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Removal of heavy metal ions by filtration on activated alumina-assisted magnetic field

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ABSTRACT

Magnetic field (MF), among others, influences more intense decomposition of many compounds, increases adsorption on the surface of the phase separation, as well as accelerates oxidation and reduction reactions. Therefore, they are used in the research as an aid for filtration process, which is one of the most popular stopping and separating processes for different components in different reservoirs. Beds usually function as an adsorbent, thus both filtration and adsorption processes are often. One of the inorganic sorbents that is used to remove metals and anions present in water is Al_2O_3. As part of this work, we investigated the use of a constant external MF as an elementary additional process to improve the filtration efficiency on activated alumina. The purpose of the study was to compare the effectiveness of the removal of elements (Fe, Mn, Cd, Cr, Cu, Pb, Zn, and Ni) from model aqueous solutions during the process of filtration assisted and not assisted by an MF on activated alumina. In addition, the purpose of the work was also to determine the influence of MF on the removal of these elements, as well as their affinity to physical properties of the adsorbate under the influence of MF. As a result of the experiment, it was proved that the MF support of the filtration on activated alumina for the removal of selected elements is more effective than the filtration without MF. Studies have shown that removal of individual metals occurs according to the following series of affinity toward alumina in magnetized samples: Pb > Mn > Ni > Zn > Cu > Fe > Cd > Cr.

Keywords: Magnetic field; Activated alumina; Filtration; Water treatment

1. Introduction

Magnetic field (MF) is a state of space or an area, where magnetic forces act to electric charges and material objects. These forces are special type of interaction occurring to a distance and connected with the presence of charged particles, magnets, or conductors with flowing electrical current [1]. Fig. 1 shows the diagram of the magnetic field lines around the permanent magnet.

Water is a dipole characterized by a non-uniform distribution of electric charge, which makes that MF to somehow interact with water changing its properties. Alterations in water properties translate into change in molecular interactions between water molecules and ions of other compounds. MF may also interact with filtration and adsorption process by changing the physicochemical properties of water and water solution subject to these processes [3–9].

Interests in the influence of MF on physicochemical properties of liquid water remarkably increased in the past century. Numerous reports and documents prove that the static or alternating MF and electromagnetic field (EMF) cause some changes in water, water solutions, and suspensions properties [3–17]. The example can be patented by Theo Vermeiren in 1953, whose device used MF to change water properties. Changes in water structure after exposure to MF found applications in many domains. At present, magnetized water has a wide spectrum of applications in chemical

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industry, agriculture, and medicine. For instance, it can support the food digestion [13]. Improvement in some crop seedlings and root elongation due to watering with magnetized water was reported [14]. It was revealed that magnetized water invokes many phenomena such as increase in the compression strength of a concrete, decrease in steel corrosion, and formation of calcium carbonate in a form of aragonite instead of calcite in pipes [15–17]. Changes in water properties due to MF depend on many factors such as strength of the field, direction of the field, exposure time, water, water solution or dissolved impurities flow rate through tested systems, and solution pH [9,10,12].

There are many ways to magnetize the water, in which various MF induction values are applied, produced by permanent magnets or electromagnets. Water subjected to permanent MF changes its specific conductivity, surface tension, and acidity [18,19].

Industry development and growing consumption rate in a society is attributed to the introduction of increasing amounts of industrial pollutants, including toxic and undesired elements, to a global water resource [20]. Industrial wastewater is abundant in organic and inorganic compounds, among which there is an enormous load of heavy metals, phosphates, sulfates, PAHs, etc. Some of these compounds are considered the priority pollutants originating from the activities associated with petroleum and its derivatives production, refineries, cellulose and paper, battery production, tanning processes, paints and pigments, fertilizers, herbicides and pesticides production, as well as from mine and metallurgic industries [21–24]. Many authors have dealt with the problem of removing heavy metals from water or wastewater [25–33]. One of the most interesting methods of removing heavy metals in addition to the MF-assisted filtration is a filtration with a filling that consists of dried plants [25–28]. For example, in order to reduce the concentration of the toxic metal cations, such as Cu and Cd, the process described in works of Chiban et al. [25–28] is rather simple, cheap, and easy to extrapolate at larger scale for a practical application to the treatment of wastewater. It uses a bed of small particles obtained by crushing of natural organic matter issued from dried plants and put in contact with metal aqueous solutions [25].

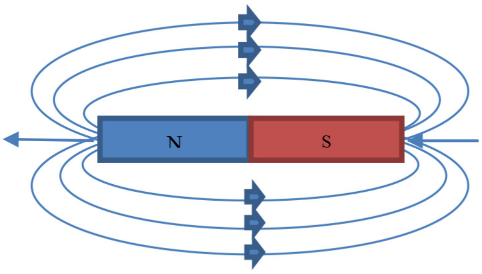

Fig. 1. Diagram of magnetic field line around magnet [1,2].

Considering the properties of alumina as a sorbent recommended by the Environmental Protection Agency for removing arsenic and selenium from drinking water and being among the best available techniques [29–32], it was decided to investigate the effect of MF as an element supporting filtration, that is used to remove selected elements from the model water solutions, which are classified as common (Fe and Mn) and industrial (Cu, Pb, Cd, Cr, Ni, and Zn) pollutants. As a result of the MF application, no by-products are generated, which can contribute to the protection of water, natural environment, and human health by limiting the use of chemicals. One of the most popular processes of retention and separation of individual components is adsorption. The mechanism that governs the adsorption of components from aqueous solutions may be susceptible to MF. There are no studies and data on the effect of MF on the filtration and adsorption processes, in which alumina is the active adsorbent. At the same time, new methods of separation of individual components from water solutions are still sought.

The purpose of the study was to compare the removal efficiency of elements—that can be contaminants of surface and underground waters (Cu, Pb, Cd, Mn, Fe, Ni, Zn, and Cr)—from model aqueous solutions in a magnetic assisted and non-assisted filtration on activated alumina. The influence of the MF on the removal of these elements was determined, as well as their affinity to physical properties of the adsorbate under the influence of MF.

2. Material and methods

The research consisted in determining the influence of MF on the efficiency of removing iron (Fe), manganese (Mn), copper (Cu), lead (Pb), cadmium (Cd), nickel (Ni), zinc (Zn), and chromium (Cr) from one-component model solutions. The experiment was performed on a laboratory scale using 500 µg/L model solutions in the dynamic adsorption process. The process was carried out at a flow rate of 6 L/h. Laboratory tests were carried out in 1 L laboratory dividers filled with activated alumina (Al_2O_3). The alumina used was in a form of white, odorless, insoluble in water granules. According to the manufacturer, the composition of activated alumina pellets was as follows: ≥93% of Al_2O_3 and ≤0.3% of Na_2O. The bulk density was 0.75–0.80 g/mL, specific surface area of the granules was ≥300 m^2/g, and the pore volume was 0.30–0.50 mL/g. The dose of sorbent was 450 g/L. The magnetization of samples, that is, the use of MF, was applied by pretreatment of prepared samples of individual single component solutions with MF for a period of 10 min. Magnetic induction of ferrite magnets used for magnetization was B = 118 mT. These magnets do not require any corrosion protection. They can be used in water. Measurement of magnetic induction of magnets was made using the HGS-10A gauss meter. Table 1 shows the properties of the magnets used.

Table 1
Characteristics of the magnets used for the experiment

Diameter (mm)	Height (mm)	Magnetization direction	Density (g/cm^3)	Resistivity (Ω cm)	Induction of remanence (T)	Weight (g)
50 (±2.5%)	10 (±0.1)	Along the 10 mm dimension	4.5	10^4–10^8	0.37	~88.3

For magnetization, the water tank (made of polyethylene terephthalate material conducting MF waves) was surrounded by ferrite permanent magnets. The magnetic induction measured through the bottle wall was 57 mT. Sample of a one-component model solution was magnetized for 10 min. At the same time in the same identical bottle, there was a sample of tested element kept without MF. This treatment was aimed at eliminating the possible influence of the adsorption of the component on the vessel walls. Both samples were then filtered through a laboratory divider filled with activated alumina. Fig. 2 shows an experiment diagram.

Concentrations of each element derived from the one-component model solutions (Cu, Pb, Cd, Mn, Fe, Ni, Zn, and Cr) before adsorption and post-process were determined using a Thermo Scientific iCE3300 atomic absorption spectrometer applying flame atomization and graphite cuvette. For the determination of each element, standard specimens were prepared in 50 mL flasks to enable a calibration curve consisting of four to five measurement levels for each of the elements to be analyzed.

Samples after magnetic-assisted filtration and control samples, in addition to the concentration of individual elements, were also subjected to measurement of the pH, electrolytic conductivity, and potentiometric potential by means of a multimeter WTW InoLab® Multi 9430. The whole experiment was performed in five replicates.

Achieved results were statistically processed. The scope of statistical analysis included basic parameters: arithmetic mean, median, standard deviation, variance, and extreme values of individual components (minimum and maximum). All calculations and statistical analyses were performed using Statistica 12.5 for Windows 10 Home Edition. The removal efficiency for individual metals by means of MF assisted and non-assisted filtration was also calculated according to Eq. (1). The sorption capacity of alumina in relation to the control solutions of particular elements and solutions treated with MF were also calculated according to Eq. (1).

$$R = \frac{C_o - C_k}{C_0} \cdot 100\% \tag{1}$$

C_0—initial concentration, μg/L; C_K—final concentration after Al_2O_3 filtration, μg/L.

The sorption capacity of alumina in relation to the control solutions of particular elements and solutions treated with MF were also calculated according to Eq. (1).

$$A_0 = V \cdot \frac{C_0 - C_k}{m} \tag{2}$$

A_0—absorptive capacity of activated alumina to bond the elements, μg/g; V—volume of solution that flowed through the laboratory separator, L; C_0—initial concentration, μg/L; C_K—final concentration after Al_2O_3 filtration, μg/L; m—Al_2O_3 mass used for the filtration process, g.

3. Results and discussion

Filtration is very often a basic technological process, both in water and sewage and sludge circuits in industrial plants purifying post-production wastewater with high content of some elements as well as in sewage treatment plants [9]. Thus, it is justified to seek solutions supporting this process and increasing efficiency with low cost and energy.

Table 2 shows the average results of concentrations of individual elements tested before and after filtration process in both control and magnetized samples. The copper concentration in the model samples after filtration process was 47.28 ± 5.79 μg/L, whereas in magnetized samples, the concentration after the process was 36.67 ± 7.15 μg/L. On the other hand, the initial concentration in the raw samples was 536.14 ± 15.88 μg/L. The calculated percentage removal efficiency R shown in Fig. 3 in the control samples was 91.48, while in samples treated with MF was 93.38. In the samples of lead solution (Pb) before filtration, the average concentration was 532.10 ± 7.28 μg/L, and after the process, the final concentration of lead in control samples was 61.67 ± 2.84 μg/L. Lead concentration was 24.90 ± 2.81 μg/L. The effectiveness of lead removal in control samples was 87.14%, while in treated samples 95.36%. Lead was characterized by the greatest increase in removal efficiency after MF application. When analyzing samples of cadmium solutions, the lowest removal efficiency of filtration on activated alumina was 72.52%, while in the MF-treated samples, the efficiency was 77.67%. Expressing these values in concentration units, they were as follows: initial concentration, 653.07 ± 20.87 μg/L; concentration in control samples, 176.21 ± 7.86 μg/L;

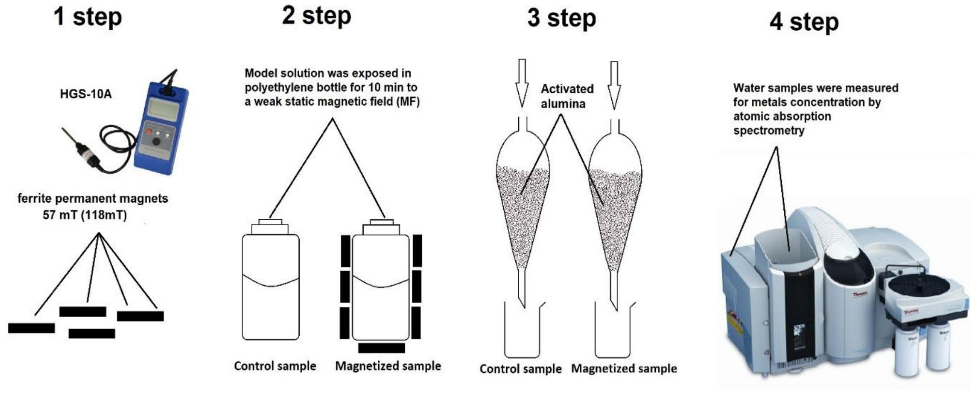

Fig. 2. Diagram of the experiment.

Table 2
Basic statistics for elements in sample solutions: before adsorption and after adsorption—control and magnetization

Parameter (μg/L)	A	B	C	A	B	C	A	B	C
	Copper (Cu)			Lead (Pb)			Cadmium (Cd)		
Arithmetic mWean	536.38	47.28	37.31	532.10	61.67	24.90	653.07	176.21	147.67
Geometric mean	536.14	46.91	36.67	532.05	61.61	24.74	652.73	176.07	147.60
Median	533.51	49.34	34.20	535.34	59.86	24.53	657.37	179.43	147.23
Standard deviation	15.88	5.79	7.15	7.28	2.84	2.81	20.87	7.86	4.54
Variance	252.02	33.58	51.18	52.96	8.08	7.87	435.46	46.38	20.63
Minimum value	515.62	38.42	29.50	520.60	58.92	21.21	621.80	165,43	141.52
Maximum value	560.23	54.45	48.87	540.41	66.30	29.11	680.37	183.89	154.34
	Manganese (Mn)			Iron (Fe)			Nickel (Ni)		
Arithmetic mean	446.88	34.67	25.89	548.42	84.59	65.39	528.28	43.78	32.09
Geometric mean	446.53	34.52	25.84	548.18	84.47	63.87	528.15	43.11	31.17
Median	443.80	33.17	27.11	543.80	83.17	63.32	530.29	48.34	31.20
Standard deviation	17.79	3.37	1.83	18.87	5.19	16.38	13.31	8.43	8.92
Variance	316.38	8.52	2.51	267.08	20.24	201.94	132.92	53.44	59.95
Minimum value	423.60	31.51	23.32	528.10	79.12	47.24	511.12	32.22	22.12
Maximum value	473.60	39.34	27.29	573.60	91.59	87.11	543.55	51.45	43.87
	Zinc (Zn)			Chrome (Cr)					
Arithmetic mean	557.16	70.66	36.16	661.98	164.02	150.88			
Geometric mean	557.09	70.57	36.08	661.90	163.92	150.84			
Median	555.34	69.86	34.23	661.34	163.41	152.34			
Standard deviation	10.45	4.28	2.78	12.08	6.59	4.17			
Variance	81.85	13.74	5.78	109.41	32.59	13.06			
Minimum value	545.41	65.92	34.21	647.56	156.33	145.22			
Maximum value	570.80	76.30	40.11	677.12	172.43	155.13			

A — Model sample before adsorption process; B — Control sample; C — Magnetized sample.

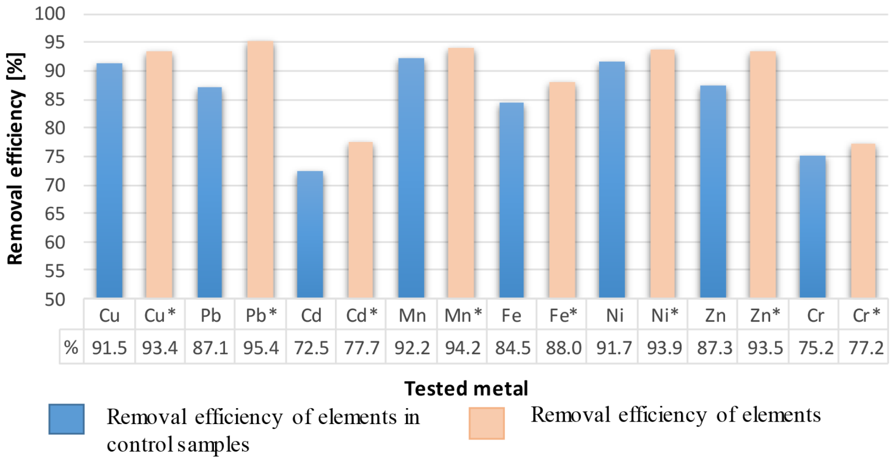

Fig. 3. Comparison of removal efficiency (*R*) of individual elements in control and magnetic field samples.

concentration in MF-treated samples, 147.67 ± 4.54 μg/L. In the case of manganese, the removal efficiency in the control samples was 92.24%, while in the samples under the influence of MF was 94.21%. Iron removal in comparison with manganese was significantly lower and was 84.58% in control samples and 88.88% in MF-treated samples. The manganese initial concentration was 446.88 ± 17.79 μg/L, and the iron concentration was 548.42 ± 18.87 μg/L. Concentration of iron as a result of the filtration process in the control samples was reduced to 84.59 ± 5.19 μg/L and in the samples under MF was 65.39 ± 16.38 μg/L. The concentrations of manganese in samples were as follows: initial concentration, 446.88 ± 17.79 μg/L; concentration in control samples, 34.67 ± 3.37 μg/L; and concentration in MF, 89 ± 1.83 μg/L.

By analyzing the results obtained in nickel-containing samples, the initial concentration of the element prior to the filtration process on activated alumina was 528.28 ± 13.31 μg/L, the final concentration in the control samples after filtration was 43.78 ± 8.43 μg/L, and in samples under MF treatment was 32.09 ± 8.92 μg/L. The following *R* values were used for the removal efficiency: in control samples, 91.71%, and in samples under MF, 93.93%. In the case of zinc, the removal efficiency of this element by the filtration process amounted to 87.32% in control samples and 93.51% in MF samples. The initial concentration of zinc in the solution before filtration process was 557.09 ± 10.45 μg/L, while after the process in the control samples 70.57 ± 4.28 μg/L and in MF samples 36.08 ± 2.78 μg/L.

The last analyzed element was chromium. The efficiency of the removal of chromium in the filtration process on activated alumina was 75.22%, and in the magnetic-assisted filtration process, it was higher and amounted to 77.21%. The initial concentration of chromium was 661.98 ± 12.08 μg/L, and the final concentration in control samples was 164.02 ± 6.59 μg/L, whereas in samples after MF action was 15.88 ± 4.17 μg/L.

In literature, works can be found that prove the usefulness of activated alumina for the purification of aqueous solutions containing heavy metals on Al_2O_3. Studies on the removal of metals from industrial wastewater were carried out by Naiya et al. [34], who conducted application studies using samples containing Pb(II) and Cd(II). The researchers achieved the removal efficiency of about 80% in the first cycle (on previously unused aluminum oxide) for lead about 98%, and in the last cycle (after three-time Al_2O_3 regeneration) yielding about 80%. For cadmium (Cd) on the unused filter material, Naiya et al. [34] reported 92% removal efficiency, and the removal effect was about 72% after triple regeneration of activated alumina. Literature also provides results of tests on the removal of heavy metals from water or wastewater during the filtration process on cheap, high-quality natural filter materials with large grain size. A number of such studies on the removal of selected elements using different particle sizes of natural materials (particle size 2.36–4.75 mm) were conducted by Aziz et al. [35]. Their research involved the removal of cadmium (Cd), lead (Pb), zinc (Zn), nickel (Ni), copper (Cu), and chromium (Cr) at a concentration of 2 mg/L. They tested the purification of aqueous solutions from the abovementioned elements in the filtration process on waste construction materials, gravel, and in the aeration and sedimentation processes [35]. In turn, Karnib et al. [36] present studies on the removal effect of metals such as Cd, Pb, Cr, Ni, and Zn in the range of 30–200 ppm concentrations during sorption on activated carbon. The percentage removal of all tested metals was highest at 30 ppm and was respectively: for Cd, 86.0%; for Pb, 83.0%; for Cr, 50.6%; for Ni, 90.0%; and for Zn, 83.6%. Erdem et al. [37] and Wu et al. [38] have also shown that the adsorption efficiency of metals decreases with the increase in the initial metal concentration. Ashtoukhy et al. [39] explain that in low concentrations, the metals are adsorbed by specific sites, and at increasing concentrations, the individual sites are saturated and the ion exchange sites are filled, leading to less adsorption efficiency. In this work, low concentrations of metals were used, because in natural groundwater in Poland there are no higher concentrations. The selected concentrations were intended to reproduce natural water.

No group of researchers attempted to support the MF filtration process. Our own research confirms that magnetization of water can increase the efficiency of removing heavy metals from aqueous solutions. Research at low metal concentrations using Al_2O_3 gives promising results.

Table 3 shows the average results with the standard deviation for simultaneously measured solution parameters such as redox potential, pH, and electrolyte conductivity. The redox potential in samples of the individual elements before the filtration process ranged from 227 to 308 mV, whereas in the control samples after the process, it was lower in each case and ranged from 57 to 124 mV depending on the element, whereas in MF samples, no significant differences were observed.

The pH of analyzed samples of the individual elements before filtration process varied from about 5.10 to 7.09. The pH value was not regulated. The changes resulted from the type of metal ion solution and contact with the adsorbent. On the other hand, after the filtration process on activated alumina, the increase in pH of the control samples and MF-treated samples was observed. The reason for the increase in pH value of water filtered on activated alumina is the amphoteric nature of this material. At the contact of water with Al_2O_3, hydroxides are formed on the surface, which raise the pH of water flowing through the filter bed [33]. Chiban et al. [26] also showed the effect of pH on the process of removing metal ions in the filtration process on dried plant material. Dependence of pH on the metal removal effect was also tested by Aziz et al. [35] by shaking samples with calcium carbonate. In Aziz et al.'s work [35], final pH was 8.5 and efficiency reached over 90%. The efficiency obtained in the filtration process on the gravel was as follows: 43%–72% for Cd, 42%–78% for Pb, 46%–70% for Zn, 44%–73% for Ni, 45%–75% for Cu, and 47%–72% for Cr. In the case of crushed waste construction materials, the effect of removal of individual metals oscillated within 65%–80%. The results obtained by Aziz et al. [35] indicate that heavy metal removal was more affected by the type of filter material used rather than directly by pH. Studies on the removal of these metals show that porous materials containing calcium carbonate achieve the best removal results. Adsorption and precipitation of heavy metals as metal oxides and possibly carbonates belong to two mechanisms that contribute to the removal of metals from aqueous solutions [35]. However, the removal of heavy metals such as copper and lead in the filtration process of dried plant material is much more effective even at higher concentrations than those employed in the work. Benhima et al. [25] in his work conducting an experiment on two different wastewater types (domestic and industrial) were tested and good results were obtained for removal of Pb and Cd at more than 90%. The removal of the metal ions wastewater was observed for metal ions (Pb, Cd, Cu, and Zn) at about 100%, using inert organic matter as absorbent [25].

The electrolytic conductivity of tested solutions of individual elements in samples before the filtration process ranged from 60.3 to 66.1 μS/cm. On the other hand, after the filtration process on activated alumina, the increased electrolytic conductivity of tested solutions was observed in the case of control samples, and in the case of magnetized samples, even higher than in the control ones.

Based on the obtained values of removal efficiency for individual elements, a sequence of affinities of investigated

Table 3
Mean values of redox potential, electrolytic conductivity, and pH in samples

Parameter	A	B	C	A	B	C	A	B	C
	Copper (Cu)			Lead (Pb)			Cadmium (Cd)		
Redox potential (mv)	281 ± 17	104 ± 10	92 ± 8	301 ± 26	127 ± 13	110 ± 16	285 ± 30	122 ± 14	131 ± 10
pH (–)	6.03 ± 0.07	9.08 ± 0.07	9.19 ± 0.07	5.10 ± 0.09	7.75 ± 0.09	8.93 ± 0.10	7.97 ± 0.06	8.25 ± 0.08	8.78 ± 0.07
Electrolytic conductivity (μS/cm)	60.3 ± 3.1	18.0 ± 3.7	172.0 ± 2.3	63.5 ± 1.9	108.2 ± 2.6	100.7 ± 3.6	62.2 ± 2.6	120.1 ± 1.6	125.1 ± 2.7
	Manganese (Mn)			Iron (Fe)			Nickel (Ni)		
Redox potential (mv)	227 ± 6	57 ± 6	47 ± 2	308 ± 4	120 ± 5	119 ± 17	272 ± 4	114 ± 9	96 ± 5
pH (–)	6.75 ± 0.23	9.45 ± 0.17	9.62 ± 0.28	5.44 ± 0.08	9.26 ± 0.43	9.58 ± 0.21	6.16 ± 0.14	9.00 ± 0.08	9.27 ± 0.21
Electrolytic conductivity (μS/cm)	63.3 ± 1.2	161.4 ± 4.9	172.2 ± 4.4	66.1 ± 2.5	249.0 ± 8.2	210.3 ± 10.5	64.1 ± 1.5	168.7 ± 1.4	172.6 ± 4.9
	Zinc (Zn)			Chrome (Cr)					
Redox potential (mv)	285 ± 2	124 ± 3	106 ± 1	283 ± 1	121 ± 3	129 ± 3			
pH (–)	5.33 ± 0.14	7.91 ± 0.05	9.13 ± 0.08	7.09 ± 0.04	8.32 ± 0.09	8.89 ± 0.12			
Electrolytic conductivity (μS/cm)	62.4 ± 2.1	104.8 ± 2.8	96.2 ± 1.4	65.3 ± 0.6	121.7 ± 1.9	129.3 ± 0.3			

A — Model sample before adsorption process; B — Control sample; C — Magnetized sample.

elements was constructed according to the intensity of adsorption to the physical properties of the filter material, which was activated alumina: Mn > Ni > Cu > Zn > Pb > Fe > Cr > Cd. A sequence of affinities of selected elements was also determined according to the effect of the MF on the removal effect during the filtration process on Al_2O_3: Pb > Mn > Ni > Zn > Cu > Fe > Cd > Cr.

Table 4 shows the sorption capacity used for the material filtration process and calculated on a basis of the tests. The sorption capacity of alumina in the case of elemental samples ranged from 0.0916 to 0.1107 μg/g for manganese samples and chromium samples, respectively. In the case of samples subjected to MF, the alumina sorption capacity was slightly higher and ranged from 0.0936 to 0.11136 μg/g for manganese samples and chromium samples, respectively. Probably the sorption capacity of activated alumina was higher at the higher initial concentrations of tested elements. The analyzed experiment should be carried out with larger and different concentrations of the elements studied, which would then be the opportunity to describe the process using Langmuir and Freundlich isotherms as it did in the works of Chiban et al. [25–27].

Some elements, because of the possibility of accumulation in the human body, contribute to many diseases posing a threat to health, therefore, new methods of their effective removal from water solutions and water are sought [40–42]. These include MF and less popular filtration on aluminum oxide. Water subjected to permanent MF changes its conductivity, surface tension, and pH value [18–19]. On the other hand, strong MFs also increase the viscosity of water. Research has shown that the external MF affects the number of hydrogen bonds, the structure of liquid water, and the diffusion coefficient of water molecules between other water molecules. Toledo et al. [17] conducted research and calculations based on measurements of enthalpy, viscosity, and surface tension, which demonstrated that MF significantly influenced the breaking and deformation of hydrogen bonds between water molecules. MFs affect the competitiveness of intra and inter molecular hydrogen bonds, which entails the weakening of large structures and the formation of small structures with stronger hydrogen bonds within water clusters [43]. Results achieved by Toledo et al. [17] have shown that viscosity, surface tension, and evaporation enthalpy have increased in the water that was affected by the MF. The increase in these physical parameters arises the molecular interactions, and thus

Table 4
Results of the calculated sorption capacity of activated alumina for control and magnetized samples

Sorption capacity	A_0 (μg/g)	A_0^* (μg/g)
Cu	0.1087	0.1110
Pb	0.1045	0.1127
Cd	0.1060	0.1123
Mn	0.0916	0.0936
Fe	0.1031	0.1161
Ni	0.1077	0.1103
Zn	0.1081	0.1158
Cr	0.1107	0.1136

A_0—Activated alumina sorption capacity for control samples.
A_0^*—Activated alumina sorption capacity for magnetized samples.

changes in chemical properties of water [17]. These factors can increase the efficiency of water purification from heavy metals, and in particular, increase the viscosity of treated solution can help to increase the removal of the components contained. The filtration bed usually serves as an adsorbent, thus the processes of both filtration and adsorption are often parallel [11]. Retention of the particles in a given filter bed is determined by the viscosity forces. The codetermining effect of adsorption is the attraction of the removed particles to the grains of the filter bed. The effectiveness of this phenomenon is the result of the forces of attraction and repulsion, and it mainly depends on the dimensions and electrokinetic potential of the removed particles and grains of the filter material as well as the ionic strength of the solution to be processed. Hence the use of an MF can have a significant effect on the efficiency of physical adsorption. On the other hand, the influence of MF on chemical adsorption is noticeable, but it involves the binding of adsorbate particles (particles of pollutants) to active adsorbent sites. Molecules of adsorbate can be maintained on the surface of the sorbent (activated carbon or other sorption bed, e.g., activated alumina) by forces such as hydrogen bonds, dipole–dipole interactions, van der Waals forces, and electrostatic forces [44]. MF significantly affects the hydrogen bonds between water molecules and affects the competitiveness of intra and intermolecular hydrogen bonds, which entails the weakening of large structures and the formation of small, yet stronger hydrogen bonds within water clusters that may be more easily bound to other molecules, for example, present on the surface of the potential sorbent [17,43]. Filtration and sorption, as basic processes or intensified by other agents, are effectively used to remove various substances from the water and aqueous solutions, from relatively simple through difficultly removable, complex organic compounds.

New proposed solutions, that is, supporting filtration on Al_2O_3 using MF can contribute to optimizing the existing processes in water technology. Toxic elements can enter the human's body with food or drinking water. The World Health Organization's recommendations [42] provide stringent health-related values for such heavy metals as iron (Fe), manganese (Mn), copper (Cu), lead (Pb), cadmium (Cd), nickel (Ni), zinc (Zn), and chromium (Cr). Some of these elements may be present in elevated concentrations in waters, and others may enter the waters during their treatment [43].

As a result, more and more attention is paid to the monitoring of the quality of surface and underground waters for their heavy metals content and for technological processes that make their elimination highly efficient [45–50].

4. Conclusions

- Based on the research, it was found that the MF support of the filtration on activated alumina for the removal of selected elements is more effective than the filtration without MF. The MF is an efficient, energy-saving process that is free of chemicals and environmentally friendly. As a result of the collected information, it has been found that in the future, the influence of MF on the physicochemical properties of water and properties of the sorption materials can be used more frequently and on a larger scale, but effectiveness of the MF is small and perhaps uneconomical.
- The highest efficiency of non-magnetic-assisted filtration was recorded for manganese (Mn) samples (R = 92.24%), while the lowest in cadmium (Cd) samples (R = 72.52%). On the other hand, the greatest effect in the MF assisted filtration was found for samples of lead (Pb) solutions (R = 95.36%), whereas the smallest in samples of chromium (Cr) solutions (R = 77.21%).
- Studies have shown that removal of individual metals occurred according to the following series of affinity toward activated alumina in control samples not subjected to MF exposure: Mn > Ni > Cu > Zn > Pb > Fe > Cr > Cd, while in magnetized samples, the affinity sequence was as follows: Pb > Mn > Ni > Zn > Cu > Fe > Cd > Cr.
- As a result of filtration of model solutions on activated alumina, it was found in the post-process samples that the pH values were significantly higher than in the pre-process samples. The reason for this is the properties of the applied filter material—activated alumina.
- Studies have shown that the removal efficiency of selected elements from the aqueous solution was noticeably higher in the case of samples subjected to the MF. The highest difference was found in samples of lead solution (Pb), which amounted to 8.22%. The smallest difference in efficiency was found for copper (Cu) (1.90%), manganese (Mn) (1.97%), and chromium (Cr) solutions (1.99%). In the case of other elements tested, the increase in efficiency in samples subjected to the MF was: Cd, 5.15%; Fe, 3.50%; Ni, 2.22%; and Zn, 6.19%.
- The sorption capacity of alumina in the case of elemental samples ranged from 0.0916 to 0.1107 μg/g for manganese samples and chromium samples, respectively. In the case of samples subjected to MF, the alumina sorption capacity was slightly higher and ranged from 0.0936 to 0.11136 μg/g for manganese samples and chromium samples, respectively.

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References

[1] D. Holliday, R. Resnick, J. Walker, Fundamentals of Physics, Vol. 3, PWN, Warszawa, 2006.
[2] I. Skoczko, E. Szatyłowicz, Possibility of Using Magnetic Field in Environmental Engineering, Vol. 11, Environmental Engineering-Through a Young Eye, pp. 333–355, 2015. (in Polish)
[3] Z. Xiao, Q. Zhou, H. Qin, J. Qiao, X. Guan, The enhancing effect of weak magnetic field on degradation of Orange II by zero-valent iron, Desal. Wat. Treat., 57 (2016) 1659–1670.
[4] L. Hołysz, E. Chibowski, A. Szcześ, Influence of impurity ions and magnetic field on the properties of freshly precipitated calcium carbonate, Water Res., 37 (2003) 3351–3360.
[5] E. Chibowski, L. Hołysz, A. Szcześ, M. Chibowski, Some magnetic field effects on in situ precipitated calcium carbonate, Water Sci. Technol., 49 (2004) 169–176.
[6] K. Higashitani, H. Iseri, K. Okuhara, A. Kage, S. Hatade, Magnetic effects on zeta potential and diffusivity of nonmagnetic colloidal particles, J. Colloid Interface Sci., 172 (1995) 383–388.
[7] S.A. Parsons, B.L. Wang, S.J. Judd, T. Stephenson, Magnetic treatment of calcium carbonate scale – effect of pH control, Water Res., 31 (1997) 339–342.

[8] J.S. Baker, S.J. Judd, Magnetic amelioration of scale formation, Water Res., 30 (1996) 247–260.
[9] A. Szcześ, E. Chibowski, L. Hołysz, P. Rafalski, Effects of static magnetic field on water at kinetic condition, Chem. Eng. Process., 50 (2011) 124–127.
[10] J.M.D. Coey, S. Cass, Magnetic water treatment, J. Magn. Magn. Mater., 209 (2000) 71–74.
[11] T. Piecuch, J. Piekarski, G. Malatyńska, Filtration to form a sludge with a low compressibility on the filter mesh, Miner. Res. Manage., 30 (2014) 83–97. (in Polish)
[12] L. Hołysz, A. Szcześ, E. Chibowski, Effects of a static magnetic field on water and electrolyte solutions, J. Colloid Interface Sci., 316 (2007) 996–1002.
[13] P. Xiao-Feng, D. Bo, The changes of macroscopic features and microscopic structures of water under influence of magnetic field, Physica B, 406 (2008) 3571–3577.
[14] T. Stankiewicz, K. Kozak, J. Podleśny, S. Pietruszewski, Influence of magnetically treated water on germination and growth of lupine seedlings, Acta Scientiarum polonorum, Technica agraria, 11 (2012) 21–32. (in Polish)
[15] F. Alimia, M.M. Tlili, M. Ben Amora, G. Maurin, C. Gabrielli, Effect of magnetic water treatment on calcium carbonate precipitation: influence of the pipe material, Chem. Eng. Process., 48 (2009) 1327–1332.
[16] N.S. Zaidi, J. Sohaili, K. Muda, M. Sillanpää, Magnetic field application and its potential in water and wastewater treatment systems, Sep. Purif. Rev., 43 (2014) 206–240.
[17] E.J.L. Toledo, T.C. Ramalho, Z.M. Magriotis, Influence of magnetic field on physical–chemical properties of the liquid water: insights from experimental and theoretical models, J. Mol. Struct., 888 (2008) 409–415.
[18] A. Fathi, T. Mohamed, G. Claude, G. Maurin, B.A. Mohanmed, Effect of a magnetic water treatment on homogeneous and heterogeneous precipitation of calcium carbonate, Water Res., 40 (2006) 1941.
[19] Y.I. Cho, S.H. Lee, Reduction in the surface tension of water due to physical water treatment for fouling control in heat exchangers, Int. Commun. Heat Mass Transfer, 32 (2005) 1–9.
[20] D. Park, Y.S. Yun, J.H. Jo, J.M. Park, Biosorption process for treatment of electroplating wastewater containing Cr (IV): laboratory-scale feasibility Test, Ind. Eng. Chem. Res., 45 (2006) 5059–5065.
[21] Y. Pamukoglu, F. Kargi, Biosorption of copper (II) ions onto powdered waste sludge in a completely mixed fed-batch reactor: estimation of design parameters, Bioresour. Technol., 98 (2007) 1155–1162.
[22] Y.S. Ho, A.E. Ofomaja, Biosorption thermodynamics of cadmium on coconut copra meal as biosorbent, Biochem. Eng. J., 30 (2006) 117–123.
[23] S.E. Bailey, T.J. Olin, M.R. Bricka, D.D. Adrian, A review of potentially low-cost sorbents for heavy metals, Water Res., 3 (1999) 2469–2479.
[24] A. Edidiong, M. Alastair, N. Petrus, S. Flor, F. Xiaolei, Adsorption of Cd(II) and Pb(II) ions from aqueous solutions using mesoporous activated carbon adsorbent: equilibrium, kinetics and characterisation studies, J. Environ. Chem. Eng., 5 (2017) 679–698.
[25] H. Benhima, M. Chiban, F. Sinan, P. Seta, M. Persin, Removal of Cd(II) and Pb(II) ions from aqueous solution by adsorption onto micro-particles of dry plants, Colloids Surf., B, 61 (2008) 10–16.
[26] M. Chiban, A. Soudani, F. Sinan, M. Persin, Single, binary and multicomponent adsorption of some anions and heavy metals on environmentally friendly *Carpobrotus edulis* plant, Colloids Surf. B, 82 (2011) 267–276.
[27] M. Chiban, G. Carja, G. Lehutu, F. Sinan, Equilibrium and thermodynamic studies for the removal of As(V) ions from aqueous solution using dried plants as an adsorbents, Arabian J. Chem., 9 (2016) S988–S999.
[28] M. Chiban, F. Sinan, Removal of Cu(II) ions from aqueous solution by microparticles of dried *Carpobrotus edulis* plant in a column system, Water Qual. Res. J. Can., 46 (2011) 259–267.
[29] S.A. Davis, M. Misra, Transport model for the adsorption of oxyanions of selenium (IV) and arsenic (V) from water onto lanthanum-and aluminum-based oxides, J. Colloid Interface Sci., 188 (1997) 340–350.
[30] T.S. Singh, K.K. Pant, Equilibrium, kinetics and thermodynamic studies for adsorption of As(III) on activated alumina, Sep. Purif. Technol., 36 (2004) 139–147.
[31] US EPA, Removing Multiple Contaminants from Drinking Water: Issues to Consider, EPA 816-H-07-004, 2007.
[32] T.F. Lin, J.K. Wu, Adsorption of arsenite and arsenate within activated alumina grains: equilibrium and kinetics, Water Res., 35 (2001) 2049–2057.
[33] I. Skoczko, E. Szatyłowicz, Studies on the efficiency of groundwater treatment process with adsorption on activated alumina, Ecol. Eng., 18 (2017) 211–218.
[34] T.K. Naiya, A.K. Bhattacharya, S.K. Das, Adsorption of Cd(II) and Pb(II) from aqueous solutions on activated alumina, J. Colloid Interface Sci., 333 (2009) 14–26.
[35] H.A. Aziz, M.N. Adlan, K.S. Ariffin, Heavy metals (Cd, Pb, Zn, Ni, Cu and Cr(III)) removal from water in Malaysia: post treatment by high quality limestone, Bioresour. Technol., 99 (2008) 1578–1583.
[36] M. Karnib, A. Kabbani, H. Holail, Z. Olama, Heavy metals removal using activated carbon, silica and silica activated carbon composite, Energy Procedia, 50 (2014) 113–120.
[37] E. Erdem, N. Karapinar, R. Donat, The removal of heavy metal cations by natural zeolites, J. Colloid Interface Sci., 280 (2004) 309–314.
[38] X. Wu, F. Zhao, M. Chen, Y. Zhang, C. Zhao, H. Zhou, Factors affecting the adsorption of Zn^{2+} and Cd^{2+} ions from aqueous solution onto vermiculite, Adsorpt. Sci. Technol., 28 (2008) 145–155.
[39] E. El-Ashtoukhy, N. Amin, O. Abdelwahab, Removal of lead(II) and copper(II) from aqueous solution using pomegranate peel as a new adsorbent, Desalination, 223 (2008) 162–173.
[40] L. Jarup, Hazards of heavy metal contamination, Br. Med. Bull., 68 (2003) 167–182.
[41] G.C.M. Watt, A. Britton, H.G. Gilmour, M.R. Moore, G.D. Murray, S.J. Robertson, Public health implications of new guidelines for lead in drinking water: a case study in an area with historically high water lead levels, Food Chem. Toxicol., 38 (2000) 73–79.
[42] WHO 2017, Guidelines for Drinking Water Quality, 4th ed., Word Heath Organization, Geneva, 2017.
[43] L. Jiang, X. Yao, H. Yu, X. Hou, Z. Zou, F. Shen, C.H. Li, Effect of permanent magnetic field on water association in circulating water, Desal. Wat. Treat., 79 (2017) 152–160.
[44] A.L. Kowal, M. Świderska-Bróż, Water Treatment, PWN, Warszawa, 2009. (in Polish)
[45] M. Błażejewski, A. Pruss, Heavy Metal Content in the Roadside Lane of Road A2 in the Area of Poznan, M. Janosz-Rajczyk, Częstochowa-Ustroń, Eds., Micro pollution in the environment in the light of EU regulations, 8–10 October, Czestochowa University of Technology, pp. 245–249, 2000. (in Polish)
[46] M.R. Lasheen, G. El-Kholy, C.M. Sharaby, Assessment of selected heavy metals in some water treatment plants and household tap water in Greater Cairo, Egypt Manage. Environ. Qual., 19 (2008) 367–376.
[47] O. Chaalal, A.Y. Zekri, R. Islam, Uptake of heavy metals by microorganisms: an experimental approach, Energy Sources, 27 (2005) 87–100.
[48] G. Liu, X. Zhang, J.W. Talley, Effect of copper (II) on natural organic matter removal during drinking water coagulation using aluminum-based coagulants, Water Environ. Res., 79 (2007) 593–599.
[49] J. Jeż-Walkowiak, M.M. Sozański, A. Pruss, Ł. Weber, Research on Arsenic Sorption on Selected Filtration Materials. Second International Conference "Metals and Related Substances in Drinking Water" (METEAU) Cost Action 637, 29–31 October, IWA Publishing, Lisbon, Portugal, 2008.
[50] A. Pruss, J. Jeż-Walkowiak, Z. Dymaszewski, M. Michałkiewicz, Elimination of Heavy Metals from Water of Warta River by Infiltration and Filtration Process, IV International Congress of Environmental Engineering, The Committee of Environmental Engineering, Lublin, pp. 235–244, 2009. (in Polish)