

# 1 Waste management in the mining industry of metals ores, coal, oil and natural 2 gas - a review

3 **Szymon Kalisz**<sup>1</sup>, **Katarzyna Kibort**<sup>1</sup>, **Joanna Mioduska**<sup>1</sup>; **Marek Lieder**<sup>1</sup>; and **Aleksandra**  
4 **Małachowska**<sup>1\*</sup>

5 <sup>1</sup> Gdańsk University of Technology, Faculty of Chemistry, Department of Process  
6 Engineering and Chemical Technology; [szymon.kalisz@pg.edu.pl](mailto:szymon.kalisz@pg.edu.pl);  
7 [katkibor@student.pg.edu.pl](mailto:katkibor@student.pg.edu.pl); [joanna.mioduska@pg.edu.pl](mailto:joanna.mioduska@pg.edu.pl); [lieder@pg.edu.pl](mailto:lieder@pg.edu.pl)

8 \* Correspondence: [aleksandra.malachowska@pg.edu.pl](mailto:aleksandra.malachowska@pg.edu.pl); Tel.: +48584372637

9 **Abstract:** Waste generated due to mining activity poses a serious issue due to the large  
10 amounts generated, even up to 65 billion tons per year, and is often associated with the risk  
11 posed by its storage and environmental management. This work aims to review waste  
12 management in the mining industry of metals ores, coal, oil and natural gas. It includes an  
13 analysis and discussion on the possibilities for reuse of certain types of wastes generated from  
14 mining activity, and discusses the benefits, disadvantages and the impact of waste  
15 management on the environment. The article presents current methods of waste  
16 management arising during the extraction and processing of raw materials and the threats  
17 resulting from its application. Furthermore, the potential methods of mining waste  
18 management are discussed through an in-depth characterization of the properties and  
19 composition of various types of rocks. The presented work addresses not only the issues of  
20 more sustainable management of waste from the mining industry, but also responds to the  
21 current efforts to implement the assumptions of a circular economy, which is aimed at closing  
22 the loop. The methods of recycling by-products and treating waste as a resource more and  
23 more often not only meet environmental expectations, but also become a legal requirement.  
24 In this respect, the presented work can serve as a valuable support in decision-making about  
25 waste management.

26 **Keywords:** mining waste management, natural energy resources, metal-bearing ores,  
27 chemical composition, environmental impact assessment

## 28 **1. Introduction**

29 Currently, in the world, open-pit and underground mines actively operate to extract valuable  
30 metallic and energy resources (Radić et al., 2016). This paper focuses on six raw materials:  
31 copper, lead, zinc (metallic raw materials) and coal, crude oil, and natural gas (energy raw  
32 materials). The work focuses on analyzing the discussed raw materials relative to five  
33 countries that are recognized as leaders in terms of resources and production of a given raw  
34 material. For copper, these are Chile, Peru, China, USA, and the Democratic Republic of Congo  
35 (DRC) (Flanagan, 2019; Kotarska et al., 2018); for zinc: China, Peru, Australia, USA, and India  
36 (Maghfouri et al., 2018). Most lead is mined in China, Peru, the USA, Mexico, and Russia  
37 (Mymrin et al., 2020). Oil and gas are mined in the USA, Russia, Saudi Arabia, Canada, the  
38 United Arab Emirates, Iran, Canada, and China (Ismail et al., 2017). Among these countries,

39 only in the United States there are located all of the above-mentioned raw materials.  
40 However, China is also at the forefront in terms of owned resources and their extraction,  
41 except for crude oil.

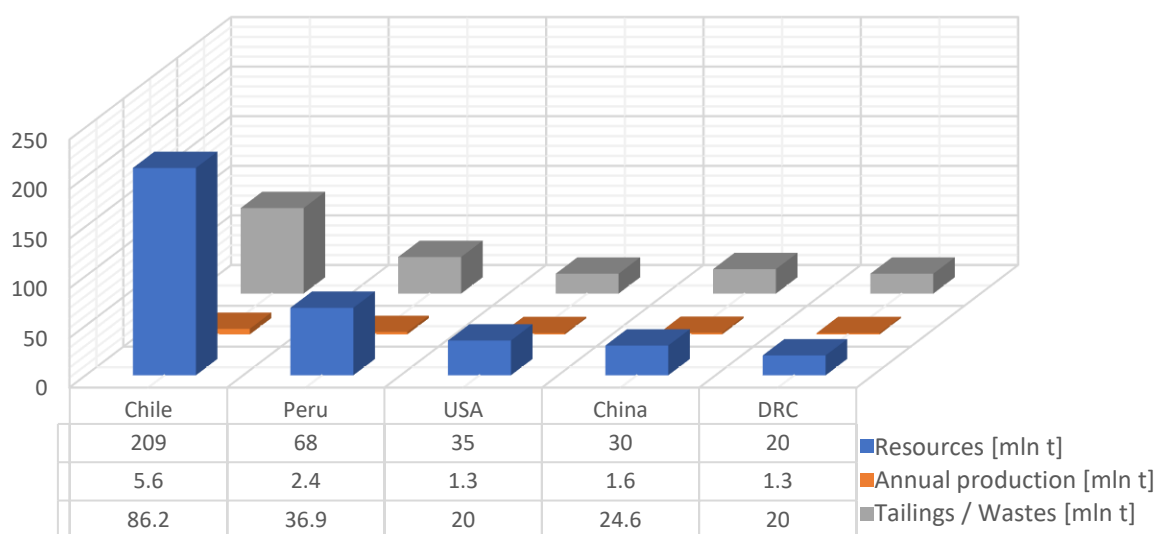
42 Naturally, the large variety of raw materials found in the USA and China result from the  
43 massive area of both countries, amounting to over 9 million km<sup>2</sup> (Brown et al., 2020). The wide  
44 range of latitude and longitude determines a broad climatic spectrum for those countries,  
45 which is conducive to the conditions for the formation of raw materials in the past and now.  
46 Equally crucial for the formation of the discussed raw materials were tectonic movements and  
47 the formation of the surface due to geological processes (Drachev et al., 2010; Mann et al.,  
48 2005). It is worth emphasizing that the United States is situated on active tectonic plates, e.g.,  
49 the San Andreas Fault, which runs through western and southern California, which is  
50 characterized by rich sources of oil and natural gas (Mann et al., 2005).

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55 natural gas (Mann et al., 2005).

56 In the case of China, the most active are 3 tectonic faults: Weibschuan, Pengguan, Baichuan,  
57 causing cyclical shocks (4,000 movements in 15 years), contributing to mineralization and  
58 filling in the resulting void spaces in rocks (Song et al., 2018).

59 Peru is rich in copper, zinc and lead, while Russia has the largest reserves of lead, oil and gas.  
60 However, Russia is situated on one of the most stable tectonic plates - Eurasian, which reduces  
61 the further mineralization of ores in this region of the world. Therefore, oil and gas originate  
62 there from the existing geological formations . Other countries are the leaders for one or two  
63 of the raw materials. Significant deposits of oil and gas are observed in the Arab states. In turn,  
64 in Australia and India, the geology is characteristic of the presence of metalliferous elements  
65 (Drachev et al., 2010; Flanagan, 2019).

66 Figure 1-6 presents countries with the largest deposits and the largest amounts of extracted  
67 raw materials. The amount of produced waste was estimated based on the literature data.  
68 The data in the graphs represent the resources that have been estimated and reported in  
69 geological journals and texts (Bakalarz, 2019; Dudeney et al., 2013; Flanagan, 2019) for the  
70 country concerned. The annual extraction of the raw material in a given country was  
71 presented on the basis of data presented by the plants that extract the given raw material.  
72 Data on the annual extraction of raw materials are also made public in official reports (Brown  
73 et al., 2020). The amount of waste produced was estimated on the basis of data that includes  
74 the amount of metal or raw material in the deposit and on the basis of reports that refer to  
75 the ratio of the amount of raw material extracted to the amount of waste produced, expressed  
76 as a percentage (Çoruh et al., 2012).



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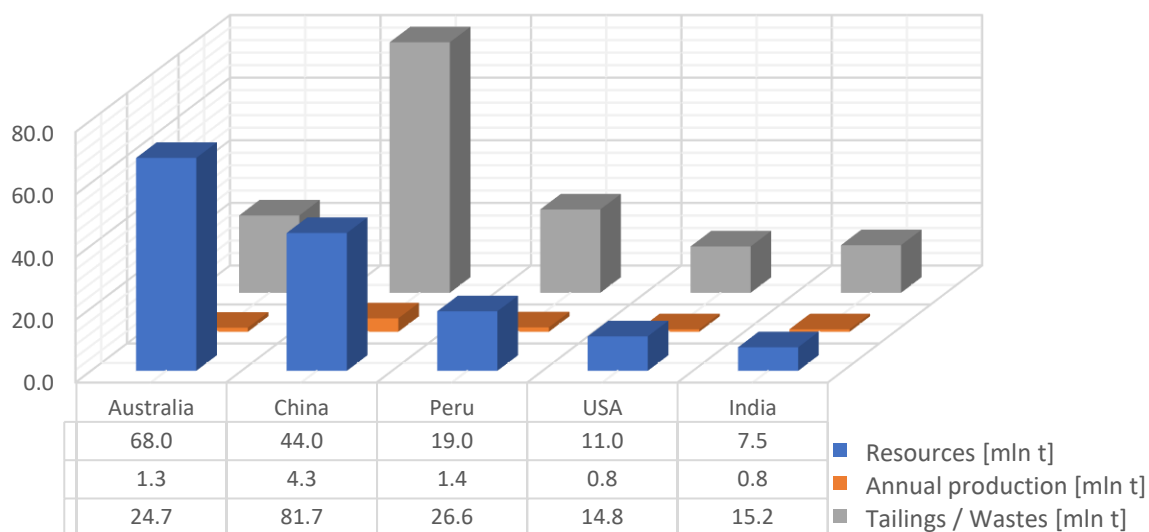
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**Figure 1.** Countries with the largest resources of deposits, annual production and the average amount of waste produced from copper

80 The largest copper deposits are located in Chile (209 mln tones) and Peru (68 mln tones),  
 81 wherein the annual extraction in Chile is more than twice that of Peru. The remaining  
 82 countries, i.e., the Democratic Republic of the Congo, China, and USA have resources ranging  
 83 from 20 to 35 million tons, with annual production 77% lower than that of Chile. Since the  
 84 amount of raw material extracted is closely correlated with the amount of waste generated  
 85 during the extraction process, the presented values indicate, why Chile produces 400% more  
 86 waste than the Democratic Republic of Congo.

87 In Europe, Poland is the leader in extraction and production of copper. The biggest Polish  
 88 producer, KGHM Polish Copper, extracts up to 702 thousand tons of raw material per year in  
 89 total. With an average copper content of about 2% in Polish deposits, and extraction of 566  
 90 thousand tons, over 28 thousand tons of copper ore flotation tailings are formed (KGHM,  
 91 2020). During mineral enrichment, on average 94% of the material is treated as waste  
 92 (Kotarska, 2012). Annually, Chile extracts about 60 times more copper than Poland and as  
 93 much as 99% is waste. Both countries stockpile similar amount of flotation tailings,  
 94 constituting 60-70% of the primary raw material (Łuszczkiewicz, 2000; Steliga and Uliasz,  
 95 2012).

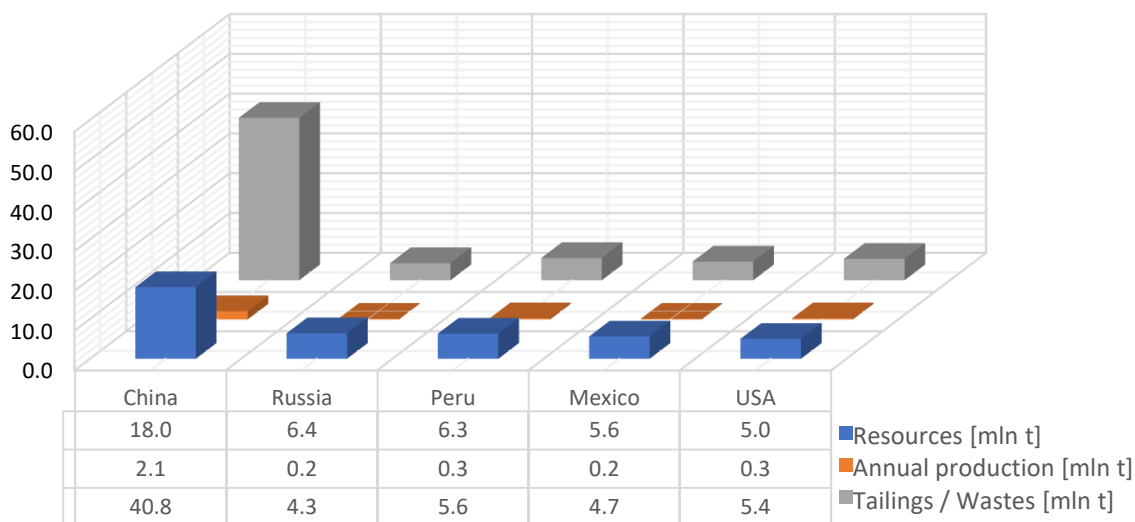




96

97 **Figure 2.** Countries with the largest resources of deposits, annual production and the  
 98 average amount of waste produced from zinc

99 The highest zinc deposits are located in Australia (68 mln tones) and China (44 mln tones).  
 100 Despite China deposits are around 35% less, it extracts about 3 times more than Australia.  
 101 Similarly, to Peru, which has less than 3.6 times zinc deposits than Australia but extracts 7%  
 102 more. The largest amount of waste from the zinc extraction processes is generated by China,  
 103 reaching around 81.7 million tons, which is 307% more than in Peru, being second on the list  
 104 (Amy C. Tolcin, 2020; Brown et al., 2020).



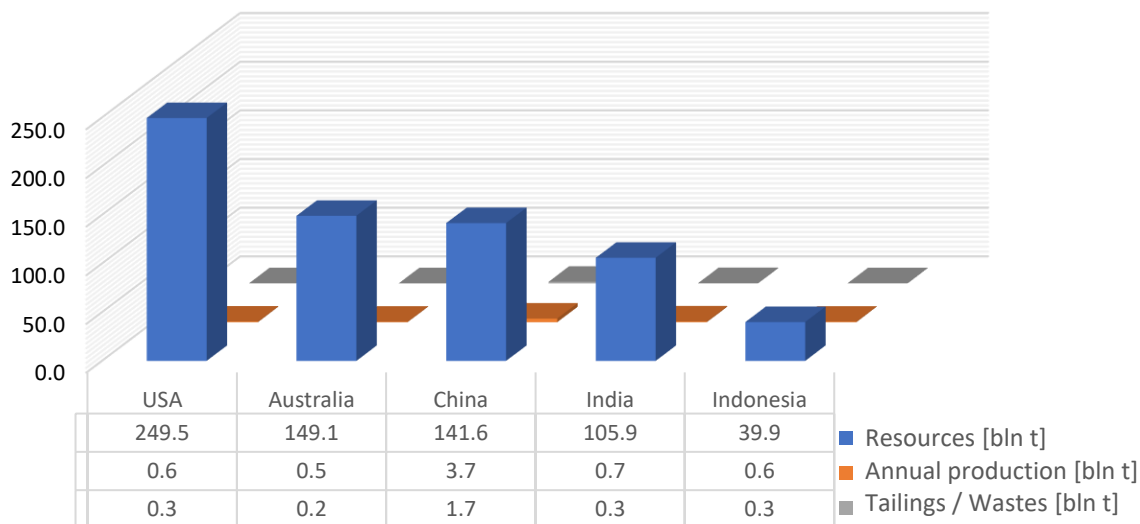
105

106 **Figure 3.** Countries with the largest resources of deposits, annual production and the  
 107 average amount of waste produced from lead

108 The largest lead mineralization occurs in China, where the deposit's potential is 18 million tons  
 109 and is approximately 2.8 times greater than the deposits in Russia or Peru and 3.2 times  
 110 greater than in the other countries. China is the undisputed leader, when it comes to mining

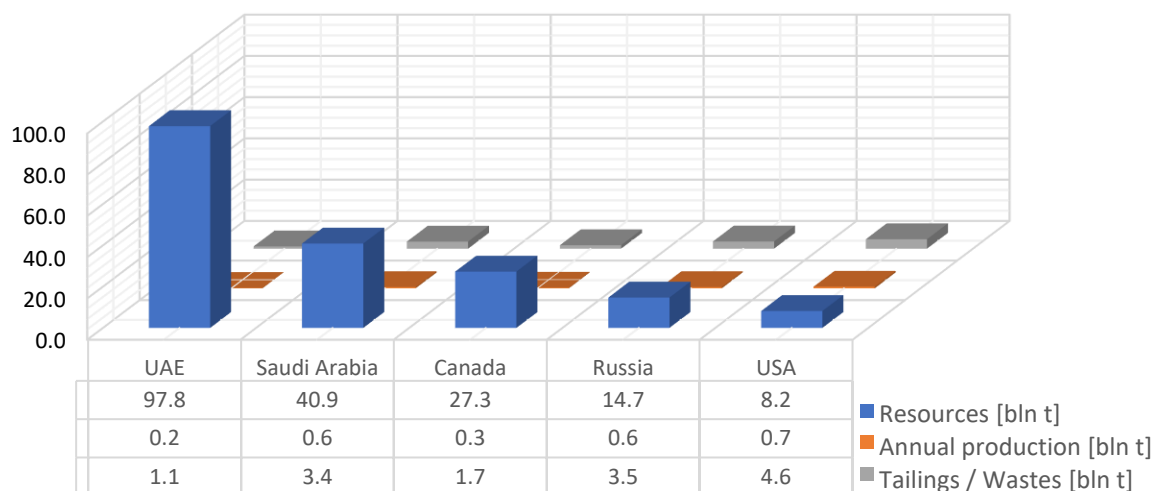


111 of lead, since it brings it out 700% more than other countries. Similarly, as in the case of the  
 112 aforementioned metalliferous raw materials, China is also an inglorious leader in terms of  
 113 waste generated from the lead mining process (Yin et al., 2020).



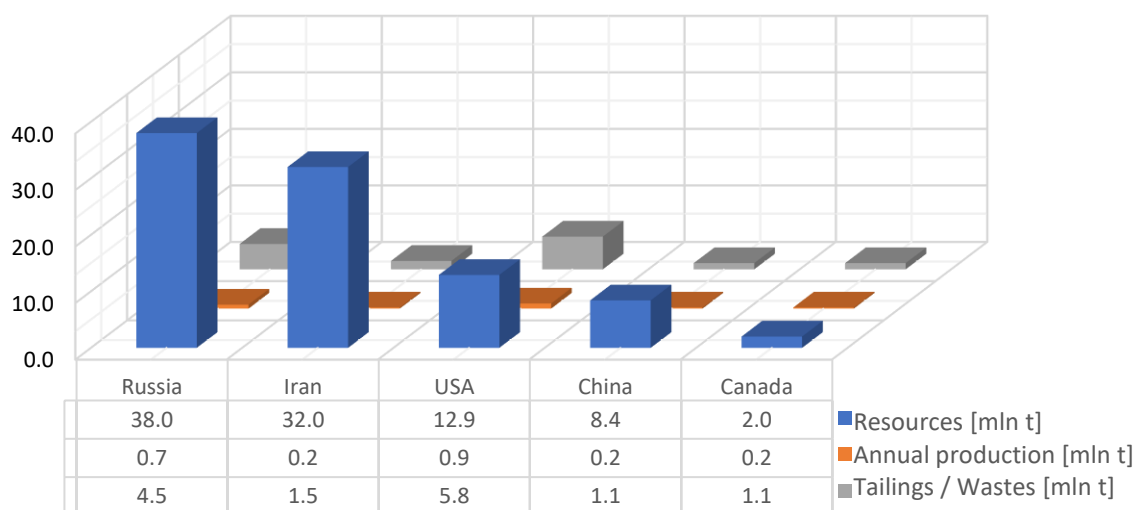
114  
 115 **Figure 4.** Countries with the largest resources of deposits, annual production and the  
 116 average amount of waste produced from coal

117 Coal deposits found in the United States are estimated at around 250,000 million tons, while  
 118 smaller resources, ranging from 105,000 million tons to about 150,000 million tons, are in  
 119 India, China and Australia (“Coal and lignite production,” 2019). Annually, Chinese coal  
 120 production is about 4,000 million tons, while other forefront countries extract 85% less. This  
 121 is related not only to smaller coal deposits, but also to climate policy. However, coal waste  
 122 accounts for approximately 46% of the annual output for each of the leaders (Fečko et al.,  
 123 2013).



124  
 125 **Figure 5.** Countries with the largest resources of deposits, annual production and the  
 126 average amount of waste produced from oil

127 The majority of crude oil extraction is carried out by Arab countries, such as the United Arab  
 128 Emirates, which has 97,800 tcm (trillion cubic meter) and Saudi Arabia having less than half of  
 129 the deposits of the United Arab Emirates. However, despite having the biggest resources,  
 130 these countries are not producing the most. The leader is the United States, which despite  
 131 having 92% smaller oil deposits than the United Arab Emirates, extracts it up to 415% more  
 132 (“Crude oil production,” 2019).



133

134 **Figure 6.** Countries with the largest resources of deposits, annual production and the  
 135 average amount of waste produced from gas

136 Russia has the largest natural gas reserves in the world, estimated at 38 tcm, which is 16%  
 137 more than the estimated natural gas deposits in Iran. Similarly, to the crude oil, despite not  
 138 having the biggest resources, the USA is the largest producer of this raw material. Iran, Canada  
 139 and China produce similar amounts, despite large differences in their resources. Compared to  
 140 the US, annually they extract around 77% less (“Natural gas production,” 2019). Charts with  
 141 regard to global extraction, resources and waste from metals, and energy raw materials are  
 142 presented in the appendix (Fig I and Fig II).

143 Data on resources and annual production (Fig. 1 - Fig. 6) show what sizes of raw materials  
 144 individual countries have. The distribution of the share of the distinguished countries has been  
 145 similar so far, as it corresponded to the resources held. However, the situation has recently  
 146 changed due to the prevailing pandemic. As a result of sanitary restrictions and people  
 147 infected with covid-19, the efficiency of mines decreased due to the limited number of  
 148 working personnel. In some countries, mining activities have been reduced or terminated,  
 149 such as South Africa, where the shutdown of the mining process led to the closure of mines  
 150 and the dismissal of workers. The restrictions led to the suspension of many industrial and  
 151 construction productions, which led to a dramatic drop in demand for metals. There has been  
 152 a decline in the prices of metals and minerals, mainly aluminum (down 15%), copper (down  
 153 14%), gold, lead and nickel, thereby putting the incomes of countries based on exploration of  
 154 raw materials at risk (Laing, 2020).

155 The introduced restrictions related to movement affected the transport sector, including  
156 aviation, and this in turn affected the fuel market. These sectors accounted for 60% of the oil  
157 demand. As a result of the pandemic, demand decreased from 100 million barrels in January  
158 2020 to less than 75 million barrels in April 2020. The International Energy Agency (IEA)  
159 predicted that global demand for natural gas in 2020 will decrease by 4 %. From December  
160 2019 to June 2020, the number of drilling and gas rigs in the US decreased from 805 to 265.

161 Downtime caused by the pandemic contributed to the lack or problems with the availability  
162 of certain materials on the market, and this also contributed to a sharp increase in the prices  
163 of metal raw materials as well as oil and gas (Moore et al., 2020; Nyga-Łukaszewska and Aruga,  
164 2020; Zanoletti et al., 2021).

165 This work aims to review waste management in the mining industry of metals ores, coal, oil  
166 and natural gas. It includes an analysis and discussion on the possibilities for reuse of certain  
167 types of wastes generated from mining activity, and discusses the benefits, disadvantages and  
168 the impact of waste management on the environment.

169 To meet the goal and to discuss waste management according to its characteristics, the  
170 research begins with the review on the properties and composition of metal-bearing ores and  
171 energy rock resources. Furthermore, it compares it with the variability in mineralogical  
172 composition of the wastes generated during processing and production. This knowledge and  
173 understanding of the technology of wastes acquisition allows estimating the amount  
174 generated, the variability between particular processes, and evaluate best and most  
175 environmentally friendly way of its future re-use and management.

176 The literature reviewed and placed in this paper, was selected in such a way as to present the  
177 world resources, annual extraction of selected metals and energy raw materials, and  
178 estimated amounts of produced waste, in order to show the scale of the amount of waste  
179 produced and the related management possibilities. The authors focused not only on  
180 published data in articles, but also on information that is available in individual mines and  
181 companies. Furthermore, a literature review was carried out on the geological basis of metals  
182 and energy raw materials, and mineralogical and phase composition of mine waste. These  
183 compositions vary according to the publication dates of the manuscripts. These differences  
184 result from technological changes in individual mining and material processing plants.  
185 Therefore, the authors chose the latest publications. On this basis, current data on the  
186 management of the above-mentioned waste and new possibilities of their use were  
187 presented.

## 188 **2. Geological aspects**

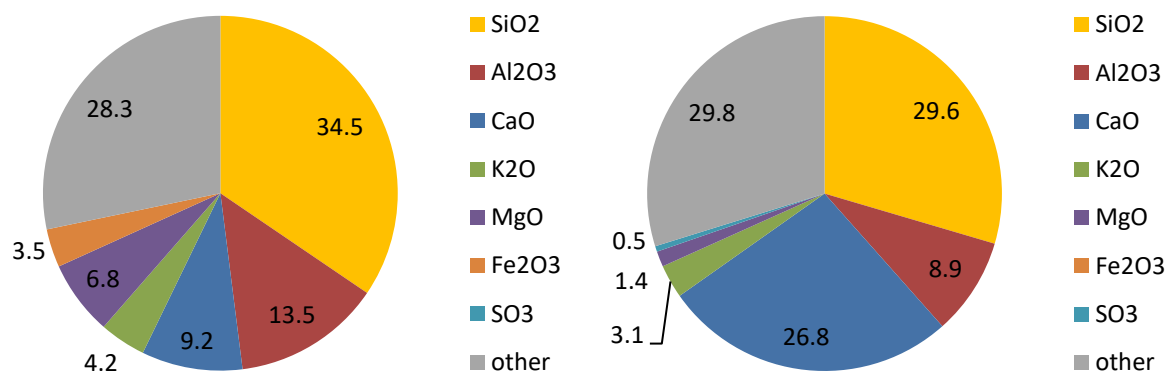
189 A comprehensive analysis of the raw materials discussed in this paper is important as the aim  
190 is to analyze both the waste and the structure of the base component, which contain valuable  
191 minerals that end up in the waste. Due to their value, the raw material and accompanying

192 rocks should be managed as best as possible, for example to produce a new product  
 193 (concretes, coatings, pavements), but also to reduce possible environmental toxicity.

194 *2.1. Copper, zinc and lead*

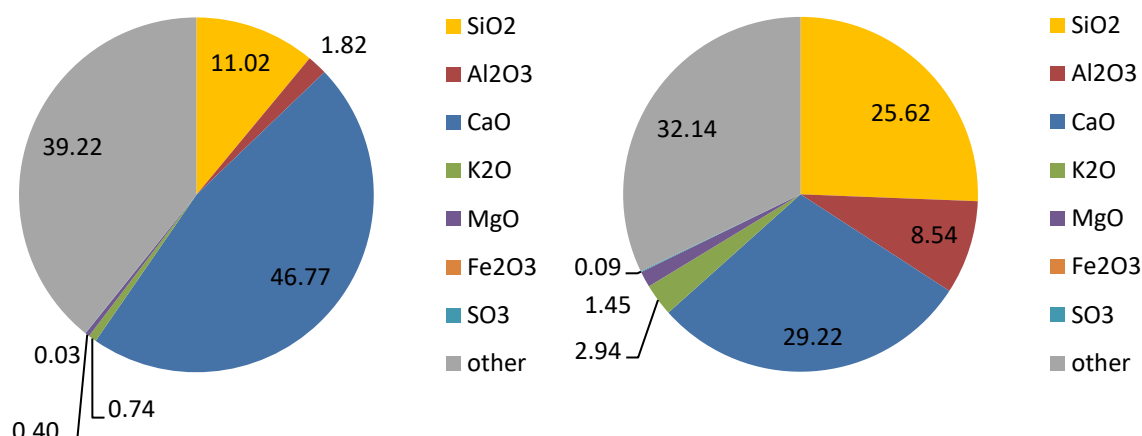
195 Copper is a metalliferous raw material obtained from rocks. It is extracted over 87-90% from  
 196 sulphide ores and up to 9-12% from metal oxides (“Przeróbka kopalni miedziowych,” 2008).  
 197 Zinc and lead are also obtained from rock ores.

198 Acquiring raw materials for copper, zinc and lead requires mining them along with the rock in  
 199 which they are contained. The raw material is extracted from the rock by means of flotation,  
 200 whereas the remnants are considered as useless waste. Native copper ore deposits are  
 201 extremely rare and constitute only about 1% of all its mineral deposits (“Copper alliance,”  
 202 2018, “Informator Metale Nieżelazne,” 2005). The mineralogical compound of rock waste  
 203 results from the types of geological layers that may vary from region to region. The compound  
 204 of copper ores for selected types of rocks are presented below. The main constituent is a  
 205 gangue, which accounts for over 90% by weight, while copper minerals are less than 1 wt%.  
 206 In the Figure 7 and Figure 8, copper is indicated in the "other" group along with other  
 207 compounds of metallic origin in small amounts (Matlakowska et al., 2014).



208  
 209 **Figure 7.** Mineralogical compound of shale rocks (left) and marls (right) containing Cu  
 210 minerals



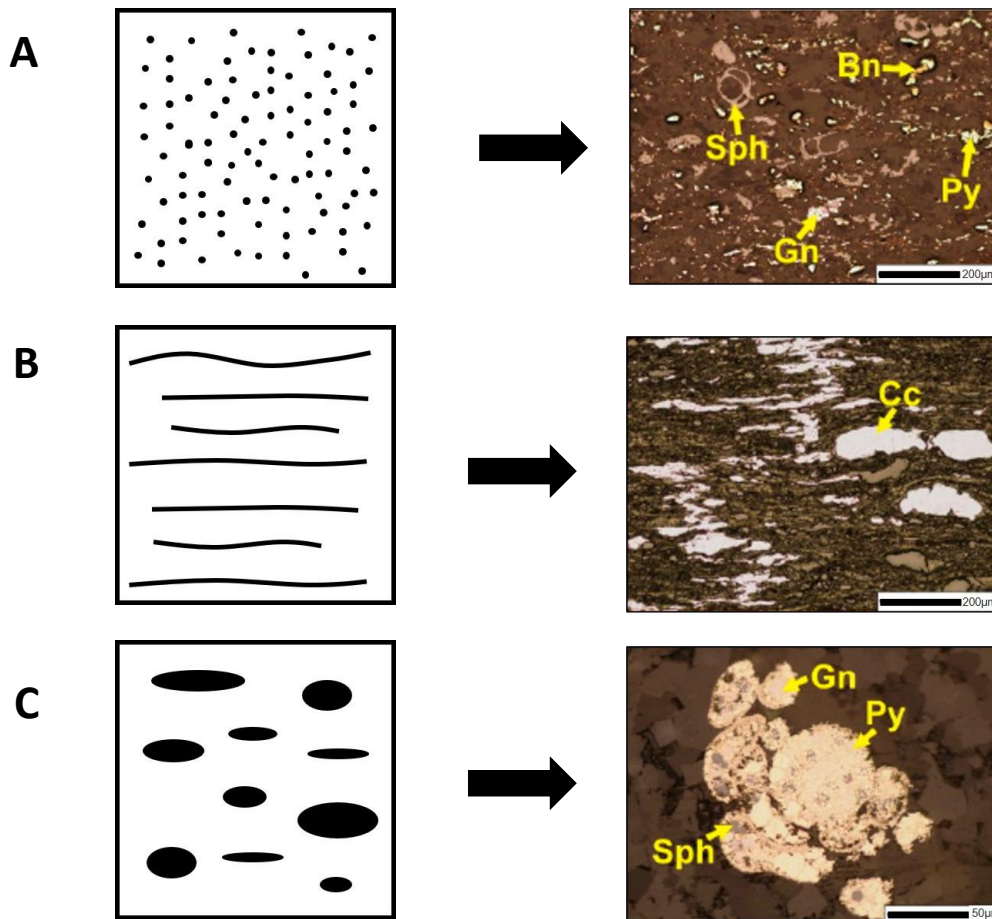


211  
 212 **Figure 8.** Mineralogical compound of Zechstein limestone (left) and spotted marls containing  
 213 Cu minerals

214 Copper mineralization is observed in various types of rocks. Copper compounds are contained  
 215 in igneous and sedimentary rocks of the Sierra Gorda deposit - the largest copper-  
 216 molybdenum ore deposit in the world, located in the Atacama Desert in Chile. Copper occurs  
 217 there in the form of sulphides and oxides in granodiorite, granite and monzodiorite rocks. Due  
 218 to the large area of the deposit, the mineralization of the raw material also took place there  
 219 in volcanic rocks, mainly in tuffs and andesites, and mudstones and claystones of sedimentary  
 220 rocks (López and Ristorcelli, 2011; Pieczonka et al., 2017; Ristorcelli, S., Ronning, P., Fahey, P.  
 221 and Lustig, 2008). Copper compounds in sedimentary rocks are also found in Polish copper  
 222 deposits, which have been mineralized in shales, dolomites and sandstones. (Kibort and  
 223 Małachowska, 2018; Konopacka and Zagożdżon, 2014).

224 Copper is also contained in Chinese sandstone deposits in the Chuxiong Basin. Sandstones are  
 225 the result of the formation of geological features in the Cretaceous. Copper mineralization is  
 226 visible in rock deformations (faults, anticlines, crevices) and in places that contacted with  
 227 water. A shale zone is also distinguished there, which is consistent with the Permian copper  
 228 shale from the European region. Copper minerals are mainly observed in the form of lenses  
 229 and dominant thin lamination (Chen et al., 2000; Hsi-chi et al., 1968; Huang et al., 2019)

230 The quantity of the extracted raw materials is influenced by the rock texture of the sediment  
 231 deposits, in which the raw material occurs. Thus, it is important to consider the texture when  
 232 analysing the potential of any resources for production (Kibort and Małachowska, 2018).  
 233 Copper in rocks can occur in different forms, what is graphically presented in Figure 9: – it  
 234 occurs as dispersed or finely dispersed, filling rock spaces, e.g., in sandstones, – mineralized  
 235 veins, usually occurring according to the location of the rock layers (shales), and – irregular  
 236 sockets, known as lenticular, characterized by an oval shape observed in the form of lenses  
 237 and dominant thin lamination (Chen et al., 2000; Hsi-chi et al., 1968; Huang et al., 2019, Kibort  
 238 and Małachowska, 2018; Oszczepalski et al., 2019).

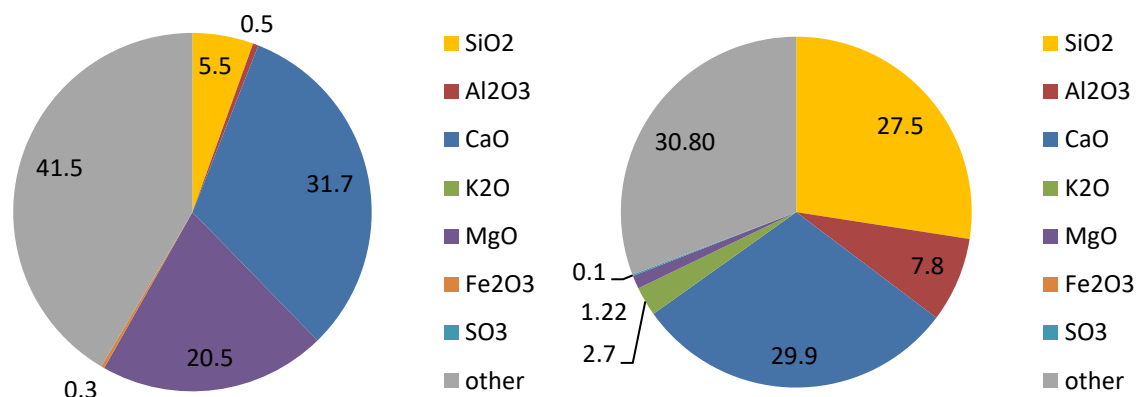


239 **Figure 9.** Forms of copper: A - dispersed, B – mineralized veins, C – lenses

240 Zinc and lead are most often found in the form of a single ore and are mostly extracted from  
 241 sulphide ores. In the recent years zinc has been obtained by the hydrometallurgical method  
 242 using electrolysis (Cabała, 2010). In its native state, zinc does not occur naturally. The main  
 243 minerals of zinc are zinc blende (sphalerite - zinc sulphide) and smithsonite (zinc carbonate).  
 244 Zinc blende is the most important zinc ore, containing also large amounts of cadmium, lead  
 245 and even silver, indium and gallium (Kołodziejczyk, 2019). Cadmium accompanies almost all  
 246 zinc ores.

247 The most important lead ores are galena (PbS - lead (II) sulphide) and anglesite (PbSO<sub>4</sub> - lead(II)  
 248 sulphate). Galena is found in igneous and sedimentary rocks. It is accompanied by compounds  
 249 of antimony, bismuth, zinc, copper, silver, gold and iron. Most often it contains only a few  
 250 percent of lead, while pure lead sulphide may contain it up to 86%. In the case of zinc and  
 251 lead, similar forms of occurrence are observed as in the case of copper, and the mineralization  
 252 and distribution depend on the hydrogeological and thermal conditions. The presence of zinc  
 253 and lead minerals in carbonate rocks is associated with hydrothermal processes of transfer of  
 254 compounds from lower geological formations to the higher layers containing sulfur  
 255 compounds, forming compounds with zinc and lead. Another source is the deposition of lead  
 256 zinc in carbonate layers as a result of entering the cooler layers, preventing dissolution of the  
 257 elements and further penetration (Van der Graaf, 2018). In Figure 10 are mineralogical  
 258 compound of dolomite containing zinc minerals and marls containing lead minerals with the

259 minerals Zn and Pb being classified in the group "other". Zn and Pb content did not exceed 1  
 260 wt.% (Biernacka et al., 2005).



261  
 262 **Figure 10.** Mineralogical compounds of dolomite (left) containing Zn minerals and marls  
 263 (right) containing Pb minerals

264 The largest zinc mineralization was observed in dolomite sedimentary rocks and smaller in  
 265 igneous rocks (Abu-Hamattah and Al-Amr, 2008; Höller and Gandhi, 1997). To a lesser extent,  
 266 the mineralization of zinc and lead is observed in metamorphic gneiss in the form of sulphide  
 267 ores of the Ramura-Agucha deposit and graphite-mica-sillimanite shales (Kumar, 2013). A  
 268 similar situation of mineralization is observed in the Barney Creek Formation in Australia,  
 269 where zinc and lead deposits are mostly found in dolomite and shale rocks (Haines, P.W.,  
 270 Pietsch, B.A., Rawlings, D.J., Madigan, T.L., Findhammer, 1993; Hughes, 1990; Page et al.,  
 271 2000). The mineralization of zinc and lead compounds is observed in an overhang of gneiss  
 272 strands of the Rampura-Agucha deposit in the form of sphalerite and galena. They are in the  
 273 form of fine to coarse grains with inclusions of feldspar, quartz, sillimanite and chlorite  
 274 (Kumar, 2013).

275 A similar condition occurs in the European region with zinc and lead, referred as MVT deposits  
 276 (Mississippi Valley Type). The name results from the similarity of the properties of the deposit  
 277 to the compounds found in the Mississippi River Valley. The largest European zinc-lead region  
 278 is located in Poland and is characterized by the presence of raw materials in carbonate rocks,  
 279 the mineralization of which dates back to the period from the Devonian to the Jurassic.  
 280 According research (Gałkiewicz and Śliwiński, 1983), the mineralization of zinc and lead  
 281 follows tectonic structures (PIG-PIB, 2020; Piwowarski and Żeglicki, 1977).

282 Zinc deposits associated with carbonate rocks are also observed in Iran, where they are found  
 283 in the Dolomites and Lower Permian dolomitic limestones. A characteristic feature of this  
 284 deposit is the absence of zinc sulphides. Below the layer of zinc-lead ore deposit, there are  
 285 shales and sandstones, and above gypsum, sandstone and shale rocks (Maghfouri-Moghadam  
 286 et al., 2009).

287 The forms of zinc and lead minerals are described as similar to those of copper. They fill gaps  
288 and tectonic breaches. The most common are lenticular forms, as well as nests, stockworks  
289 and lines, which occur according to the stratification of the ore deposit (Nieć et al., 2018;  
290 Piwowarski and Żeglicki, 1977)

## 291 2.2. *Coal*

292 Coal mining is associated with the acquisition of the raw material along with accompanying  
293 rocks. Occurring coal seams are characterized by a different geology and period of formation.  
294 Such condition can be observed in the Chinese layered coal seam structure, where the  
295 influence of the marine environment on the geology of accompanying rocks is undoubtedly  
296 visible. Those coal seams are mainly associated with sedimentary rocks including sandstones  
297 and to a lesser extent mudstones and bauxite. Lime inclusions also appear there (Fang et al.,  
298 2013; Jin et al., 2013). Carbon stratification by sedimentary rocks is also observed in the  
299 European region. An example is the Upper Silesian Coal Basin, in which sandstone may  
300 constitute from several to 70% of the accompanying rocks. Further west, the sandstone  
301 content is lower, while claystone and shale predominate (Galos and Szlugaj, 2010)

## 302 2.3. *Crude oil and natural gas*

303 The drilling sector is characterized by a wide spectrum of rocks extracted as a drilling waste,  
304 which is influenced by the location and depth of the drilling that may pass through several  
305 significant and minor geological strata. For example, the geology of oil and gas fields in the  
306 Gulf of Mexico is made up by an alternation of shales and sandstones at a depth of 5,000-  
307 5,300 m. Carbonate rocks also appear in the lower section of the well (approx. 6,000 m)  
308 (British Petroleum, 2010; Dice, 2017). Further down, from about 6,800 m to 7,500 m, salt  
309 deposits are present (“bp Statistical Review of World Energy,” 2020, “Natural gas production,”  
310 2019; Dice, 2017)

311 Sandstones and sandy clays constitute the rock layers of the Baltic hydrocarbon deposits.  
312 Quaternary clays also occur with them. Free rock spaces are most often filled with silt or  
313 organic material. The Northern Baltic Sea Basin is characterized by the transition of sandy  
314 rocks into clay, loams and mudstones. Therefore, it can be concluded that the Baltic region  
315 consists of those four rock types (Sikora and Wojna-Dyłaż Elżbieta, 2010).

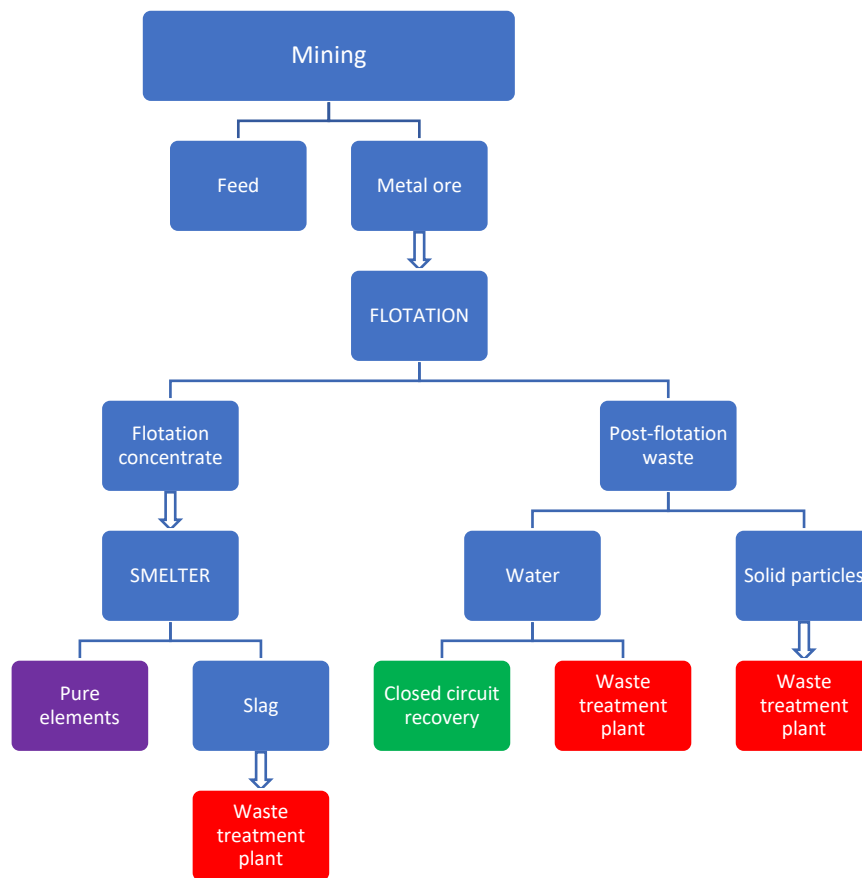
## 316 3. **Properties of mining and processing waste**

317 Mining and processing of rocks and metal ores generates large amounts of waste rocks,  
318 (gangue), from the extraction process, tailings (from flotation and enrichment) and  
319 metallurgical waste (from the smelter).

320 During metal processing in a smelter, a waste called slag is produced (Gorai et al., 2003). The  
321 extraction of copper in one mine generates an average of 2.3 million tons of waste per year  
322 (Çoruh et al., 2012). Similarly, in the case of zinc and lead, 1 ton of extracted metal generates

323 19 tons of flotation waste and gangue (Bouguermouh et al., 2018). Figure 11 presents a  
 324 general scheme of how metal raw materials are processed.

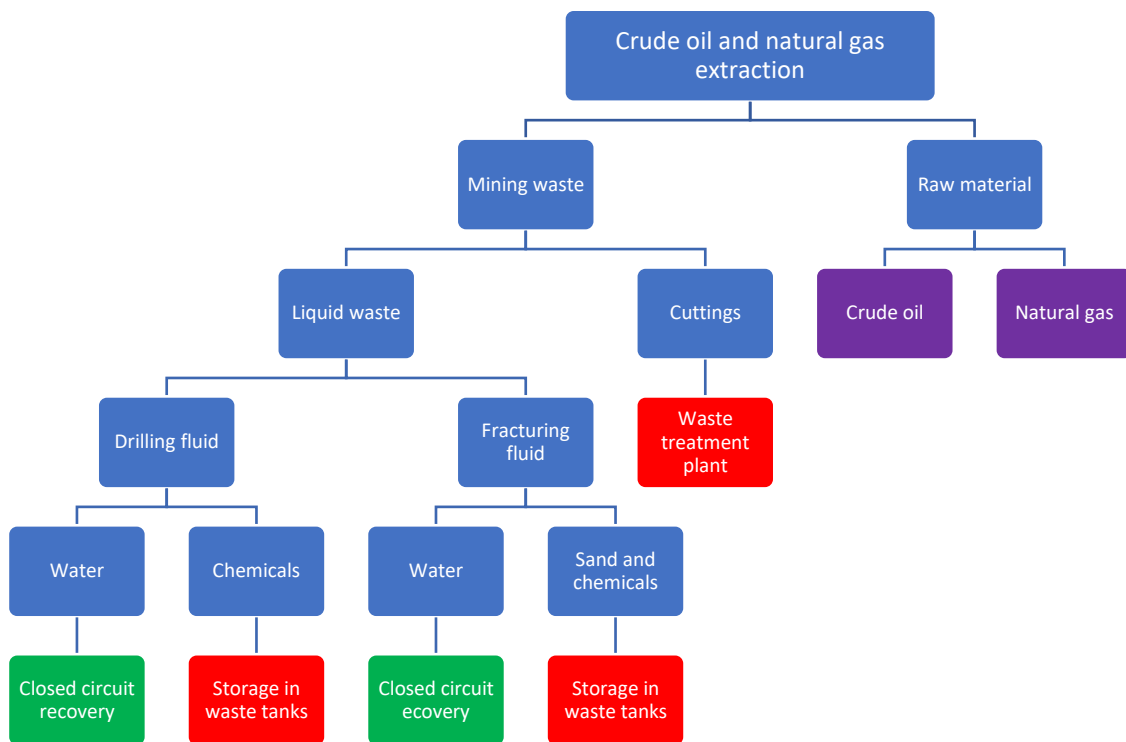
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326 **Figure 11.** Diagram of the extraction of metal raw materials

327 Processing of energy resources such as coal, oil or gas, as in the case of metals, produces liquid  
 328 waste, and solid waste - drill cuttings. As a result of coal mining, a waste rock, in the case of  
 329 coal constitute about 30% (Kopacz, 2015), and the rest of the generated waste are tailings  
 330 containing gangue and large amounts of water, which is recycled in a closed circuit (Hudson-  
 331 Edwards et al., 2011).

332 The oil and gas industry also produces specific waste, known as drilling (around one million  
 333 tons) and cuttings. The extraction of raw materials generates waste rock, such gangue and  
 334 drill cuttings (Huang et al., 2018) as well as drilling and fracturing fluid. A general diagram of  
 335 waste generation during the extraction of crude oil and natural gas is shown in Figure 12



336 **Figure 12.** Diagram of waste generation during the extraction of crude oil and natural gas

337 **3.1. Copper, zinc and lead**

338 The extraction of copper, zinc and lead ores as well as the processing of these raw materials  
 339 affects the quality of the environment. Mines produce a large amount of waste because the  
 340 metal-containing ore is a small fraction of the total volume of material extracted. The waste  
 341 material is generated in the processes of mining, extraction, processing and further treatment,  
 342 and its quantity depends on a number of factors related to the geological structure of the rock  
 343 mass, the quality of the deposits, methods of excavation and enrichment technology (Baic and  
 344 Witkowska-Kita, 2011; Galos and Szlugaj, 2014; Tumidajski et al., 2008).

345 Mining waste constitutes mainly gangue, which is removed at the stage of deposit  
 346 preparation, and waste from the extraction and processing of the raw material. The amount  
 347 of the waste depends on the type of a mine: whether it is underground or open-pit. The waste  
 348 from mining and preparatory works includes those generated, among others, while drilling  
 349 new shafts. They are characterized by high variability of petrographic composition. The share  
 350 of clay, sandstone, mudstone and overgrowth is varied. The grain composition of this material  
 351 is in the range of >300 mm. In open-pit mines, the surface material is called an overburden,  
 352 which is used to backfill the place, where the raw material was mined.

353 The waste from processing operations includes coarse-grained scrubber waste, grain class 20–  
 354 200 mm; medium-grain waste from jigs, grain class 2–20 mm and fine-grain waste from spirals,  
 355 grain class 0.5–2.0 mm. The content of organic parts in the waste material ranges from 42%  
 356 in the case of jigs to 60% in the case of spirals. The mineral content ranges from 58 to 40%,

357 respectively. The processing waste also includes sludge waste. They come from a chamber and  
358 belt presses. These are very fine-grained waste with a grain size of less than 0.5 mm. In terms  
359 of petrography, they are characterized by a significant share of clay and coal.

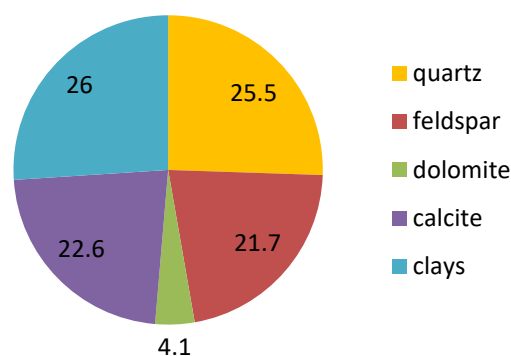
### 360 3.2. Coal

361 Coal mining, in relation to the production of other raw materials discussed in this study,  
362 generates the least amount of solid waste, which is managed through landfilling. The  
363 generated waste mainly comes from accompanying rocks that are separated in the froth  
364 flotation process. The waste from flotation can be further subjected to an enrichment (Melo  
365 and Laskowski, 2006). Wei et al. 2015, (Wei and Peng, 2015) used a diesel collector for coal  
366 flotation, while methyl isobutyl carbinol (MIBC) was used as a frother, while Peng2015 used  
367 N-dodecane and 2-octanol as a collector and frother. From the literature review it is seen that  
368 oily reagents are commonly used, despite they should be neutralized before storage.

### 369 3.3 Oil and gas

370 The extraction of crude oil and natural gas involves drilling. Wastes from oil and gas extraction  
371 are mainly drill cuttings from drilling holes, contaminated drilling mud to facilitate production  
372 operations. The chart below shows an example of the cuttings mineralogical composition,  
373 which is the average value for ten depths within the range from 2500 to 5000 m. The main  
374 minerals of cuttings are quartz, feldspar, calcite and clay minerals. The content of each of them  
375 ranges from about 21 to 26%. Dolomite has the lowest content equal to 4.1%.

376



377

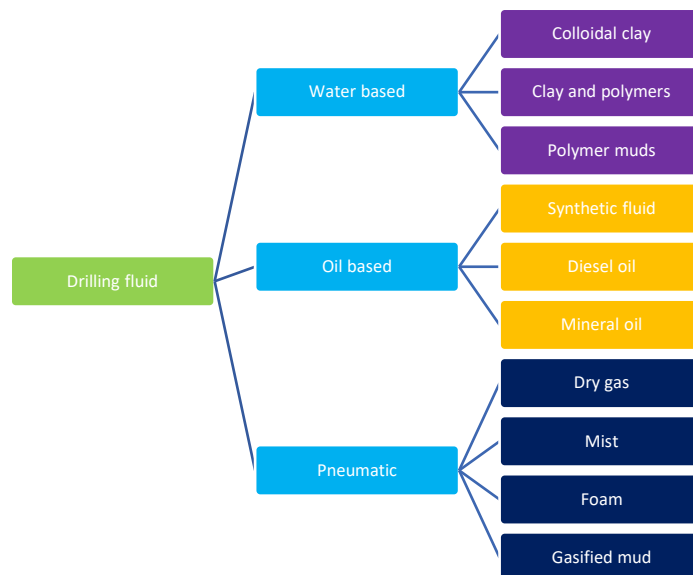
378 **Figure 13.** Example of mineralogy of drill-cuttings

379 Drill cuttings variability in composition may be the result of natural geological processes or the  
380 result of contamination with components of water or oil-based drilling fluids. The group of  
381 liquid contaminants also includes the fracturing fluid consisting of 90 to 95% of water and  
382 chemical additives. To reduce the resource consumption, the flowback fluid from the  
383 fracturing process is treated and reused (Steliga and Uliasz, 2012).



384 Drilling works are carried out to the point of contact with the source hence the drill cuttings  
385 and drilling fluid are slightly contaminated with crude oil. This qualifies them as harmful to  
386 the environment and intended for disposal or neutralization. The chemical composition of  
387 drilling fluids can also contaminate solid and water wastes. There are three most popular types  
388 of drilling fluids: water-based, oil-based and pneumatic (Eldridge, 1996; Pereira et al., 2019),  
389 the compositions of which are shown in Figure 13.

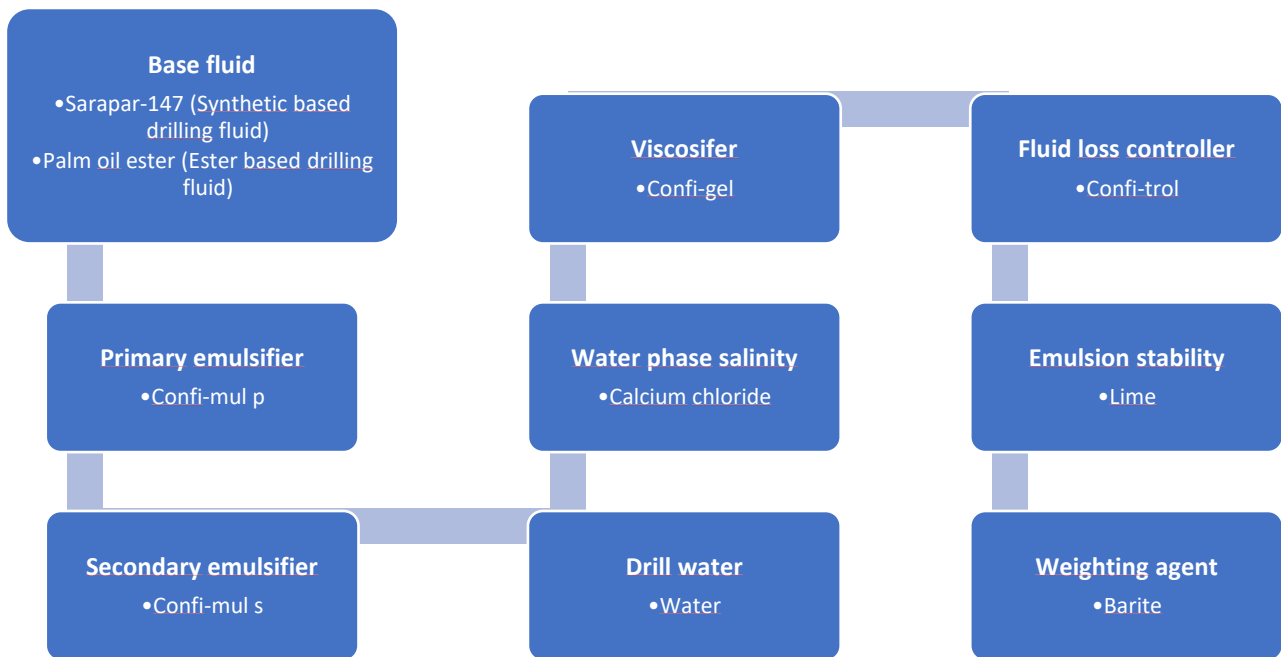
390 Water-based drilling fluids, such as synthetic ones, have a minimal impact on the environment  
391 and can therefore be disposed offshore. As most harmful and toxic drilling fluids are  
392 considered those based on oils. That type cannot be returned to the environment without  
393 purification and neutralization processes (Kujawska and Pawłowska, 2020). Types of drilling  
394 fluid is presented in Figure 14 according to (Ismail et al., 2017). Similarly, as petroleum-based  
395 fluids, which are not permitted for offshore disposal and generated drill cuttings need to be  
396 cleaned prior to storage.



397 **Figure 14.** Types of drilling fluid

398 In turn, synthetic-based drilling fluids are preferred due to their technical characteristics and  
399 minimal environmental impact. An exemplary composition of the drilling fluid is shown in  
400 Figure 15 (Ismail et al., 2015).





401 **Figure 15.** An example of a drilling fluid

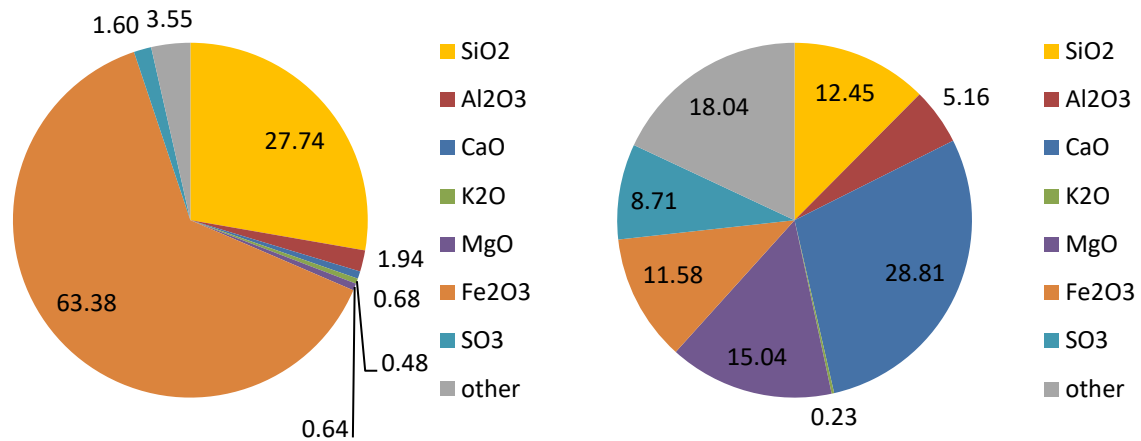
402 **4. Composition of waste from mining activity**

403 The composition of waste from raw material extraction was analyzed in terms of the following  
 404 compounds: SiO<sub>2</sub>, Fe<sub>2</sub>O<sub>3</sub>, Al<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub>, CaO, CuO, ZnO, PbO, PbO<sub>2</sub>, Cr<sub>2</sub>O<sub>3</sub>, SO<sub>3</sub>, K<sub>2</sub>O and MgO.

405 The main components of flotation process of copper are silica (SiO<sub>2</sub>), which comprises from  
 406 27% to 59%, and iron oxide (III), Fe<sub>2</sub>O<sub>3</sub>, representing from trace amounts up to 65% (Çoruh et  
 407 al., 2012). The basic components of zinc and lead flotation waste are calcium oxide, CaO (up  
 408 to approximately 26%), iron (III) oxide (approximately 12%), magnesium and sulfur oxides  
 409 (around 11% each) and silicon dioxide (8.4%). Copper minerals constitute up to 1 wt.%. while  
 410 lead minerals up to approx. 0.3 wt.%. In Figure 12, both Cu and Pb are grouped as 'other'.  
 411 Other compounds such as Al<sub>2</sub>O<sub>3</sub>, Na<sub>2</sub>O, K<sub>2</sub>O, TiO<sub>2</sub>, P<sub>2</sub>O<sub>3</sub>, As<sub>2</sub>O<sub>2</sub>, PbO<sub>2</sub>, ZnO, Cl are present in  
 412 trace amounts (Bakalarz, 2019; Çoruh and Ergun, 2006; Grudinsky et al., 2020; Kowalczyk,  
 413 2019; Koziół and Uberman, 1996; Liu et al., 2020; Nowak, 2008; Stanojlović and Sokolović,  
 414 2014; Steliga and Uliasz, 2012). Figure 16 shows averaged data of the content of mineralogical  
 415 compounds in the post-flotation tailings based on the analysis of literature data from (Lutyński  
 416 and Szyrka, 2010; Rad and Modarres, 2017) the recognized compounds comply with the  
 417 deposit geology (Alp et al., 2008; Çoruh et al., 2012;). The identified compounds are consistent  
 418 with the previously described geology of copper, zinc and lead deposits. Depending on the  
 419 occurrence of the rock formation, they may differ in the intensity (% content) of the  
 420 occurrence of individual mineralogical compounds.

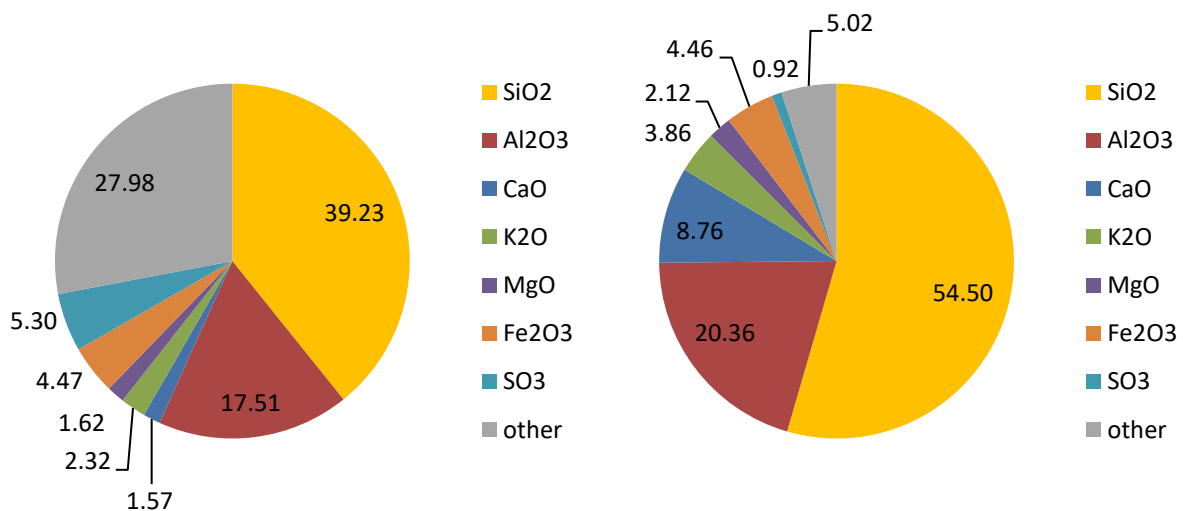
421 Post-flotation waste from the processes of obtaining zinc and lead was analyzed on the basis  
 422 of two authors what is presented in Figure 12 (Nowak, 2008; Śliwka et al., 2019). The average  
 423 values indicate more even distribution of components than in the case of copper waste. Zinc  
 424 and lead wastes are characterized by the highest CaO content, ranging from 26% to 29%,  
 425 which is consistent with the typical geology of the deposit. A lower content was recorded for

426 MgO (15%), Fe<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub> (about 12% each) and SO<sub>3</sub> with a content up to 9%. There was no  
 427 presence of CuO, PbO and Cr<sub>2</sub>O<sub>3</sub>. (Asadi et al., 2017; Muravyov and Fomchenko, 2018). Other  
 428 compounds such as Al<sub>2</sub>O<sub>3</sub>, K<sub>2</sub>O, TiO<sub>2</sub>, P<sub>2</sub>O<sub>3</sub>, PbO<sub>2</sub> are present in trace amounts. Zn minerals  
 429 constitute up to 3 wt.%, while minerals Pb approx. no more than 0.3 wt.%. Both Zn and Pb are  
 430 presented in the Figure 12 as components of the "other" group.



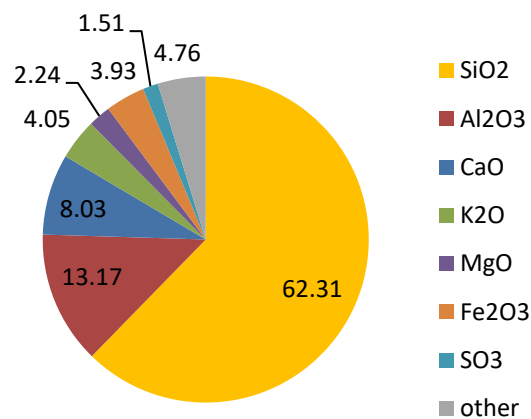
431  
 432 **Figure 16.** Mineralogical compounds of post-flotation waste from Cu ores (left) and Zn and  
 433 Pb ores (right)

434 Figure 17 shows the results of the average mineralogical compound of coal flotation waste are  
 435 the average value based on the results presented by research groups (Kara, 2014; Lutyński  
 436 and Szpyrka, 2010; Piszcz-Karaś et al., 2019; Rad and Modarres, 2017). The highest content  
 437 was recorded for silica (39% - 60%) and Al<sub>2</sub>O<sub>3</sub> (c.a. 17.5%). The content of the remaining  
 438 components was ranging from 1.5% to about 5%. The compounds like CuO, ZnO, PbO, PbO<sub>2</sub>,  
 439 Cr<sub>2</sub>O<sub>3</sub> were not recorded in the composition of coal waste.



440  
 441 **Figure 17.** Mineralogical compounds of coal post-flotation waste (left) and coal ash (right)

442 The mineralogical compound of waste and drill cuttings obtained as a result of oil and gas  
 443 extraction works varies depending on the existing geological layers, what is shown in Figure  
 444 18 (Chen et al., 2000; Çoruh et al., 2012; Hsi-chi et al., 1968; Huang et al., 2019; Kibort and  
 445 Małachowska, 2018; Konopacka and Zagożdżon, 2014; Longarini et al., 2014; López and  
 446 Ristorcelli, 2011; Nowak, 2008; Pieczonka et al., 2017; Ristorcelli, S., Ronning, P., Fahey, P. and  
 447 Lustig, 2008). Wastes from oil and gas extraction are mainly rocks contaminated with  
 448 components of drilling fluid. Drilling waste compounds were analyzed on the basis of 4  
 449 literature sources by (João et al., 2017; Köse, 2019; Piszcz-Karaś et al., 2019; Rykusova et al.,  
 450 2020). The average result of drilling wastes shows that the silica content was over 60%, Al<sub>2</sub>O<sub>3</sub>  
 451 was 13% and CaO was 8%. The content of Fe<sub>2</sub>O<sub>3</sub>, K<sub>2</sub>O, MgO and SO<sub>3</sub> ranged from 1.5 to 4%.  
 452 The remaining components were characterized by the content below 1%, except for PbO and  
 453 PbO<sub>2</sub>, which were not present.



454  
 455 **Figure 18.** Mineralogical compounds of cuttings from oils & gas sector

456 **5. Waste management**

457 **5.1. The current state of post-mining waste management**

458 The most popular method of post-flotation waste management is ground storage in waste  
 459 neutralization tanks. In Europe, the largest landfill and a facility for neutralizing copper  
 460 flotation waste is the “Żelazny Most Mining Waste Treatment Plant”, owned by KGHM Polska  
 461 Miedź, located in the Lower Silesia in Poland. The facility, where the waste is stored, is limited  
 462 by the embankment, which is designed to prevent the waste from scattering. There is a  
 463 pipeline in the upper part of the shaft to transport sewage by water. When waste is deposited,  
 464 it spontaneously segregates: coarse-grained material falls close to the discharge point to form  
 465 a beach, and water and dust flow to the landfill to form a sedimentation basin. Recycled water  
 466 from the drained sediment is used in the flotation process (Çoruh and Ergun, 2006; Grudinsky  
 467 et al., 2020; Kowalczyk, 2019) In the Żelazny Most also liquid flotation waste (sewage) from  
 468 copper extraction is stored. Table 1 presents the parameters of the Żelazny Most waste  
 469 treatment facility, the current state and assumptions for the coming years (Grabas and Pawlik,  
 470 2017).

471

**Table 1.** Parameters of the ‘Żelazny Most’ Mining Waste Treatment Plant

Parameters	Size	
	Present	Future
Total area [km <sup>2</sup> ]	16	22
Total collected waste [mln m <sup>3</sup> ]	560	969
Length of embankments [km]	14.3	-
Maximum dam height[m]	36-62	over 100
Poolarea [km <sup>2</sup> ]	7.5-8	-
Beach area [ha]	794	-

472 In appendix are photos of the largest places disposal of post-flotation waste (Figure IV). The  
 473 areas of the reservoirs range from about 8 up to 20 km<sup>2</sup>. For economic and logistical reasons,  
 474 they are located in the vicinity of the mine.

475 A good pro-environmental solution is afforestation of brownfield sites. The literature is rich in  
 476 research on the use of plant cover as a method of reviving such sites. The use of specific types  
 477 of trees can have very good effects on people and the environment (Ciarkowska et al., 2017;  
 478 Ciarkowska and Hanus-Fajerska, 2008; Mleczek et al., 2016).

479 Selected species of trees and plants can contribute to the increase in the content of organic  
 480 matter in the soil and the development of a soil system capable of meeting the nutrient and  
 481 water needs of other plants and microorganisms. Hence, the introduction of specific trees  
 482 might be also an effective tool in reducing the risk of damaging dams prior to surface water  
 483 migration.

484 Waste from coal mining is managed, however only in 44%. Among the waste related to coal  
 485 mining and processing, the following types of waste are distinguished: flotation, slag, bottom  
 486 ash and fly ash. Post-flotation waste may be subjected to the enrichment process; slag - can  
 487 be used in construction as a material used in civil engineering (road construction), it can also  
 488 act as a sealing material. Bottom ash is a good filter material or, after appropriate  
 489 transformation, can be used as fertilizer or granulate for plants, while fly ash is mainly used in  
 490 construction. Researchers (Lazutkina and Buler, 2003) proposed the use of carbon ash (an  
 491 aluminosilicate material) mixed with borax to create glass coatings on steel surfaces in order  
 492 to protect the steel from deformation at high temperatures.

493 Fly ash is deposited in ash dumps in Australia and half of this is processed into beneficial  
 494 products such as concrete (“Unearthing Australia’s toxic coal ash legacy,” 2019). The global  
 495 average of coal ash reuse is 53%, wherein India reuses 61%, the UK 70% and Japan 97%. In  
 496 turn, in China waste constitutes 10-15%, and only 69% is managed, which gives about 535  
 497 million tonnes of unused waste (Maiti and Pandey, 2020; Pacholewska et al., 2007). Waste  
 498 from coal processing and coking plants may contain valuable components. Pavlovich et al.  
 499 (Pavlovich et al., 2004) proposed the use of phthalic anhydride, present in post-processing  
 500 waste, as a raw material for the production of anti-corrosion and abrasion-resistant products.

501 One common method of mining waste management is underground storage, used among  
502 others for backfilling workings and sealing goafs, when there is too much waste from current  
503 production, which cannot be used otherwise. Waste management through underground  
504 storage is used mainly in the extraction of natural aggregates, where can be used to neutralize  
505 mine drainage and post-flotation sewage (Meggyes et al., 2008).

506 In order to manage drilling cuttings and mining waste, similarly as in the case of post-flotation  
507 waste, a landfilling is used. However, this method requires the pretreatment of drill cuttings,  
508 since they can contain heavy metals in an amount exceeding the permissible levels regulated  
509 by applicable law (*Announcement of the Marshal of the Sejm of the Republic of Poland of*  
510 *October 8, 2020 on the publication of the uniform text of the Act on mining waste, Dz. U. 2020,*  
511 *pos. 2018, 2020; Europejski and Unii, 2006). Otherwise, storage of untreated drill cuttings in*  
512 *designated areas or agricultural areas may result in the release of undesirable components*  
513 *into the soil and groundwater, causing contamination. On average, one well can produce*  
514 *about 1,000 m<sup>3</sup> of solid waste – drill cuttings, and from 800-1,200 m<sup>3</sup> of liquid waste (Kujawska*  
515 *et al., 2016; Steliga and Uliasz, 2012). In selected European countries, such as in Poland,*  
516 *gangu - drill cuttings, is managed in 86%, however mainly by landfilling.*

517 Based on the types of contamination, there are 3 options for the disposal of drilling waste:

- 518 • disposal at sea,
- 519 • land disposal,
- 520 • re-injection into the drilling field, reconstruction of the well.

521 Waste treatment methods differ among countries. Almost always, disposal at sea or on land  
522 is restricted by regulations and most often is associated with additional restrictions as to the  
523 storage of hazardous substances on unsecured areas. Drilling cuttings, in the form of solid  
524 waste, require treatment of oily substances and storage in adapted landfills. Solid and toxic  
525 waste need storage in special, sealed tanks. Re-injection of drill cuttings into the well is a  
526 favorable disposal option, if the drilling waste is not contaminated and has been subjected to  
527 pretreatment process (Permata and McBride, 2010).

## 528 5.2. Closed water circuit

529 Proper management of water used in the flotation process and the extraction of raw materials  
530 is a very important element from economic and environmental point of view. Due to the  
531 potential risk of soil contamination, and thus the negative impact on plants and animals,  
532 researcher carry out studies on the biological purification and treatment of water and its reuse  
533 in technological processes related to mining (Daldoul et al., 2019; Shengo and Mutiti, 2016).  
534 The flotation process can be used for water treatment, as shown in the article (Rubio et al.,  
535 2002).

536 The quality of the water used in the flotation, as well as pH and the content of dissolved solids,  
537 are of great importance for the process efficiency. To obtain optimal conditions, it is  
538 recommended to use both recycled water and water from the network (Farrokhpay and Zanin,

539 2012; Lin et al., 2020). However, water recycling in a closed loop is also desirable and  
540 considered as capable of reduction the number of reagents, decrease in Na<sub>2</sub>S content, and  
541 consequently a reduction in water consumption by as much as 34.62%.

542 The biohydrometallurgical method, using post-flotation water, can recover valuable cobalt  
543 (Dudeney et al., 2013; Parbhakar-Fox et al., 2018). Monitoring the quality of unused post-  
544 flotation water is a very important for assessing the stability of the structure of reservoirs and  
545 dams, in which these wastes are collected (Retka et al., 2020).

546 Waste management in the Oil & Gas sector largely relies on the water treatment used for  
547 drilling. As a result of contact with highly saline water and the shale itself in the fracturing  
548 zone, the drilling fluid is enriched with chlorides and barium salts. Contaminated water from  
549 drilling works in the production of crude oil and natural gas is circulated. Very often it can be  
550 reused up to 100%, for example, the United States recycles more than 90% of polluted water.  
551 Contaminated water from drilling processes can be returned to the surface, cleaned with  
552 vibratory screens, centrifuges, hydrocyclones, etc., and reused for further drilling purposes. It  
553 is assumed that more than 90% of the flowback fluid is recycled at the well stations and used  
554 for subsequent drilling processes. The rest of the polluted water is directed for disposal  
555 (Steliga and Uliasz, 2012). In order to recover a significant amount of the fracturing fluid, in  
556 other words flowback fluid, consisting of 90 to 95% of water and chemical additives, the fluid  
557 undergoes a treatment procedure (Steliga and Uliasz, 2012).

558 The exploration and drilling site is usually protected by lining with cement slabs and foil to  
559 minimize the risk of toxic compounds getting into the soil and surface waters (Dudeney et al.,  
560 2013). Example of the storage sites is Łebień drilling rig which is shown in Figure VI, in the  
561 appendix.

### 562 5.3. *The impact of waste management on the environment*

563 Metal mining is a key part of the economy for many countries. Many countries decide to  
564 explore small deposits of raw materials for which the demand is growing every year. As a  
565 consequence, the amount of waste produced also increases (Bamigboye et al., 2021; Nikolić  
566 et al., 2019).

567 It is practically impossible to prevent the generation of post-mining waste. Tailings are  
568 troublesome to handle due to their high abundance, properties, and difficulty in removal. As  
569 a result, long-term processes are used to minimize negative environmental and socio-  
570 economic consequences. The generated waste is either sent for recovery or neutralization,  
571 wherein neutralization most often means disposal in dedicated landfills.

572 The literature review is rich in examples showing that wastes from flotation process can be  
573 slightly toxic. It is confirmed by studies of plants and water that have come into contact with  
574 them, therefore their storage is not the most beneficial solution because it affects the  
575 environment and occupies a very large area, and also distorts the landscape (Behera et al.,  
576 2020).

577 A lot of papers present research (Ciarkowska et al., 2017; Kasowska et al., 2018; Mendez and  
578 Maier, 2008; Śliwka et al., 2013) in which plants, mainly trees, were planted on copper tailings  
579 to examine the accumulation of metals. The aim of using plants, known as phytostabilization,  
580 is to reduce the risk of metal migration to deeper soil layers. The experiments showed that  
581 some plants contained a critical amount of copper, which thereby confirmed high copper  
582 content in the waste, and inefficiency of the flotation process. Permissible lead levels were  
583 exceeded. The obtained results showed the best accumulation properties of metals for fungi.  
584 Additionally, an increased content of heavy metals, especially copper, was detected in pine  
585 needles.

586 Jakovjević K. and Mišlejenović et al. 2020 (Jakovljević et al., 2020), carried out a study to  
587 determine the toxicity level of plants growing in 4 soil samples taken from different parts of  
588 the post-flotation tank. The highest concentration of toxic elements (As, Sb, Zn) was  
589 determined in samples from the vicinity of the closed Stolice mine in Serbia (Zn-Pb  
590 polymetallic deposit, a flotation basin), and from Zn-Pb tailings near the Ibar River. Even  
591 though the mine was closed in 1987, it still poses a threat. The waste that was generated still  
592 contains potentially toxic elements. The greatest accumulation of these elements is near the  
593 river; therefore, they can potentially get there, polluting the river and aquatic organisms.

594 On the other hand, a water study carried out at the closed Jerada mine in Morocco, where 15  
595 to 20 million tons of waste is currently stored, showed an increase in sulphate content to over  
596 700 mg/l, with an average level of around 300 mg/l. The increase was observed during the  
597 rainy season, indicating that surface water migration has an impact on pollution levels.

598 Studies of the abandoned tailings from a mine in Mexico, revealed that the oxidation of  
599 chemicals was less intense in the settling tank than in the dam. The pH was low in the oxidized  
600 zone (down to 2.7), and was increasing with the depth, indicating that the H<sup>+</sup> ions are  
601 consumed by dissolving the aluminosilicate minerals. This results in the precipitation of iron  
602 oxides which in the presence of form cement layers in the dam. The waste contained high  
603 level of heavy metals easily washed away by water (As and SO<sub>4</sub><sup>2-</sup>). The concentration and  
604 mobility of the toxic elements is controlled by precipitation, sorption and desorption (Romero  
605 et al., 2007). In studies on the toxicity of tailings from mines in Norway, it was concluded that  
606 tailings from a mine, where no process chemicals were used, had the greatest toxicity. This  
607 means that properly selected chemicals in the flotation process is a very important factor that  
608 can minimize the toxicity of a generated waste (Brooks et al., 2019) It was also shown that the  
609 ion exchange process can be effective in purifying water after the zinc and lead ore flotation  
610 process (Woynarowska et al., 2011).

611 Being aware of the risk to the environment coming from generated waste and landfilled  
612 tailings, more effective methods are needed to reduce negative impacts on air, soil, and  
613 water. It is a challenge; hence the role of innovation is very crucial here. It is important to  
614 protect the waste from migration and to ensure the geotechnical stability of disposal site. In  
615 order to reduce the impact of waste on the environment, various techniques are applied,





616 among others physical methods that create a barrier to the migration of pollutants, e.g.  
617 geotextile separators - functioning as barrier between the ground and the stored waste, multi-  
618 layer coverings - protecting from external weather conditions, or the aforementioned  
619 biological methods, like phytostabilization or hydroseeding, in which a mixture of fertilizer,  
620 seeds and water is sprayed onto the ground to make the grass grow. It is important to protect  
621 the waste from migration and to ensure the geotechnical stability of disposal site (González-  
622 Alday et al., 2008; Karczewska et al., 2017).

623 Additionally, to provide support for environmental protection legal regulations are applied. In  
624 the EU, European Commission has introduced directives related to waste management, which  
625 among others regulate waste from extractive industries (Directive 2006/21/EC), control of  
626 major-accident hazards involving dangerous substances (Directive 2012/18/EU) and  
627 protection of groundwater against pollution and deterioration (Directive 2006/118/EC).  
628 Additionally, in accordance with Directive 2006/21/EC, Joint Research Centre provided Best  
629 Available Techniques Reference Document for the Management of Waste from Extractive  
630 Industries (MWEI BREF) (Garbarino et al., 2018). MWEI-BREF, which is a technical document,  
631 aimed at minimizing the environmental impact connected with extraction of mineral  
632 resources, includes among others generic and risk-specific BAT conclusions, generic and risk-  
633 specific objectives, information about management, as well as emerging techniques to  
634 prevent environmental deterioration coming from extractive industry (Garbarino et al., 2020).

635 Extraction of resources, which is inherent in the production of waste, to ensure short-term  
636 and long-term safety, requires following a predetermined plan, considering life cycle  
637 assessment, risk assessment, and waste deposition plan so to minimize the adverse effects on  
638 the environment and eventually human health. Additionally, it should also include a planning  
639 for closure of extraction and disposal facility, including rehabilitation, reclamation,  
640 remediation, after-closure procedures, and subsequent monitoring (Garbarino et al., 2018).

## 641 **6. New methods of waste management**

### 642 *6.1. Copper, zinc and lead*

643 The potential of the use of tailings has been discussed for many years. Already in 1996, an  
644 article was published on the possibility of using mining and energy waste in the construction  
645 of expressways and highways (Kozioł and Uberman, 1996). It was found that waste from rock  
646 mining can be used as a road aggregate for the construction of road foundation.

647 Due to the chemical and phase composition, the most frequently considered solution for the  
648 management of tailings, other than neutralization in tanks, is using it as an additive to cement  
649 (Gao et al., 2020; Gou et al., 2019; Guo et al., 2016; Liu et al., 2018; Muravyov et al., 2012;  
650 Onuaguluchi and Eren, 2012; Wang et al., 2017; Yi and Cao, 2014; Zheng et al., 2015).  
651 According to the European standard (*EN 197-1:2012. Cement. Part 1: Composition,  
652 specifications and conformity for common cements, European Standards.*, 2012), additives  
653 added in the amount of up to 40% of the cement mass improve some functional properties.



654 The greatest economic benefit resulting from the use of flotation waste in the building  
655 materials industry is the saving of cement, which can be replaced by waste, even in a small  
656 percentage (Mikula et al., 2021).

657 Chinese scientists (Guo et al., 2016) checked the pozzolanic activity of tailings generated in  
658 the process of pyrite flotation. An X-ray fluorescence analysis was performed to identify the  
659 main components of the waste. Pozzolanic materials are characterized by a high content of  
660  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$ . This was also in the case of examined waste, which additionally contained  
661 small amounts of alkali. The optimal amount of waste was determined at the level of 20% of  
662 the cement mass. This amount of waste causes that the concrete has still good workability.

663 Coal tailings can also be used as pozzolanic material. This was shown in the research: (Yagüe  
664 et al., 2018). Very fine samples had the best properties, however they required thermal  
665 activation treatment (Qiu et al., 2011).

666 The use of dry copper tailings may increase the yield point, which is an undesirable effect,  
667 however the use of pre-moistened waste has reduced this disadvantage. The samples showed  
668 a higher initial water absorption rate and resistance to chloride penetration and acids  
669 (Onuaguluchi and Eren, 2012).

670 Concrete mixes with the addition of tailings are characterized by water resistance and better  
671 hydrophobicity than traditional cement mortar (Liu et al., 2017). The addition of tailings from  
672 reverse flotation can significantly improve the watertightness of cement mortars. The mixture  
673 prepared for self-compacting concrete showed high resistance to freezing and thawing, and it  
674 can be classified as XF4 concrete exposure class. Scientists from the University of Nis (Ristić et  
675 al., 2019) showed that the addition of copper tailings, in the amount of about 40% of the  
676 cement mass, did not significantly affect such parameters as air content or segregation.

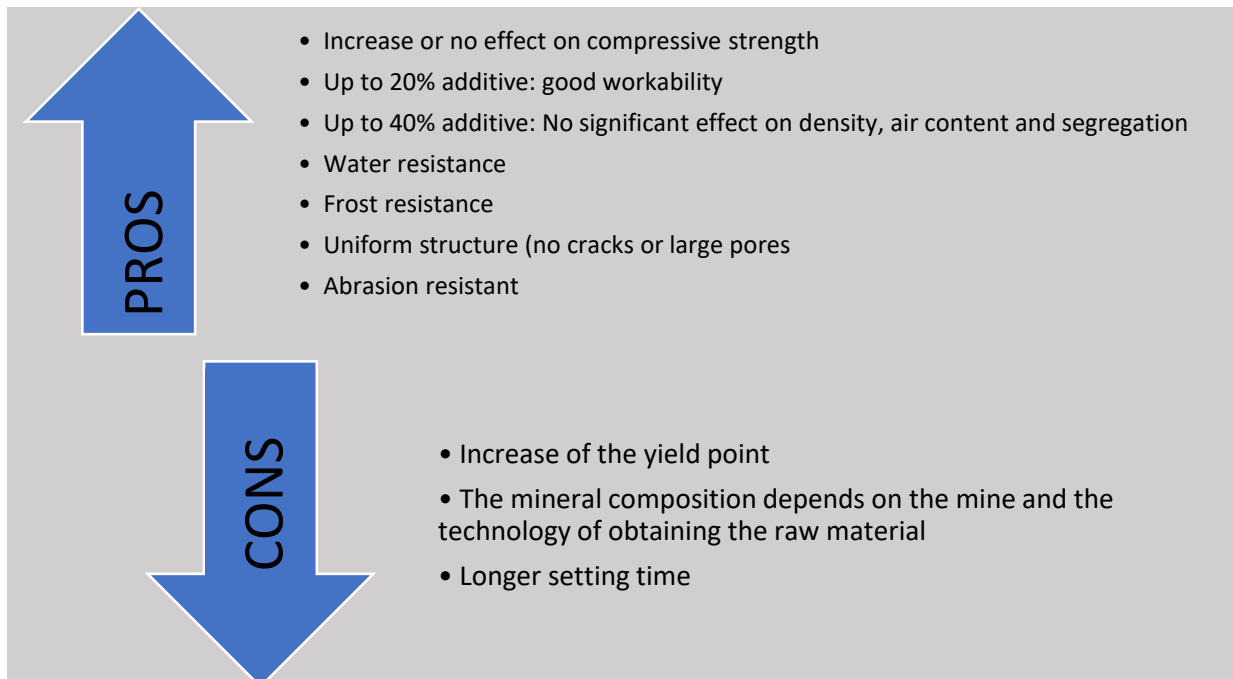
677 Low air content and high bulk density are more suitable for laying bricks (Fontes et al., 2016).  
678 The composite made of zinc and lead tailings and fly ash is a good solution for backfilling  
679 workings, however appropriate proportions of mixtures need to be kept, preventing their  
680 secondary liquefaction (Jarosiński et al., 2007; Jarosiński and Madejska, 2008).

681 Alexander Karamanov et al. (Karamanov et al., 2007) investigated the use of flotation waste  
682 as an ingredient in the production of glass-ceramics. They found that flotation wastes alone  
683 are not enough to create high-quality glass, and mixes with various additives are better. No  
684 visible air bubbles were observed in the obtained glasses. After thermal treatment, the  
685 material became homogeneous, which increased its strength. The grinding made the material  
686 similar in texture to granite.

687 Another example of using tailings is building ceramics. Mymrin V. (2020) et al. (Mymrin et al.,  
688 2020) created mixtures containing lead ore flotation tailings, foundry sand and a mixture of  
689 sand and clay. The 10% addition of waste increased the compressive strength by 8%. The SEM  
690 images showed the formation of a new amorphous glassy phase that covered all surfaces of  
691 the ceramics and closed the porous space, thus strengthening the samples (Alekseev et al.,

692 2019; Bhardwaj and Kumar, 2019; Hossiney et al., 2018; Mackay et al., 2020; Sua-iam et al.,  
693 2019).

694 Applying even a small amount of tailings to concrete is beneficial since it reduces  
695 environmental impact and contribute to land remediation (Onuaguluchi and Eren, 2012).  
696 Summary of advantages and disadvantages of using flotation waste as building materials is  
697 presented in figure 19.



698

699 **Figure 19.** Summary of advantages and disadvantages of using flotation waste as building  
700 materials

701 Flotation waste is also used to recover many valuable elements. There are many studies and  
702 publications showing that the elements copper, zinc, lead and can be obtained from waste.  
703 However, these processes also generate wastes that are even more difficult to handle. These  
704 wastes are free of key elements and contain foaming additives and chemical solvents. Over  
705 the years, the amount of exploited metal, coal, oil and gas deposits decreases, hence it is  
706 expected that the flotation process will be even more effective, and thus the post-flotation  
707 waste will have a different chemical composition, less harmful to the environment. Reducing  
708 the number of deposits and extraction from deposits of lower quality will contribute to an  
709 increase in the amount of waste.

## 710 6.2. Oil and gas extraction

711 Historically, a number of non-biological methods have been used to remove drill cuttings,  
712 including backfilling pits, landfills and reinjection wells, chemical stabilization and  
713 solidification, as well as thermal treatments such as incineration and thermal desorption. The  
714 results of the research showed that drilling waste that is not classified as hazardous, due to its  
715 high pH, could be used for the remediation of land degraded by acidification, e.g. located in

716 the vicinity of open pit sulfur mines or on heaps of mining waste containing acid minerals, e.g.  
717 pyrite (Ball et al., 2012) The confirmation of such development is also presented by Kujawska  
718 et al. (2020) (Kujawska and Pawłowska, 2020), proposing the remediation of acidic, barren  
719 and degraded soils. Another example is the use of the drill cuttings as construction aggregate,  
720 the formation of granules or burning and creating a natural fertilizer for plants.

721 Depending on properties, solid waste, cleaned from oily substances, can be used in  
722 construction. Leonard et al. (Leonard and Stegemann, 2010) presented the possibility of using  
723 two types of waste to produce Portland Cement (CEM I). One component were the stabilized  
724 and solidified drill cuttings and the second was the residue from coal combustion, i.e., fly ash  
725 with high carbon content as additional component of organic pollutants.

726 Another type of drill cuttings is from the oil sands in Canada and represents one of the most  
727 difficult challenges for the mining sector. Oil sands are cleaned using the so-called Thermo-  
728 Mechanical Cuttings Cleaner. The waste is heated to a temperature high enough to evaporate  
729 the oil and water, which are then transferred to the liquid phase in separate condensers. The  
730 by-product is a very fine quartz powder that can potentially be used as a filler material in the  
731 production of cement materials (Aboutabikh et al., 2016; Boudens et al., 2016; Huang et al.,  
732 2015; Loganathan et al., 2015).

## 733 **7. Results and discussion**

734 A review of the world literature shows increasing interest in a mining waste management.  
735 Innovative solutions are constantly searched for, which will allow waste management not only  
736 through storage, but also efficient use, striving to reduce CO<sub>2</sub> emissions and improving the  
737 quality of environment. Table 2 summarizes methods of managing individual types of waste,  
738 indicating the numerous possibilities of post-flotation and mining waste management.

739 **Table 2.** Waste management options according to waste characteristics

Source	Type of waste	Parameters	Method of waste management	References	
Copper	Waste rock and overburden	<ul style="list-style-type: none"> <li>- Compressive strength [MPa]</li> <li>- Chemical composition [%]</li> <li>- Graining [%]</li> <li>- Water absorption [%]</li> </ul>	<ul style="list-style-type: none"> <li>• aggregate in concrete and road construction</li> <li>• the backfilling of mined headings/workings and post-mining voids as a material for dry filling,</li> <li>• the backfilling of the voids that were formed as a result of mining as the material for supplemental sealing</li> <li>• the backfilling of the headings that require strengthening and stabilisation</li> <li>• the hardening of underground mine roads</li> <li>• source recovery</li> <li>• recovery of chemical elements</li> </ul>	(Henne et al., 2018; Kotarska et al., 2018; Lidelöw et al., 2017; Rossetti et al., 2019)	
	Flotation Tailings	<ul style="list-style-type: none"> <li>- Chemical composition [%]</li> </ul>	<ul style="list-style-type: none"> <li>• chemical precipitation</li> <li>• reuse of water in the flotation process</li> </ul>	<ul style="list-style-type: none"> <li>• purification of water from metals and sulfates</li> <li>• for the production of mineral binder</li> </ul>	(Nariyan et al., 2017; Rajczyk, 2017; Shengo and Mutiti, 2016)
	Smelter and tailing slag	<ul style="list-style-type: none"> <li>- Compressive and flexural strength [MPa]</li> <li>- Chemical composition [%]</li> <li>- Graining [%]</li> <li>- Friction [N]</li> <li>- Water absorption [%]</li> </ul>	<ul style="list-style-type: none"> <li>• aggregate in concrete and road construction</li> <li>• source recovery</li> <li>• for the production of mineral binder</li> </ul>	<ul style="list-style-type: none"> <li>• the hardening of underground mine roads</li> <li>• reaction catalyst</li> </ul>	(Esmaeili and Aslani, 2019; Kiventerä et al., 2020; Li et al., 2018; Mikula et al., 2021; Muleya et al., 2020; Nikolić et al., 2019; Paiva et al., 2019)
inc	Flotation waste	<ul style="list-style-type: none"> <li>- Compressive strength [MPa]</li> <li>- Chemical composition [%]</li> <li>- Water absorption [%]</li> </ul>	<ul style="list-style-type: none"> <li>• as proppant</li> <li>• reuse of water in the flotation process</li> </ul>	<ul style="list-style-type: none"> <li>• source recovery</li> <li>• hydrophobic surface</li> </ul>	(Azevedo et al., 2018; Muravyov and Fomchenko, 2018; Pietrzykowski et al., 2018; Wang et al., 2017)
	Waste water	<ul style="list-style-type: none"> <li>- Chemical composition [%]</li> </ul>	<ul style="list-style-type: none"> <li>• reuse of water in the flotation process</li> </ul>		(Azevedo et al., 2018; Kyzas and Matis, 2019)



<b>Lead</b>	Flotation waste	<ul style="list-style-type: none"> <li>- Compressive strength [MPa]</li> <li>- Chemical composition [%]</li> <li>- Water absorption [%]</li> </ul>	<ul style="list-style-type: none"> <li>• as proppant</li> <li>• as a component of the ceramics industry roofing material</li> </ul>	<ul style="list-style-type: none"> <li>• source recovery</li> </ul>	(Kudeřko, 2018; Larachi et al., 2019; Romero-García et al., 2019; Woźniak and Pactwa, 2018)
	Waste water	<ul style="list-style-type: none"> <li>- Chemical composition [%]</li> </ul>	<ul style="list-style-type: none"> <li>• coagulation with the application of lime carbide residue</li> </ul>	<ul style="list-style-type: none"> <li>• reuse of water in the flotation process</li> </ul>	(Azevedo et al., 2018; Kyzas and Matis, 2019)
<b>Coal</b>	Flotation coal enrichment	<ul style="list-style-type: none"> <li>- Chemical composition [%]</li> </ul>	<ul style="list-style-type: none"> <li>• flooring</li> </ul>		(Gupta et al., 2017; Wang et al., 2020)
	Bottom ash	<ul style="list-style-type: none"> <li>- Compressive strength [MPa]</li> <li>- Chemical composition [%]</li> <li>- Graining [%]</li> <li>- Water absorption [%]</li> </ul>	<ul style="list-style-type: none"> <li>• incinerating/fertilizer for plants</li> <li>• the backfilling of the voids that were formed as a result of mining as the material for supplemental sealing</li> </ul>	<ul style="list-style-type: none"> <li>• ceramics materials</li> <li>• phosphorus adsorbent</li> <li>• aggregate</li> </ul>	(Muthusamy et al., 2020; Namkane et al., 2017; Rani and Jain, 2017; Zhou et al., 2019)
<b>Oil &amp; Gas</b>	Cuttings, Sludges waste, Scales waste	<ul style="list-style-type: none"> <li>- Compressive and flexural strength [MPa]</li> <li>- Graining [%]</li> <li>- Water absorption [%]</li> </ul>	<ul style="list-style-type: none"> <li>• land application and landfilling</li> <li>• discharge to surface</li> <li>• recycling</li> <li>• as proppant/road construction</li> </ul>	<ul style="list-style-type: none"> <li>• incinerating/fertilizer for plants</li> <li>• aggregate</li> <li>• surface of tennis courts</li> </ul>	(Ayati et al., 2019; Davarpanah et al., 2018; de Almeida et al., 2017; Hu et al., 2021; Hussain et al., 2017; Reuben et al., 2018; Stuckman et al., 2018)
	Waste water	<ul style="list-style-type: none"> <li>- Chemical composition [%]</li> </ul>	<ul style="list-style-type: none"> <li>• surface impoundment</li> <li>• underground injection</li> <li>• waters source reduction</li> <li>• simple and enhanced separation</li> </ul>	<ul style="list-style-type: none"> <li>• dissolved air flotation</li> <li>• evaporative treatment</li> <li>• deep well</li> <li>• recovery water to the process</li> </ul>	(Abdullah et al., 2017; Adham et al., 2018; Robbins et al., 2020)

741 The article presents many advantages and additional possibilities of using flotation tailings as  
742 a partial replacement of aggregate or cement. However, one of the biggest disadvantages of  
743 post-mining waste is its chemical and thus mineralogical variability. Flotation tailings differ in  
744 their chemical composition, depending on the mined ores or whether oil or gas is being  
745 extracted. The waste may contain trace amounts of elements that may adversely affect the  
746 concrete structure, such as sulphur and iron compounds, as well as heavy metals.

747 Another issue to replace the materials used in the production of concrete is the fact that  
748 concrete plants and cement plants have a developed, proven system and do not necessarily  
749 want to retrain to new solutions.

750 In the past, the flotation waste, due to transportation problems and no development  
751 directions, was deposited in earth settlements, which degraded the natural environment,  
752 disfigured the landscape and increased the areas transformed by mining activities. Such  
753 approach led to environmental damage and exposed mines to huge losses due to waste of  
754 raw materials and fees for land use, etc. (Alwaeli M., 2009).

755 The biggest problem when using waste as components of building materials is the need to  
756 prepare the waste for use (Dash et al., 2016). Usually, the material should be additionally  
757 shredded or roasted (Kotwica et al., 2018). In order for the waste to be used effectively as an  
758 additive to building materials, additives are used such as alkaline activators (Ahmari et al.,  
759 2015). This means introducing additional chemical ingredients into the materials. All the  
760 above-mentioned activities generate costs related to the processing of waste so that it can be  
761 used.

762 Another common problem in the use of waste as components of building materials is the  
763 change in physical parameters of the material. With the use of waste, a decrease in strength  
764 (caused by the problem with the formation of appropriate tricalcium aluminates, silicates) and  
765 there are noted a decrease in the workability of concrete (high absorbability of e.g., ash)  
766 (Capasso et al., 2019). Another problem is the reduction of adhesion or discoloration of the  
767 material (e.g. in ceramic tiles, glaze layers cannot be applied) (Rahman et al., 2020).

768 When considering the use of waste in the building materials industry, in chemical aspects,  
769 there is a problem with heavy metals and their potential leachability from finished products  
770 (Dell'Orso et al., 2012). However, there are studies and publications (Yu et al., 2005) that show  
771 that cement materials do not leach dangerous amounts of heavy metals, because they have  
772 been incorporated into the structure of the hardened composite.

773 The last threat arising from the use of waste in the building materials industry is the law and  
774 standards. For safety reasons, European standards for cement, concrete and other building  
775 materials are very strict. Therefore, the condition of waste and finished building elements  
776 should be properly examined and monitored so that their use does not turn out to be harmful  
777 and dangerous, as it turned out in the case of asbestos.

778 To summarize the risks of using waste in the building materials industry, there are many  
779 obstacles and a financial effort is needed to prepare the waste for use in construction.  
780 However, as shown in the article, there are many more advantages and positive aspects to  
781 continue developing the waste utilization processes.

## 782 **8. Conclusions**

783 Mining is still a key part of the economy for many countries, and it is practically impossible to  
784 prevent the generation of post-mining waste. That is why in this work authors selected the  
785 most key resources in the mining industry, which are metals ores, coal, oil and natural gas,  
786 and focused on best solution for the generated waste to be safely managed or re-used. The  
787 proposed methods for handling with produced waste present both benefits and  
788 disadvantages, and additionally include environmental aspects that conditions a more  
789 sustainable waste management.

790 Mining wastes are high in abundance, properties, and difficult in removal. The generated  
791 waste is very often sent for recovery or neutralization, wherein neutralization most often  
792 means disposal in dedicated landfills, which is ground storage in waste neutralization tanks.  
793 Currently, this is the most popular method of post-flotation waste management, even though  
794 it is known that continuous collection of massive amounts of wastes may eventually result in  
795 disastrous environmental degradation. The waste, especially those untreated, may contain  
796 toxic and harmful elements, hence it is important to store it far from rivers and farmlands to  
797 minimize the risk of pollution of rivers and soils as well as groundwaters. However, it is not  
798 only storing and possibility of leakage to the ground, which pose a threat to the surrounding  
799 area, but also the ash that may be released from the storage tanks, which very often are not  
800 well covered. Some additional risk may arise, when wastes like for example drill-cuttings need  
801 to be pre-treated, which will involve additional waste generating processes.

802 Since the current waste management in the mining industry is very often far from being  
803 sustainable, this paper includes an overview of waste management practices that are more  
804 environmentally friendly and presents alternative methods of waste management. At the  
805 same time, this review covers data on properties and composition of mining and processing  
806 waste, aiming at identifying the unused benefits of improper waste management and  
807 handling.

808 Environmental concerns related to the management of mining waste are growing every year,  
809 which eventually leads to the need to recycling and reusing this waste. Due to the  
810 characteristic chemical composition, as shown in this article, the recycling of post-flotation  
811 and mining waste has the potential to be used in the building materials. Innovative solutions  
812 are constantly searched for, which will allow waste management not only through storage,  
813 but also efficient use, striving to reduce CO<sub>2</sub> emissions and improving the quality of  
814 environment.

815 The article contains a detailed review of the literature on geology and the current  
816 management of by-products generated in the processes of extraction and processing of raw  
817 materials. The amounts, chemical compositions, and forms of occurrence of metal ores of  
818 copper, zinc, lead, as well as coal, crude oil and natural gas deposits are discussed in detail.  
819 Waste management methods and their potential possibilities are presented and discussed.

820 Based on the literature results, new waste management options are proposed, which consider  
821 the recycling of already stored material and waste generated from current production. It has  
822 been shown that the current management of the above-mentioned waste, by depositing it in  
823 waste disposal facilities, is one of the less effective activities, and has negative impact on the  
824 environment, especially in a case of surroundings of the tanks.

825 A deeper look into the conditions and possibilities of waste management may result in  
826 drawing the attention of specialists in the fields of environmental protection and the building  
827 materials encouraging them to the use by-products from mining processes. The greater the  
828 knowledge about the possibilities of using post-flotation waste, the more effective the  
829 solutions to meet today's challenges.



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