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10 Green analytical chemistry as an integral part of sustainable education development

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25 Abstract

26 Green chemistry is an important way of thinking in the field of chemistry and aims to conduct processes
27 in accordance with the principles of sustainable development. It is the application of a wide range of
28 principles that minimize the impact of both chemical processes and products on the environment. And
29 what about analytical chemistry? Without a doubt, analytical chemistry plays an important role in the
30 sustainable development of the planet. However, this only applies if analytical procedures are of high
31 quality (sensitive, precise and accurate) and also in line with the principles of environmental
32 sustainability. This essay presents a brief discussion of the evolution of green chemistry and its
33 multidimensional impacts, including the “industry” of analytical chemistry as well as academic education
34 and research. We emphasize the difference between the term “sustainability” and “greenness”.
35 Therefore, at least basic information on sustainability in analytical chemistry is provided. We hope that
36 our considerations will inspire analytical chemists and will contribute to the further development of
37 both green analytical chemistry and sustainable analytical chemistry.

39 Keywords

40 Analytical chemistry; sustainability; green analytical chemistry; education; research

43 1. Introduction

44 The principles of green chemistry are widely used in industrial management, government policy,
45 educational practice and technological development around the world. The main aim of the so-called

46 circular economy is to balance economic growth, resources sustainability and environmental protection.
47 Green chemistry, which in fact leads to a change in attitudes and behavior in the chemical industry, can
48 be considered an important tool for achieving sustainability [1]. In addition, it has a major impact on the
49 emergence and development of new ways of thinking in specific areas of chemistry, including analytical
50 chemistry, where the term Green Analytical Chemistry (GAC) is used. In our opinion, the most difficult
51 task is to find the right way to evaluate the greenness of an analytical procedure, as many different
52 parameters must be taken into account [2]. There are some published methods for evaluating the
53 greenness of various analytical methods [3, 4, 5]. However, we must keep in mind that the terms
54 “sustainability” and “greenness” are not the same. It is well known that for development to be truly
55 sustainable, three interrelated areas – the environment, the economy and society – need to be
56 considered, while the philosophy of green analytical chemistry deals primarily with only the first of these
57 areas. We hope that our philosophical considerations inspire analytical chemists around the world to
58 reflect on this difference.

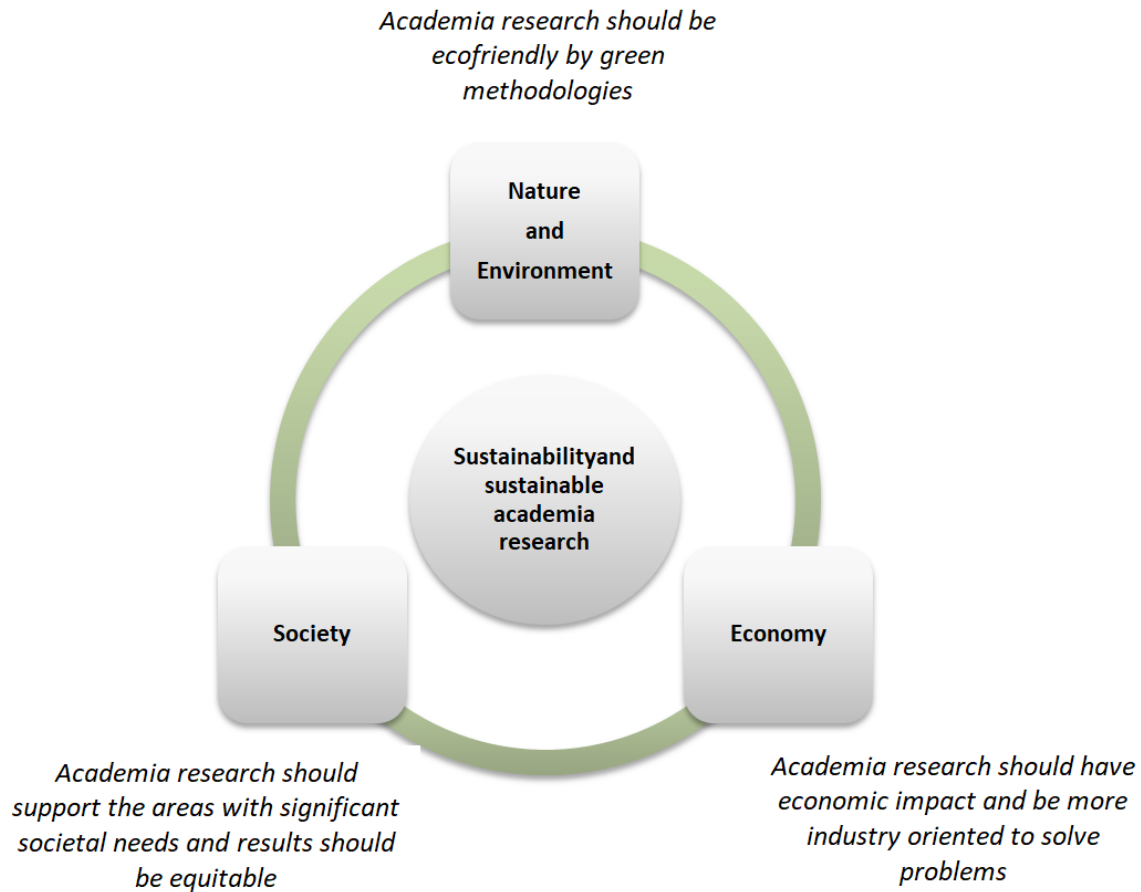
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60 2. **Brief history of sustainable development**

61 Sustainable development is now commonplace and connects almost all areas of human activity.
62 However, it is difficult to say exactly when the concept of sustainability emerged. Probably the earliest
63 reported findings date to the ideas of economist Thomas Robert Malthus from the 17th century [6]. The
64 first famous international conference on the side effects of rapid industrial growth and economic
65 development took place in New York in 1949 [7]. Later, in 1970, US President Richard M. Nixon laid the
66 foundations of the Environmental Protection Agency (EPA) [8]. Environmental concerns became part of
67 the few international agendas as well as commissions [9, 10, 11]. The three pillars of sustainable
68 development are shown in Figure 1.

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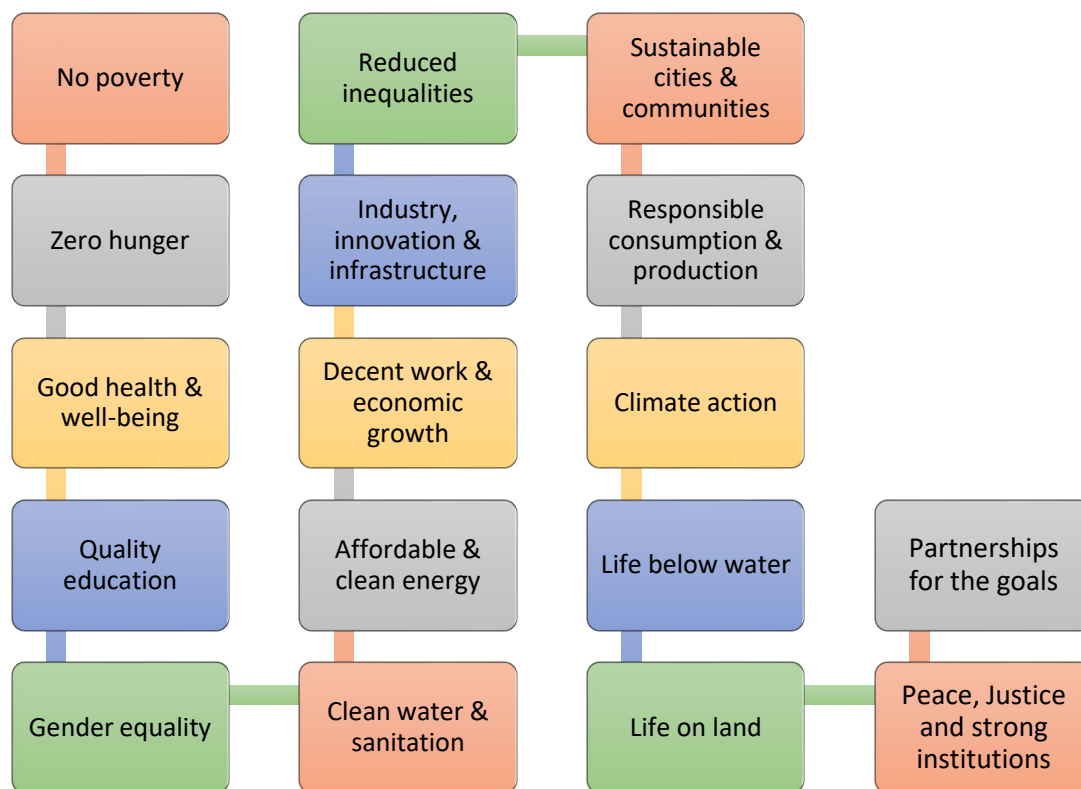




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Figure 1. The three fundamentals of sustainability and its integration in academia research

In nineties, also happened a lot in this area, for example publication of the Pollution Prevention Act, [8], activation of the program called the Alternative Synthetic Pathways for Pollution Prevention [12], performing a meetings such as “Earth Summit”. All of these efforts were reflected in the comprehensive “Agenda 21” [13]. Recently, 17 points designated as “Sustainable Development Goals” (SDG) were published (Figure 2) [14].



80

81 **Figure 2.** Sustainable development goals

82 The global acceptance of sustainability eventually led to the development of emerging areas at
 83 that time, such as “Green Chemistry”. In this are such researchers should be known

84 Anastas and Warner who outlined the main principles of green chemistry through which the
 85 goals of sustainability can be achieved. Green chemistry was defined as “The design of chemical
 86 products and processes that reduce or eliminate the use and generation of hazardous substances” [16].
 87 Since this time many implementations have placed [17, 18].

88 Among the pragmatic developments in this area were the replacement of toxic solvents, such as
 89 chlorofluorocarbons (CFCs). Alternative green solvents included the reintroduction of aqueous systems,
 90 ethanol, rediscovered CO₂ and various combinations [19]. Some processes that were discovered earlier
 91 are now associated with green processes, such catalysis, which was reported as early as 1830, or ionic
 92 liquids, which were discovered in 1914 by Paul Walden. They are particularly interesting, as they can be
 93 tailored to specific needs [20].

94

95 3. Green analytical chemistry

96 Green analytical chemistry goes hand in hand with sustainable development and corresponds to the
 97 “triple bottom line” of sustainability – the economic, social and environmental – to improve the quality
 98 of human life [21],[22]. The principles of GAC emphasize the necessity of safer, less toxic and more
 99 benign solvents or the elimination of solvents, as well as reducing energy consumption, avoiding
 100 derivatization and favoring substances based on renewable sources [23,24]. The correct application of
 101 GAC provides many benefits in various aspects of sustainability. However, we have to believe that GAC is

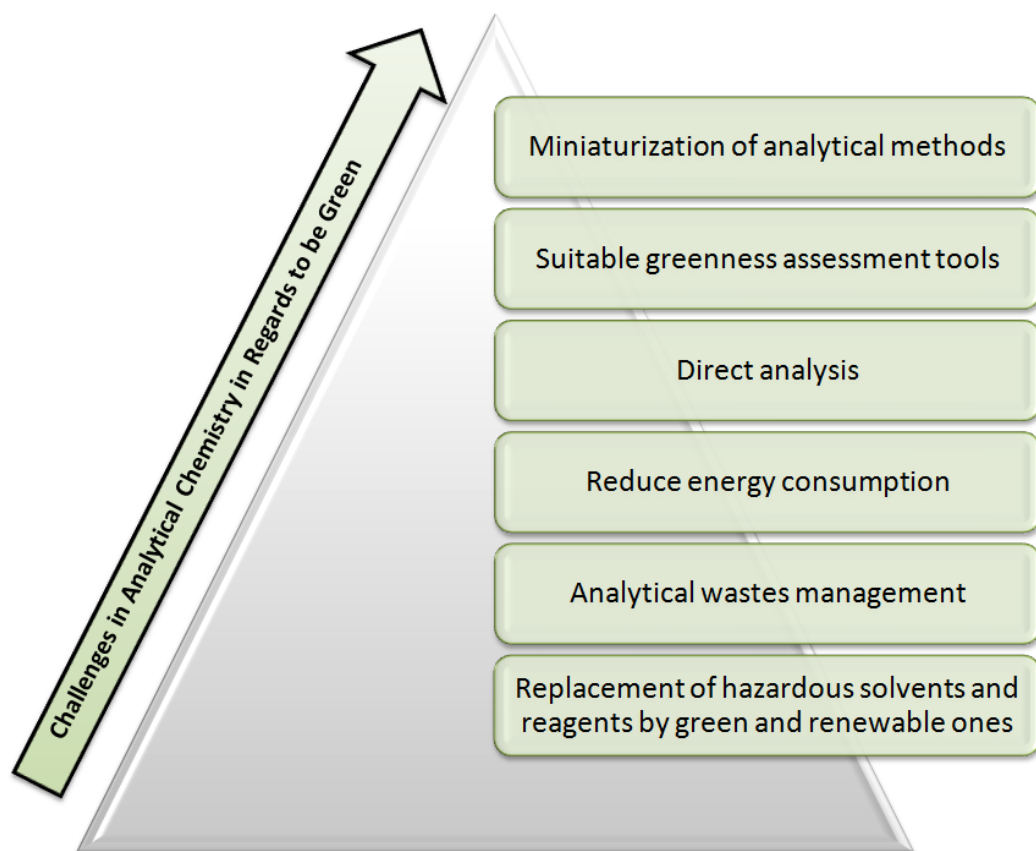


102 a way, not the goal. It is a multistep approach that should result in an analytical procedure that meets
103 both the GAC criteria and the performance criteria required by the customer [16].

104 One reason for the success of GAC in applications laboratories as well as at the academic level,
105 in general, is that green methods are less costly than classical methods [25]. Being less expensive, eco-
106 friendlier and safer makes them the current trend in developing or modifying analytical methods
107 whether in academic or industrial level laboratories.

108 The trend of GAC leads to significant challenges due to differences in the validation priorities of
109 analytical methods such as sensitivity, selectivity, accuracy, precision, and robustness, which are the
110 most important factors in this regard. In contrast, the time, cost (including purchase, operation, training
111 and space) and an analytical procedure's environmental safety are secondary [26]. Analytical chemists
112 around the world are therefore trying to find a balance between the parameters of validation of
113 analytical methods and their sustainability. The need to compromise between improving the quality of
114 the analysis and bettering the environmental aspects of analytical methods is becoming the most crucial
115 obstacle to the future implementation of GAC [27]. These challenges can be summarized in the points
116 presented in Figure 3.

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118

119 **Figure 3.** Challenges in analytical chemistry in regard to being green

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121 In addition to working on the environmental aspects of the new technology and laboratory
122 approaches within the principles of GAC, an educational approach is also important. Health and safety

123 are becoming a priority. The Green Analytical Chemistry paradigm is based on old practices, however
124 with an added value of environmental responsibility to make chemical practices more eco-friendly in
125 line with social demands [28].

126 The main educational task is to transmit a clear message to society that would shed light on
127 chemistry as a fundamental part of the solution to pollution problems and not just part of the problem
128 [28]. The modification of the analytical chemistry paradigm means complementing the basic analytical
129 properties with the incorporation of the “green” parameters. The renewed paradigm of Green Analytical
130 Chemistry Accuracy still respects representativeness, traceability, sensitivity and selectivity however
131 with a greater care of the environment, safety of operators, the greater reduction of reagents, energy,
132 solvents and decontamination of analytical wastes

133 Sustainable education in academia has a challenge before it: to transform teaching practices,
134 starting from the content of theoretical lessons to laboratory practices [28]. Teaching green analytical
135 chemistry is a challenge today for building a better future for tomorrow. This involves the development
136 of new analytical methodologies, techniques and technologies that can help future chemists and
137 chemical engineers to research, develop and minimize the environmental impacts of their work [29].
138 Ecological practices in the teaching of analytical chemistry must be based primarily on an awareness of
139 the twelve principles of green analytical chemistry [29]. The result of such training should be a new
140 generation of chemists who consider the importance of an environmentally friendly approach to
141 maintaining the sustainable development of society [28, 30]. Effective teaching and education includes
142 the use of modern memorizing and problem solving methods during seminars as well as students having
143 access to the relevant materials for self-study. Green analytical metrics would help in understanding and
144 assessing whether the methods being evaluated are green or not [29]. The effect of such teaching could
145 be a new generation of chemists who are aware of the need for ethical compromise between the
146 environment and society [28].

147

148 **4. Sustainable analytical chemistry**

149 Analytical chemistry should be eco-friendly and safer to the analyst as discussed in GAC principles. It is
150 not about to monitor the waste and pollutants but rather to green methodologies. This is achieved by
151 waste minimization through; miniaturization, using green solvents or solventless methods, minimizing
152 energy consumption, avoiding the use of auxiliary reagents and chemicals.

153 For analytical chemistry to be described as sustainable, it should consider the three pillars for
154 sustainable development – the environment, the economy and social dimensions and needs (Figure 1)
155 [1]. Many academic institutions lack a structured framework to bridge basic research and viable
156 products. Academic research needs to be more practical; it needs to seek solutions to industrial
157 problems and not only target conceptual research but also aim to have an economic impact.

158

159 Research in academia should foster the use of new extraction techniques to make sample
160 preparation steps greener; these are the most crucial and challenging steps in reducing the
161 environmental footprint of analytical techniques. In academic research, there is currently an increasing
162 demand towards replacing traditional analytical methods with portable and miniaturized sensors with
163 more interest in microfluidics and lab-on-a-chip applications. These smart and powerful analytical tools
164 can fulfill all the pillars of sustainability. Wider attention is being paid on wearable non-invasive sensors



165 as a promising tool for diagnostics and remote follow-up of patients. Electrochemical sensors provide
166 rapid measurements of different analytes in different matrices, and they are at the same time user-
167 friendly [31,32]. Furthermore, improvements in spectroscopy have made it possible for researchers and
168 scientists to develop *in situ* and in-the-field analysis techniques. For example, NMR spectroscopy can be
169 used to monitor flowing material. Low-field NMR techniques can be used to measure moisture, fat,
170 and/or fluorine contents in food analysis without pretreatment, separation or purification steps [33].

171 As was previously mentioned, analytical methods in academic research should be cost-effective [34,
172 35]; this often leads to the designing of energy-efficient methodologies, analytical tools and high-
173 throughput analysis whenever possible. Portable and disposable devices can be a cost-effective
174 alternative, since sampling is minimized; they can also be available in the field of measurements, which
175 in turn would result in minimum transportation cost [31,32]. Still, portable cost-effective instruments
176 have some drawbacks in terms of methodology selectivity and limit of detection, but more advanced
177 technologies could improve their performance, which could become a hot research area in academia.
178 Moreover, academic research should make the best use of applications and smart devices, such as smart
179 phones [36], smart watches, scanners and 3D printers, which can extract data and analytes without
180 adding extra cost. Some researchers are now using household coffee machines for extraction, as it
181 requires lesser volume of solvents and consumes less time for getting satisfactory recovery compared to
182 the traditional laboratory extractors. Classic espresso machines have been reported by researchers to
183 successfully isolate bioactive compounds, for instance, eugenol from cloves [37]. Isolation of polycyclic
184 aromatic hydrocarbons (PAHs) from soil and sediments [38] was reported using hard-cap espresso
185 machines, where the solid sample placed inside a sealed capsule undergo pressurized extraction.

186 The societal responsibility in analytical chemistry covers two major aspects; first, analytical chemistry
187 should support the areas where there is a significant societal need, this will not only support the needs
188 but also will create new job opportunities, improved use of renewable materials and energy efficiency.
189 Secondly, analytical chemistry is to introduce methodologies that are of high quality and have reliable
190 results with minimum impact on the analysts' health and environment. Additionally, the social aspects
191 of green chemistry have to involve the transmission of information to society in a comprehensible and
192 contextualized way. In another meaning, analytical procedures, the analytical devices, and results are
193 easily accessible for all in need. To align with this pillar, academia research should tackle the society
194 needs and to ensure the use of simple analytics that anyone could easily perform anywhere. Handy
195 smart devices should be explored, for example, smartphones and digital cameras, to run chemical
196 analysis for routine tests. The use of smartphones or applications can make the analytical methods far
197 more accessible, cheaper, and do not require trained personnel for operation. Some studies have
198 reported smartphone-based sensors and other wearable noninvasive sensors with different detection
199 modes for measurements in different matrices such as food, saliva, blood, and others [32]. Further
200 investigation is required in academia research to invest more in using smartphone wearable sensors and
201 tattoos as cost-effective and available point-of-care diagnostic tools, fully integrating and analyzing the
202 data without the need for additional devices in health care, environmental and food research.

203 204 **5. Conclusions and future trends**

205 Although it is true that the waste generated in analytical laboratories is sometimes larger and more
206 hazardous than the sample analyzed, it is also likely that the amount of hazardous waste generated in



207 analytical laboratories in academic research is significantly less than in industrial laboratories.
208 Nevertheless, it is a great pity that analytical procedures often contribute to further pollution of the
209 environment by the production of hazardous waste. Green analytical chemistry can therefore be seen as
210 an important area of green chemistry that needs to be given due attention.

211 Of the twelve principles of green chemistry defined at the beginning of this century, analytical
212 chemistry is primarily concerned with the eleventh principle: "Analytical methodologies need to be
213 further developed to allow for real-time, in-process monitoring and control prior to the formation of
214 hazardous substances". This principle concerns and emphasizes the use of analytical chemistry in
215 industry to improve the analytical control of technological processes, so that analytical results can be
216 used to manage technological processes online and in real time. Probably, this has largely been
217 achieved, although a large space for further development in this area certainly exists. On the other
218 hand, this principle did not deal with so-called laboratory analytical chemistry.

219 If we look at the path of green analytical chemistry, we can observe two trends: On one hand,
220 analytical equipment manufacturers are offering increasingly sophisticated instruments that allow the
221 determination of an increasing number of target analytes with lower and lower detection limits in
222 diverse samples. Of course, this is most often accompanied by an increase in price (investment costs) as
223 well as increased operating costs, in addition to increased requirements for skilled laboratory staff.

224 On the other hand, we are also seeing a tendency to miniaturize, automate and simplify devices so
225 that they are more affordable and do not require highly qualified personnel, so that even a non-expert
226 can use them. This approach is very suitable for field work and routine environmental analyses, etc.

227 Analysis is a multistep process consisting of several consecutive steps, starting with sampling and
228 including sample processing, the subsequent measurement itself as well as the cleaning of laboratory
229 equipment.

230 An analytical laboratory cannot influence the greenness of some of these steps, such as the sampling
231 process, the transport of the sample to the laboratory or the storage of the sample during transport.
232 The measurement itself depends mainly on the available equipment, customer requirements and the
233 standard protocols used. Therefore, we should focus on assessing the greenness of the analytical
234 procedure itself and not on the greenness of the whole process of analysis as such.

235 Sample pretreatment can be made greener, for example, by reducing the volume of organic solvents
236 used or by replacing hazardous reagents with less hazardous ones. As a result, in the last two decades,
237 we have witnessed the introduction of new solvents, such as SHS and DES, into analytical procedures,
238 and we have also seen the emergence of new so-called microextraction techniques that use significantly
239 smaller volumes of solvents (less than one hundred microliters) or some that can be called virtually
240 solvent-free techniques.

241 Taking all of this into account, we cannot forget why the ideology of Green Chemistry was
242 introduced. It aims to conduct laboratory work based on the principles of sustainable development. It is
243 well known that for a development to be truly sustainable, all three areas – the environment, the
244 economy and society – need to be considered, while the philosophy of green analytical chemistry mainly
245 describes the first factor. Thus, being more than just "green", which means to cover the requirements of
246 these three areas, is recommended. Therefore, if you have called your methodology "green", please
247 apply the available metrics, such as GAPI or AGREE, to ensure development towards environmental
248 sustainability. In addition, during the creation of a new project, think about the needs of the global



249 society. Be an explorer of human needs; be useful to people. Remember that your work in the area of
250 analytical chemistry does not have to be merely a simple tool for other chemists to use, but a
251 continuously developing research area with large implications for the future good.

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253

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258

259 **Authors' contribution**

260 The idea of this work was proposed by Justyna Płotka-Wasyłka who also suggested the content of the
261 manuscript and contributed in manuscript preparation mainly in write up of the abstract, introduction,
262 and conclusion and formatting of the rest of the manuscript. Aleksandra Kurowska-Susdorf wrote the
263 part connected with the education of sustainability. Heba M. Mohamad wrote the section 4: sustainable
264 analytical chemistry. Rajkumar Dewani wrote the part connected with history of sustainable
265 development and evolution of green chemistry and its multidimensional impacts. Michel Y. Fares wrote
266 the parts related with challenges in analytical chemistry in regard to being green. Vasil Andruch
267 contributed in overall manuscript preparation mainly in write up of the conclusion and future
268 perspectives and formatting of the rest of the manuscript.

269

270 **Declaration of interests**

271 The authors declare that they have no known competing financial interests or personal relationships
272 that could have appeared to influence the work reported in this paper.

273

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