [26].

230 **Table 4** Analytical procedures for resveratrol determination as alternatives in decision-making process

Alternative No.	Analytical methodology	Abbreviation	Ref.
1	Solid Phase Extraction- High Performance Liquid Chromatography- Ultraviolet Absorption Spectrophotometry	SPE-HPLC-UV	[31]
2	Direct Injection-High Performance Liquid Chromatography- Diode Array Detector- Ultraviolet-Visible Spectroscopy	DI-HPLC-DAD-UV-VIS	[32]
3	Solid Phase Micro Extraction - Multidimensional Gas Chromatography- Mass Spectrometry-Olfactometry	SPME-MDGC-MS-O	[33]
4	Reverse Phase- High Performance Liquid	RP-HPLC-UV-ED	[34]

	Chromatography- Ultraviolet Absorption- Electrochemical detection		
5	Stir Bar Sorptive Extraction-Thermal Desorption- Gas Chromatography- Mass Spectrometry	SBSE-TD-GC-MS	[35]
6	Solid Phase Extraction-Chemiluminescence detection	SPE - chemiluminescence	[36]
7	Solid Phase Extraction-Dispersive Liquid Liquid Micro Extraction- Gas Chromatography- Time Of Flight- Mass Spectrometry	SPE-DLLME-GC-TOF-MS	[37]
8	Solid Phase Extraction-Gas Chromatography- Mass Spectrometry	SPE-GC-MS	[38]
9	Direct Injection-High Performance Liquid Chromatography-Ultraviolet Absorption Spectrophotometry	DI-HPLC-UV	[39]
10	Direct Injection-High Performance Liquid Chromatography-Electrospray Ionization-Mass Spectrometry	DI-HPLC-ESI-MS	[40]
11	Differential Pulse Voltammetry-Electrodeposition Of Reduced Graphene Oxide Modified Glassy Carbon-Scanning Electron Microscopy	DPV(ERGO/GC- Electrode)- SEM	[8]
12	High Performance Liquid Chromatography- Fluorescence Detection	HPLC-FED	[41]
13	Liquid Liquid Extratcion- High Performance Liquid Chromatography-Photodiode Array Detector	LLE-HPLC-PDE	[42]
14	High Performance Liquid Chromatography- Ultraviolet Absorption	HPLC-UV	[9]
15	Liquid Chromatography-Mass Spectrometry	LC-MS	[43]
16	Microextraction by Packed Sorbent-Ultra- performance Liquid Chromatography- Photodiode Array Detector	MEPS-UPLC-PDA	[9]
17	Turbulent-Flow Chromatography- Liquid Chromatography-Mass Spectrometry	TFC-LC-MS	[44]
18	Liquid Chromatography- Ultraviolet-Visible Spectroscopy-Mass Spectrometry	LC-UV-VIS/MS	[45]
19	Capillary Electrophoresis- Electrochemical Detection	CE-ED	[6]

231

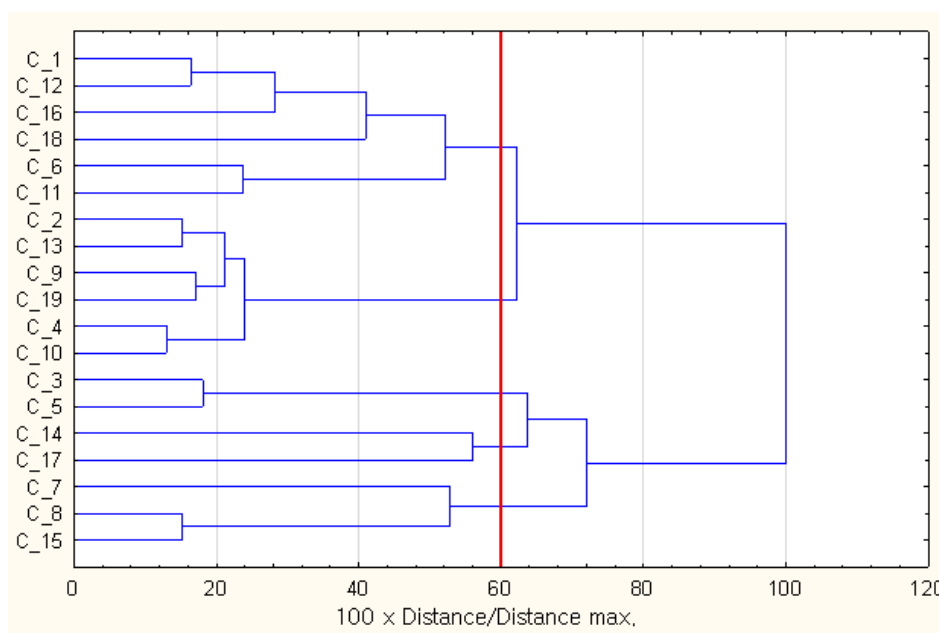
232 **2.4. Cluster analysis**

233 The high number of possible alternatives may negatively influence the analysis results, especially on CI  
234 and CR indexes. Thus, Cluster Analysis is used to reduce the number of alternatives being an input data. It is  
235 well established chemometric method [27]. Very briefly, it is aimed for grouping the objects (in MCDA called  
236 alternatives) according to their similarity. It is clustering without supervision, so unsupervised algorithm is  
237 finding internal patterns in the dataset with no *a priori* information or assumptions about data. For more details  
238 on the algorithm please refer to [28]. The grouping of variables is performed with Euclidean distance measure  
239 and Ward cluster formation method. All Cluster Analysis calculations are performed with Statistica software.  
240 Before application of cluster analysis algorithm, the initial dataset is standardized.

241 **3. Results and discussion**

242 **3.1. Clustering of analytical procedures**

243 Analysis starts from hierarchy model construction, where the main aim is to find the best methodology for  
244 resveratrol determination. First task is to define a set of criteria, sub-criteria and alternatives. Large amount of  
245 parameters is a significant problem. It is solved by dividing criteria into 3 groups and establishing sub-criteria,  
246 what is described in a previous subsection. As it is also mentioned earlier, AHP is applicable if the number of  
247 the available alternatives is low. As the initial number of alternatives is 19 it is needed to apply a method of data  
248 dimensionality reduction. Cluster analysis is a good choice as it is very simple to use and widely accepted data  
249 clustering method. The clustering interpretation is set to 60 % of the distance to maximum distance ratio.  
250 Therefore, for initial AHP analysis, instead of 19 alternatives 5 clusters of alternatives are ranked to select the  
251 most beneficial cluster, that is considered in further calculations. Fig. 1 shows clustering outcome.



252  
253 Figure. 1. The results of clustering of analytical procedures with CA

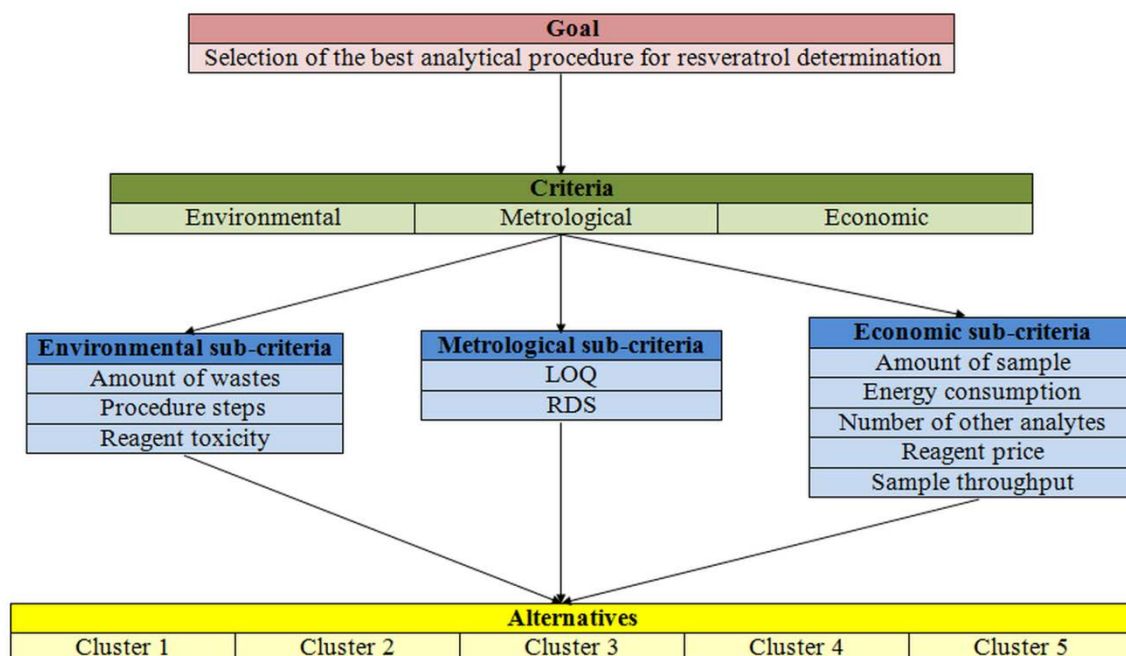
254 Selection of the best analytical procedure for resveratrol determination is presented in 2 stages. In the  
255 first one, assessment of 5 groups (5 Clusters) as the alternatives is conducted. In the second one, the selection of  
256 the optimal procedure from the winning cluster is performed. Standardized mean values of criteria for groups of  
257 alternatives obtained from the first step, are input data to AHP model.

258 The first cluster contains four analytical procedures based on liquid chromatography, one  
259 electrochemistry and one chemiluminescence based procedure. Very high sample throughput is the discriminator

260 for this group. The second cluster consists of five liquid chromatographic procedures with or without sample  
 261 preparation and one electrophoresis based procedure. They are characterized by good precision and low number  
 262 of procedural steps (these two variables can be connected as precision depends on the number of operations).  
 263 Third cluster contains two gas chromatography based procedures. The discriminators for this cluster are; poor  
 264 precision, very high reagents price, but low toxicity and numerous procedural steps. Fourth cluster gathers two  
 265 liquid chromatographic procedures that are characterized by high limits of detections, poor precision and high  
 266 requirement of sample volume. Fifth cluster contains two gas chromatographic and one liquid chromatographic  
 267 procedures. The discriminators for this cluster are high reagents toxicity and high waste generation. However,  
 268 they allow to determine other analytes than resveratrol.

269 **3.2. AHP model creation**

270 According to the scheme of hierarchy model on Fig. 2, main goal, criteria, sub-criteria and alternatives are  
 271 defined and particularly divided into specified groups. All of them are put in right hierarchical order. Then  
 272 connection between them is proposed. The goal is connected to each of the criteria, each criterion is linked with  
 273 sub-criteria and each sub-criterion is connected to each of the alternatives.



274  
 275 Figure. 2. Hierarchical structure of AHP model for selection of best analytical procedure for resveratrol  
 276 determination – first stage clusters ranking

277 After building a proper model, questionnaire is given to an expert, to set the relative importance of criteria. Their  
 278 preferences in pair-wise comparisons are defined by using the Saaty's 9-degree scale. This evaluation is made  
 279 for criteria with a respect to main goal, then for sub-criteria with a respect to the each group of criteria, and  
 280 finally for alternatives with a respect to each sub-criteria. Making pair-wise comparisons of each two  
 281 alternatives, is based on determining, which is smaller/bigger and estimate how many times (multiples). For this  
 282 purpose, calculations are made using Microsoft Excel. Here also Saaty's Fundamental Scale is used. Then given  
 283 results are introduced into matrix. With reference to rules and mathematical equations presented in section 2.1.  
 284 *AHP technique*, pair-wise comparison between elements in model are conducted. In Fig. 3 the sheet for pair-wise  
 285 comparison among clusters with respect to *Amount of sample* using Super Decision software is presented. As it is  
 286 showed in the first line, basing on parameters' values, analytical procedures classified in Cluster 1 are equally to  
 287 moderately more important than those placed in Cluster 2.

**Node comparisons between clusters with respect to Amount of sample**

Cluster 1	$\geq 9.5$	9	8	7	6	5	4	3	1	2	3	4	5	6	7	8	9	$\geq 9.5$	Cluster 2	
Cluster 1	$\geq 9.5$	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	$\geq 9.5$	Cluster 3
Cluster 1	$\geq 9.5$	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	$\geq 9.5$	Cluster 4	
Cluster 1	$\geq 9.5$	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	$\geq 9.5$	Cluster 5
Cluster 2	$\geq 9.5$	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	$\geq 9.5$	Cluster 3
Cluster 2	$\geq 9.5$	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	$\geq 9.5$	Cluster 4	
Cluster 2	$\geq 9.5$	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	$\geq 9.5$	Cluster 5
Cluster 3	$\geq 9.5$	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	$\geq 9.5$	Cluster 4
Cluster 3	$\geq 9.5$	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	$\geq 9.5$	Cluster 5
Cluster 4	$\geq 9.5$	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	$\geq 9.5$	Cluster 5

288  
 289 Figure. 3. Sample comparison results on 9-point scale

290 According to the given weight values from the questionnaire, which represent decision maker  
 291 preferences, it is found, that the environmental aspect has 20% impact on the main assessment goal, while the  
 292 metrological and economic aspect, 60% and 20%, respectively. It is understandable, that expert values the  
 293 metrological performance of analytical procedure are very high in comparison to environmental and economic  
 294 performance. The results from weighting sub-criteria with a respect to each criterion as the percentage  
 295 importance are presented in Table 5.

296 **Table 5** Weighting of sub-criteria with a respect to each criterion - percentage influence on each group of criteria

Economic		Environmental		Metrological	
Sub-criteria	Influence [%]	Sub-criteria	Influence [%]	Sub-criteria	Influence [%]
Amount of sample	6.364	Amount of wastes	20	LOQ	50






Energy consumption	9.994	Procedure steps	20	RDS	50
Number of other analytes	45.32	Reagent toxicity	60		
Reagent Price	9.463				
Sample throughput	28.858				

297 Due to the expert's opinion, taking into account economic aspect, the most important is the number of other  
 298 analytes, which may be determined by using one method, followed by sample throughput. On the other hand,  
 299 from the environmental point of view, the influence of reagent toxicity influences on environmental criteria in  
 300 around 60%, so it is the major parameter in this group. When it comes to the metrological point of view, both  
 301 parameters: LOQ and RSD, are also characterized by the same importance. The results of expert's opinion, on  
 302 the importance of criteria on the final ranking show, that RSD and LOD have the highest weight.

303 After the weighting process, CI and CR indexes are checked. In all comparisons, the inconsistency  
 304 value is smaller than 0.1, so the consistency level is satisfactory and evaluation within the matrix is acceptable.  
 305 It gives an information, that the judgments are trustworthy, thus the results obtained can be considered reliable.  
 306 What is the most important, the AHP allows to indicate sequentially, which judgments are the most inconsistent.  
 307 In this way the value, that best improves consistency is suggested [29]. However, this is not always leading to a  
 308 more accurate set of priorities, which corresponds to decision-makers' preferences. Greater consistency does not  
 309 imply greater accuracy. Nevertheless, one should strive to achieve an acceptable level of consistency.

### 310 3.3. Ranking of alternatives

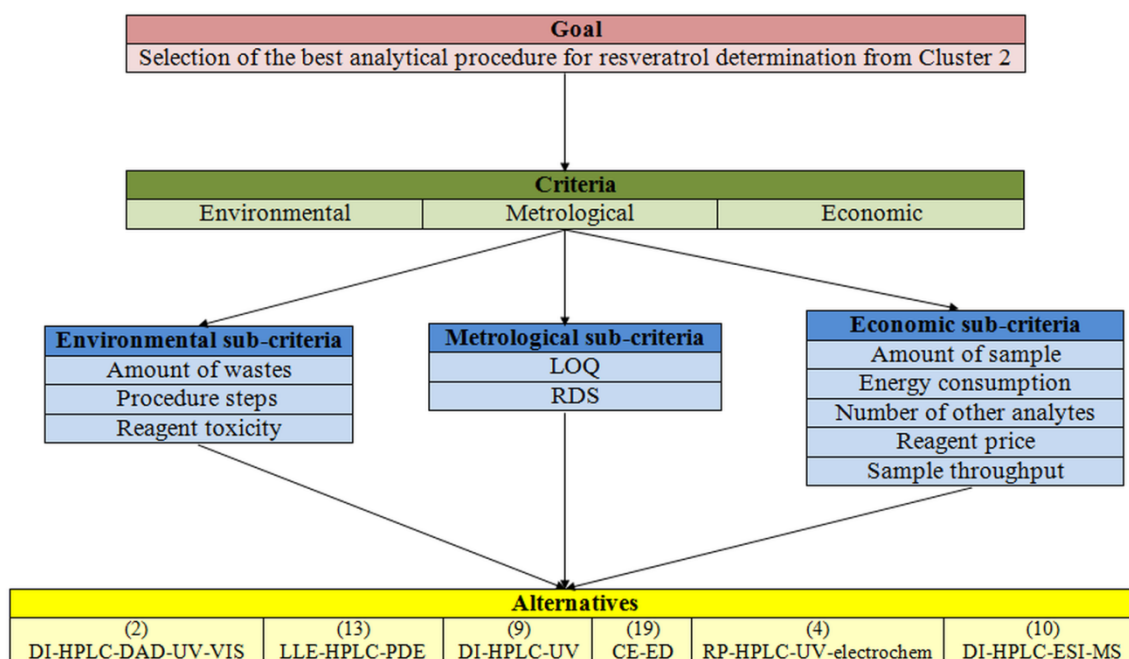
311 The AHP ranking results show, that the best group of alternatives is Cluster 2, what is presented on Fig. 4. The  
 312 Raw column is read directly from the Limit Supermatrix. The Normalized values are obtained from them by  
 313 summing and dividing each by the sum. Thus the Normals column presents the results in the form of priorities,  
 314 what is usual way to report the results. While the Ideals are obtained by dividing the Raw values by the largest  
 315 raw value.

Name	Graphic	Ideals	Normals	Raw
Cluster 1		0.615809	0.201743	0.067248
Cluster 2		1.000000	0.327606	0.109202
Cluster 3		0.663172	0.217259	0.072420
Cluster 4		0.238161	0.078023	0.026008
Cluster 5		0.535304	0.175369	0.058456

316  
317 Figure. 4. Final result for the first stage of analysis

318 Second rank is taken by Cluster 3, follow by Cluster 1 and Cluster 5. The difference between these 3 groups is  
 319 insignificant. Cluster 4 is last in ranking. Analytical methodologies included in this group are the least preferred  
 320 by decision-makers. There are two procedures in this cluster, viz high performance liquid chromatography  
 321 coupled to ultraviolet absorption and turbulent-flow chromatography coupled liquid chromatography with mass  
 322 spectrometry as detection technique. Both of these procedures are characterized by high value of LOQ and RDS,  
 323 what is not favorable (LOQ and RDS influences on metrological criteria in 50 %). In addition, high toxicity of  
 324 reagents used in these procedures is noted, what is not desirable from the idea of green analytical chemistry (the  
 325 influence of reagent toxicity influences on environmental criteria group in around 60%).

326 The last step of the research aims to find out, which analytical procedure from Cluster 2 is the most suitable  
 327 decision-maker's requirements. In this case, new hierarchy process was constructed, as described in Figure 5.



328  
 329 Figure. 5. Hierarchical structure of AHP model for selection of best analytical procedure for resveratrol  
 330 determination – second stage, ranking within winning cluster

331 Goal, criteria and sub-criteria are the same, as in the first assessment step. Also the same weight values for each  
 332 level with a respect to the higher level are put. Instead, alternatives are different. In this case, only Cluster 2 is  
 333 taken into account. Within the group there are: DI-HPLC-DAD-UV-VIS, LLE-HPLC-PDE, DI-HPLC-UV, CE-  
 334 ED, RP-HPLC-UV-electrochemical detection, DI-HPLC-ESI-MS. As it can be seen, most of the procedures are  
 335 based on high performance liquid chromatography, except one, which is based on capillary electrophoresis. Most



336 of these procedures are performed in direct way, without sample preparation step. These procedures are  
 337 different in the case of final detection technique.

338 The inconsistency values for all comparisons does not exceed 0.1 as before in the first stage, so analysis  
 339 may be continued without apprehension, that the results obtained can be unreliable. The final results show, that  
 340 DI-HPLC-UV is the best analytical methodology in terms of assumed criteria and their weights, what is  
 341 presented in Figure 6. This procedure is characterized by a low reagent toxicity as well as a low waste  
 342 generation. Moreover, metrological parameters are satisfactory. This procedure involves only two steps,  
 343 filtration and final determination. From the other site, no other analytes can be determined by application of this  
 344 methodology.

Name	Graphic	Ideals	Normals	Raw
(2) DI-HPLC-DAD-UV-VIS		0.796915	0.179057	0.059686
(4) RP-HPLC-UV-electrochem		0.996484	0.223897	0.074632
(9) DI-HPLC-UV		1.000000	0.224687	0.074896
(10) DI-HPLC-ESI-MS		0.813540	0.182792	0.060913
(13) LLE-HPLC-PDE		0.245560	0.055174	0.018391
(19) CE-ED		0.598130	0.134392	0.044797

345

346 Figure. 6. Final results for the second stage of analysis

347 Second rank is taken by RP-HPLC-UV-electrochemical detection. The difference between these 2 analytical  
 348 methodologies is insignificant. Similarly, to the above described procedure, the methodology parameters (LOQ,  
 349 RSD) are very satisfying and the number of the procedure steps is low (3). However, this procedure involves  
 350 reagents, which are more toxic than those utilized in procedure based on DI-HPLC-UV. In addition, higher  
 351 amount of wastes is generated. Against, other analytes can be detected by the application of this methodology.  
 352 Third DI-HPLC-ESI-MS is ranked, however DI-HPLC-DAD-UV-VIS is ranked just behind it. Both  
 353 methodologies involve two steps, though, the latest generates more wastes. Reagents required in both procedures  
 354 are characterized by the same degree of toxicity and the reagent price. However, procedure based on DI-HPLC-  
 355 ESI-MS is characterized by better metrological parameters.

356 It is worth to notice, that generally the highest ranks are taken by method, which are based on direct injection.  
 357 The results are not surprising, because the possibility of direct injection is characterized by many advantages.  
 358 First of all in this case sample preparation stage is avoided and so number of analytical steps – one of assessment  
 359 criteria. This operation is related to production of lots of waste, consumption of lot of time and it is also a source



360 of most errors during the analysis. It is also connected with environmental aspect. While indirect injection, no  
361 solvents are required. That is why, these methodologies may be called as green ones. Moreover, all of these  
362 procedures are characterized by good analytical parameters.

363 The last one in the ranking from the Cluster 2 is LLE-HPLC-PDE. This is consistent with the results obtained  
364 above, due to fact, that this methodology includes liquid-liquid extraction. This one is characterized by inverse  
365 properties than those taking into account direct dosing.

366 It's worth pointing out, that the results obtained relate only to this specific case, where weight values for each  
367 criteria - environmental, metrological, economic are established on 20%, 60% and 20%. If we modify the  
368 weights, for instance on 25%, 50%, 25% respectively, then the results will be essentially the same. Changes of  
369 criteria's or sub-criteria's weights while maintaining similar values' relations, will not influence outcomes  
370 significantly. The tool, that may predict how much changes of parameters' values will affect final score is  
371 Sensitivity Analysis [30]. Super Decisions software also makes possible to perform a complex sensitivity  
372 analysis. However, it is not applied in this case study, due to fact, that it is not the main aim of the study and  
373 values are based on questionnaire's results indicating stakeholders' preferences.

#### 374 4. Summary

375 AHP algorithm applied in the selection of the most appropriate analytical procedure is a useful tool. Application  
376 of the methodology, presented in this study, allows to select the best solution in proper way concerning various  
377 criteria. The large dataset, inappropriate for AHP assessment is reduced with CA. Such procedure leads to rank  
378 analytical procedures considering metrological parameters as well as environmental and economic aspects. The  
379 application of presented methodology for the selection of proper analytical methodology for determination of  
380 selected analytes can be considered green, since low environmental impact is noticed.

381 For the first time AHP is used for selection of optimal analytical procedure due to decision makers' preferences.  
382 Nowadays, conducting chemical analysis in accordance with sustainable development is challenging. AHP  
383 algorithm is an valuable aid to find a compromise between metrological, environmental and economic aspects.

384 In this study, the AHP is applied for data analysis obtained for procedures used for determination of trans-  
385 resveratrol in wine samples. The procedure ranked as the best is based on direct injection-high performance  
386 chromatography coupled to ultraviolet absorption spectrophotometer. This proves the competitiveness of direct  
387 analytical procedures. Moreover, the procedure DI-HPLC-UV is also characterized by good metrological



388 parameters. The application of Super Decisions software is easy to be applied and can be used as routine tool for  
389 analytical procedures comparison.

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### 393 **Compliance with Ethical Standards**

394 **Conflict of Interest:** Magdalena Fabjanowicz declares. that she has no conflict of interest. Marta Bystrzanowska  
395 declares, that she has no conflict of interest. Jacek Namieśnik declares, that he has no conflict of interest. Marek  
396 Tobiszewski declares, that he has no conflict of interest. Justyna Płotka-Wasyłka declares, that she has no conflict  
397 of interest.

398 **Ethical approval:** This article does not contain any studies with human participants or animals performed by any  
399 of the authors.

400 **Informed consent:** Not applicable.

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