VILNIUS GEDIMINAS TECHNICAL UNIVERSITY
FACULTY OF ENVIRONMENTAL ENGINEERING
DEPARTMENT OF ENVIRONMENTAL PROTECTION AND WATER ENGINEERING

Monika Stonkutė

EXPERIMENTAL RESEARCH ON APPLICATION OF YEAST IN HEAVY METAL REMOVAL FROM POLLUTED WATER

MIELIŲ TAIKYMO SUNKIŲJŲ METALŲ ŠALINIMUI IŠ UŽTERŠTO VANDENS EKSPERIMENTINIAI TYRIMAI

Master’s degree Thesis

Study programme of Environmental Protection Technology and Management, state code 6211EX034
Study field of General Engineering

Vilnius, 2021

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Supervisor assoc. prof. dr. Dainius Paliulis 2021-05-20
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(Title, Name, Surname) (Signature) (Date)

Vilnius, 2021

(the document of Declaration of Authorship in the Final Degree Project)

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(Study programme, academic group no.)

DECLARATION OF AUTHORSHIP IN THE FINAL DEGREE PROJECT

2021-05-14
(Date)

I declare that my Final Degree Project entitled Experimental Research On Application Of Yeast In Heavy Metal Removal From Polluted Water is entirely my own work. The title was confirmed on 08 March, 2021 by Faculty Dean's order No. 43 ap. I have clearly signaled the presence of quoted or paraphrased material and referenced all sources.

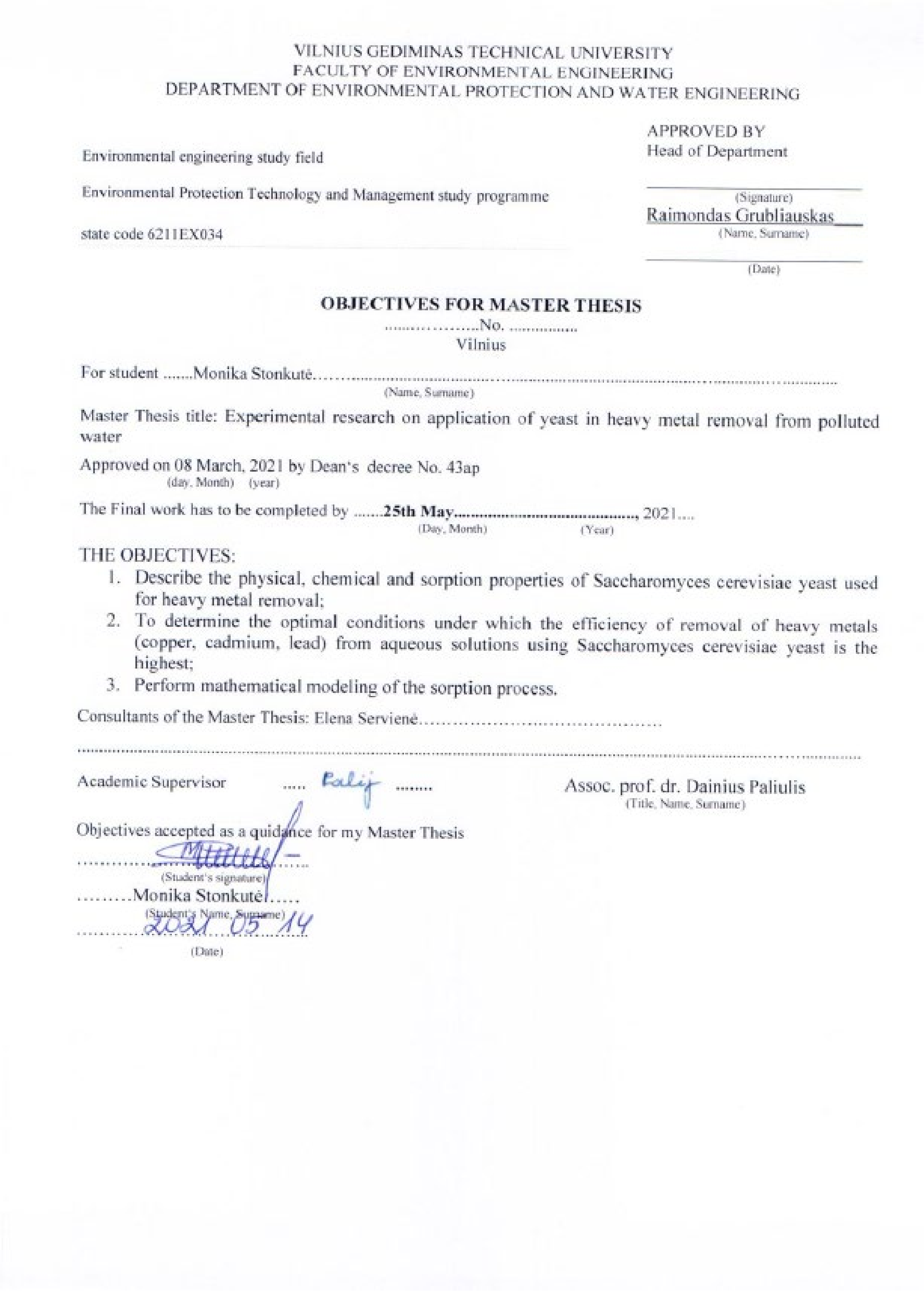
I have acknowledged appropriately any assistance I have received by the following professionals/advisers: doc. dr. Elena Servienė

The academic supervisors of my Final Degree Project are assoc. prof. dr. Dainius Paliulis and dr. sc. ing. Jelena Pubule

No contribution of any other person was obtained, nor did I buy my Final Degree Project.

(Signature) Monika Stonkutė
(Given name, family name)

Task of supervisor



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(Date)

Environmental engineering study field

Environmental Protection Technology and Management study programme

state code 6211EX034

OBJECTIVES FOR MASTER THESIS
………………..No. ……………
Vilnius

For student …….Monika Stonkutė………………………………………………………………………
(Name, Surname)

Master Thesis title: Experimental research on application of yeast in heavy metal removal from polluted water

Approved on 08 March, 2021 by Dean's decree No. 43ap
(day, Month) (year)

The Final work has to be completed by …….**25th May**………………………………….., 2021….
(Day, Month) (Year)

THE OBJECTIVES:

1. Describe the physical, chemical and sorption properties of Saccharomyces cerevisiae yeast used for heavy metal removal;
2. To determine the optimal conditions under which the efficiency of removal of heavy metals (copper, cadmium, lead) from aqueous solutions using Saccharomyces cerevisiae yeast is the highest;
3. Perform mathematical modeling of the sorption process.

Consultants of the Master Thesis: Elena Servienė………………………………………

………

Academic Supervisor ….. …….. Assoc. prof. dr. Dainius Paliulis
(Title, Name, Surname)

Objectives accepted as a quidance for my Master Thesis

………………………………….
(Student's signature)
………Monika Stonkutė…..
(Student's Name, Surname)
…………2021 05 14……
(Date)

ANNOTATION

The master thesis was about the use of *Saccharomyces cerevisiae* yeast to remove lead, copper and cadmium ions from artificially contaminated water. The main objective of this work was to perform experimental studies and to evaluate the influence of adsorption parameters on the adsorption process using *Saccharomyces cerevisiae* and *Brewer's* yeast as an adsorbent and to perform numerical modeling of the adsorption process. The first chapter contains literature review on the sources of heavy metals, their effects on humans and the environment, possible methods for the removal of heavy metals from contaminated water and the physical – chemical properties of *Saccharomyces cerevisiae* yeast. The second chapter describes the methodology for the preparation of adsorption experiments using yeast. The third chapter presents the results of experimental adsorption studies. The fourth chapter was devoted to mathematical modeling of adsorption using Visual MINTEQ software. The appendices contain the author's publication and the conference proceedings. The work consists of the following parts: introduction, literature review, methodology, results, mathematical modeling of the adsorption process, conclusions, recommendations, references and appendices. The volume of thesis is 88 pages excluding references and appendices. It also contains 43 illustrations, 25 tables and 96 references.

Keywords: adsorption; heavy metals; lead ions; copper ions; cadmium ions, *Saccharomyces cerevisiae* yeast; Visual MINTEQ software

ANOTĀCIJA

Maģistra darbs bija par *Saccharomyces cerevisiae* rauga izmantošanu svina, vara un kadmija jonu noņemšanai no mākslīgi piesārņota ūdens. Šī darba galvenais mērķis bija veikt eksperimentālus pētījumus un novērtēt adsorbcijas parametru ietekmi uz adsorbcijas procesu, izmantojot *Saccharomyces cerevisiae* un pārtikas raugu kā adsorbentu, un veikt adsorbcijas procesa skaitlisko modelēšanu. Pirmajā nodaļā sniegts pārskats par literatūru par smago metālu avotiem, to ietekmi uz cilvēku un vidi, iespējamām metodēm smago metālu atdalīšanai no piesārņotā ūdens un *Saccharomyces cerevisiae* rauga fizikāli ķīmiskajām īpašībām. Otrajā sadaļā aprakstīta metodika adsorbcijas eksperimentu sagatavošanai, izmantojot raugu. Trešajā nodaļā sniegti eksperimentālo adsorbcijas pētījumu rezultāti. Ceturtā nodaļa ir veltīta adsorbcijas matemātiskai modelēšanai, izmantojot Visual MINTEQ programmatūru. Pielikumos ir autora publikācija un konferences rakstu krājums. Darbs sastāv no šādām daļām: ievads, literatūras apskats, metodika, rezultāti, adsorbcijas procesa matemātiskā modelēšana, secinājumi, ieteikumi, atsauces un pielikumi. Darbs sastāv no: 88 lappusēm bez saitēm un pielikumiem. Maģistra darbā ir 43 ilustrācijas, 25 tabulas un 96 atsauces.

Atslēgas vārdi: adsorbcija; smagie metāli; svina joni; vara joni; kadmija joni, *Saccharomyces cerevisiae* raugs; Visual MINTEQ programmatūra

CONTENT

DEFINITIONS AND TERMS

Absorption – the absorption of a substance from a solution or gas mixture by the entire volume of the absorbing body (Lietuvninkas, 2012).
Adsorption – is the absorption of a substance from a solution or gas mixture on the surface of an absorbing body (Lietuvninkas, 2012).
Adsorbate – a substance absorbed during adsorption (Lietuvninkas, 2012).
Adsorbent – absorbent material (Lietuvninkas, 2012).
Anions – particles to which an electron or several electrons have joined, which has acquired a negative charge (Lietuvninkas, 2012).
BOD – biological oxygen demand (Lietuvninkas, 2012).
Cations – particles that have lost an electron or several electrons, acquired a positive charge (Lietuvninkas, 2012).
CNS – central nervous system (Lietuvninkas, 2012).
COD – is the amount of oxygen consumed for the oxidation of organic matter in wastewater or water, using the dichromatic method, which is expressed in mg/l (Adamonytė and Misevičienė, 2012).
Desorption – is the removal of absorbed or adsorbed material from a sorbent (Lietuvninkas 2012).
FAAS – flame atomic absorption spectrometry (Lietuvninkas, 2012).
Heavy metals – are a group of chemical elements from vanadium to bismuth (Pb, Cu, Zn, Ni, Cd, Co, Hg, etc.) with a density greater than 6 g/m^3. They do not include precious metals, but include some metalloids (Sb, As, Se, Ge, Te) and lower density metals (Sr, Rb, Sc) (Lietuvninkas 2012).
Maximum levels (MRLs) – are the maximum levels of a substance in soil, expressed in mg/kg dry matter, established on the basis of scientific knowledge, which do not harm human health indefinitely or even lifetime through plants, water, air and do not affect heredity directly to future generations or indirectly (HN 60: 2004).
pH – is an indicator of hydrogen ions (Lietuvninkas, 2012).
PNS – peripheral nervous system (Lietuvninkas, 2012).

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ABBREVIATIONS

As – arsenic;
Au – gold;
Cd – cadmium;
Cr – chromium;
Cu – copper;
Hg – mercury;
HM – heavy metals;
Mn – manganese;
MRL – maximum allowable concentration;
Ni – nickel;
Pb – lead;
T – temperature, ° C;
Zn – zinc.

INTRODUCTION

Problem

Both surface and groundwater can be contaminated with a variety of chemicals, making it dangerous to use water for domestic usage. Pollutants can enter the water with precipitation, sewage, transport exhaust gasses, fertilizers, industrial dust and snowmelt water. Contamination of surface and groundwater with oil products or landfill leachate is also possible (Ojo et al., 2012).

Water can be contaminated with heavy metals (HM), petroleum products, detergents, radioactive isotopes, mineral or organic fertilizers. These pollutants enter the environment in a variety of ways: incineration of municipal waste, extraction of metal ores, improper operation of landfills, production of synthetic products, use of automobiles, improper operation of sewage sludge sites or industrial waste storage sites (Pazand et al., 2018). Heavy metals can also enter the environment through natural processes, such as volcanic eruptions or weathering of rocks (Motuza, 2013).

Heavy metals include more than forty chemical elements with a relative atomic mass above 40. Heavy metal ions are non–biodegradable, toxic and carcinogenic at very low concentrations and therefore generally pose a serious threat to the environment and public health (Liu et al., 2008). Heavy metals may accumulate in the surroundings , so they are termed “perpetual pollutants” and fall into the class of important environmental pollutants.

Copper, cadmium and lead are some of the most commonly emitted heavy metals from various industries. Unfortunately, wastewater is not always treated up to the legal limit values, which can lead to heavy metals entering and contaminating surface or ground water. If we want to solve the problem of wastewater pollution by heavy metals, it is important to analyze the methods used for the removal of HM and select the optimal method of their removal.

Relevance of the work

Heavy metals are characterized by carcinogenic, mutagenic and teratogenic effects, which manifest themselves not only in oncological diseases, but also in developmental disorders of the organism, weakened immunity and impaired reproductive functions (Jan et al., 2015). The negative effects of heavy metals are not only recorded in humans or animals, their toxic effects can also occur in plants.

Heavy metals tend to accumulate and migrate from one ecological niche to another. Heavy metal pollution is a major ecological problem worldwide, so eliminating it is particularly important. The aim is to create more advanced water treatment technologies using the simplest, most economical, long–lasting, natural and high–cleaning materials.

Copper, cadmium and lead are among the most common in heavy metals industry and energy companies and in agricultural wastewater. Efficient and inexpensive ways to remove heavy metals from industrial effluents are being sought around the world. Adsorption could be considered one of the alternative methods of treatment of wastewater contaminated with HM. Process of adsorption has been shown to be a cheap and very effective method to remove many heavy metals from water or aqueous solutions.

The use of adsorbents of biological origin for the removal of heavy metals from wastewater is a promising method due to the low costs, rapid biodegradation and easy availability of adsorbents. The application of yeast (*Saccharomyces cerevisiae*) as a removal agent of HM from contaminated aqueous solutions has been little studied. The scientists listed below have performed experiments in this field: I. Zinicovscaia, S. N. Farhan, K. Parvathi, N. Ahalya, I. A. Anaemene, M. Bilal, C. Can, M. Czikkely, J. F. Duncan, R. W. Gaikwad, Y. Göksungur, A. M. Goncalves, S. Halnor, R. M. Hlihor etc.

The aim of the study was to investigate the application of yeast (*Saccharomyces cerevisiae*) to the removal of heavy metals from contaminated water and the factors influencing its efficiency and simulate modeling of the adsorption process.

Work tasks

- Describe the physical, chemical and sorption properties of *Saccharomyces cerevisiae* yeast used for heavy metal removal.
- Determine the optimal conditions under which the efficiency of removal of heavy metals (copper, cadmium, lead) from aqueous solutions using *Saccharomyces cerevisiae* yeast is the highest.
- Perform mathematical modeling with Visual MINTEQ software of the biosorption process of yeast.

Novelty of the work

The novelty of the work consists of complex studies, during which the optimal conditions for the purification of aqueous solutions contaminated with HM using an adsorbent prepared from *Saccharomyces cerevisiae* yeast were identified.

Practical value of the work

The performed experimental studies and the results of those studies allowed to determine whether yeast could be used or not for the removal of heavy metals from contaminated water. The efficiency of yeast sorption properties at different concentrations of heavy metals in solution was determined using different yeast and heavy metal contact times, sorbent content and pH.

The study of the sorption properties of low–cost, environmentally friendly, easily and widely applicable adsorbents allows the development of practical treatment systems or water treatment plants and at the same time reduce the pollution of the environment with heavy metals. The use of an adsorption process with less studied adsorbents may be one of the most promising ways to remove heavy metals from wastewater.

Acknowledgments

The author gratefully acknowledge doc. dr. Elena Servienė (Nature Research Center, Vilnius) for providing *S. cerevisiae* yeast.

1. PURIFICATION OF CONTAMINATED WATER FROM HEAVY METALS BY THE APPLICATION OF YEAST

1.1. Sources of heavy metals in the environment

Chemical elements with a relative atomic mass greater than 40 form a group of heavy metals. HM are one of the most important groups of pollutants, occupying one of the leading sources of environmental pollution – pesticides, acid rain, oil spills, chemical pollution and urban noise. HM is one of the largest group of pollutants in soil, marine and industrial wastewater. As trace elements, heavy metals are essential for living organisms, but may have different toxic effects depending on the species and amount. Lead (Pb), cadmium (Cd) and copper (Cu) – toxic heavy metals – are most commonly found in the environment (Bhat et al., 2019).

When studying the amounts of heavy metals in the environment, the amount of a single element found is less important than the interrelationship between the chemical elements and the total amount observed. Heavy metals enter the environment with various air pollutants or waste. HM accumulates in soil, bottom sediments, plants, animals, and human organisms. The accumulation in the soil depends on the amount of these metals in the soil solution, the acidity (pH) of the soil and the adsorption capacity of the soil. Cadmium accumulates most intensively in plants; moderately intensively, in descending order – zinc, mercury, copper, lead, and weakly – manganese, nickel, chromium (Bhat et al., 2019).

Research on heavy metals reveals that the entry of HM into ecosystems and their accumulation in food chains is a consequence of anthropogenic activities (Hassaan et al., 2016). It should also be mentioned that there are possible sources of naturally occurring HM in the environment, for example, as volcanic eruptions or rock weathering (Motuza, 2013).

The main sources of environmental pollution with heavy metals are transport, agricultural activities (mineral fertilizers, pesticides), industrial and energy companies (Hassaan et al., 2016). Increased production of chemicals, electroplating (including battery production), fertilizers, mining, paper, pesticides, metallurgy, fossil fuels, leather processing and wastewater, especially in developing countries, contributes to faster releases of heavy metals into the environment (Hassaan et al., 2016).

Toxic metals are largely distributed in the environment through industrial effluents, organic waste, waste incineration, transportation and energy production. Heavy metals can disperse far from sources, depending on whether they are in the form of gaseous compounds or solid particles. These pollutants are leached from the air to land or water surfaces (Mahurpawar, 2015). Heavy metals are also transported with surface runoff from mining or production areas and this contributes imperceptibly and uncontrollably to the environment and water pollution by heavy metals.

Lithuania also deals with pollution caused by heavy metals. Heavy metal ions are detected in urban and industrial wastewater. The largest number of dischargers containing wastewater with heavy metal ions is in eighteen rivers and the Curonian Lagoon. The main toxic metals and their sources are listed in Table 1.1.

Table 1. 1. Sources of heavy metals (Mahurpawar, 2015)

Metal	Source
Arsenic (As)	Phosphate and fertilizers, metal hardening and textiles
Cadmium (Cd)	Phosphate fertilizers, electronics, pigments and dyes
Chrome (Cr)	Metal plating and photography
Copper (Cu)	Electronics
Lead (Pb)	Paints and batteries
Nickel (Ni)	Electroplating
Zinc (Zn)	Galvanization of iron and steel, galvanization
Mercury (Hg)	Combustion of solid fuels

Arsenic (As) is widely used in the industrial sector and in the production of wood preservatives. Previous studies have found out that arsenic is also found in cigarettes. This metal is also used in the production of pesticides (Chung et al., 2014).

Cadmium (Cd) is toxic metal affecting the environment. One of the main sources of cadmium emissions into the surroundings are alloy production, pigments, plastics, batteries, mining and refining (Bernhoft, 2013). This chemical element is also used in the nuclear industry, in the production of paints and phosphors (Benavides et al., 2005). The permissible limit concentration of cadmium in wastewater is from 0.2 to 0.5 mg/l (Order of the Minister of Environment of the Republic of Lithuania "On Approval of Rules for Reduction of Water Pollution with Priority Hazardous Substances", 2001). Cadmium from industrial contaminated effluents accumulates in sludge when entering water bodies.

Chromium (Cr) can be found in nature in ultramaphic rocks formed during the magmatism process (Motuza, 2013). Trivalent chromium (III) is common form of chromium in the environment. With strong oxidative properties, another type of chromium is possible – hexavalent (VI) chromium. Chromium is found in fertilizers and small amounts of it can be detected in sewage sludge. Chromium is also found in fly ash, mined in metal mines (Saha et al., 2011).

Copper (Cu) is a natural chemical element with an average of about 50 ppm in the soil. It is present in all animals, plants and in small amounts it is an essential nutrient for humans and animals (Carvalho et al., 2015). The main sources of environmental copper emissions are copper mining, smelting and refining, industrial plants producing copper products. The main source of copper in drinking water is the leaching of copper from pipes and bath fittings due to acidic water (Jiwan et al., 2011).

One of the sources of **lead (Pb)** is the renovation of old steel structures, which can generate large amounts of lead dust. Another source of lead pollution is road transport. For gasoline, lead is used as an anti–knock agent. Incineration of lead – containing waste (synthetic materials, anti – corrosion paints, etc.) also releases significant amounts of lead into the environment. The metallurgical industry, lead refineries and fuel plants also contribute to environmental pollution by lead and lead compounds. Lead and its compounds in dusty or soluble form are particularly strong environmental poisons. Lead, like other heavy metals, accumulates in sludge, sediments and poses a risk to the environment. In older buildings where drinking water is still supplied through lead pipes, the lead content may exceed the allowable norm (Zhang et al., 2015).

Most **nickel (Ni)** on Earth is inaccessible. In the earth's core, nickel makes up about 10 % of its composition (Motuza, 2013). Most of the ores from which nickel is extracted are iron – nickel sulfides such as pentlandite (Arzoo et al., 2017).

Zinc (Zn) is used for galvanizing iron sheet. This chemical element is included in many alloys such as brass, bronze and others. Mixing zinc oxide (ZnO) with a concentrated solution of $ZnCl_2$ or H_3PO_4 gives a mass that hardens quickly and is used to fill teeth. ZnO is mainly used as a filler in the rubber industry. The poisonous zinc compound is the phosphide Zn_3P_2, which is widely used to poison rodents (rats and mice) (Plum et al., 2010). Zinc sulfide ZnS is a white, almost water – insoluble substance used as a white dye. Crystalline ZnS, exposed to X–rays or radioactive materials, begins to glow. Therefore, it is used to make X–ray screens prepared for a mass that glows in the dark and is applied to dials and digits in watches and clocks (Ajiboye et al., 2015).

One of the biggest sources of **mercury (Hg)** pollution in Europe and elsewhere is the burning of solid fuels – coal, lignite, peat and wood. Mercury also enters the environment from the following industries: electricity and metal production (Bernhoft, 2012).

M. Leivuori et al. made a research about distribution of heavy metals in sediments of the Gulf of Riga, Baltic Sea. The Gulf of Riga is a semi - enclosed bay close to the central Baltic Sea. The Gulf is surrounded by Latvia and Estonia, it is about 100 km wide and has an area of 19 000 km^2 (Leivuori et al., 2000). This study presented the concentrations of selected heavy metals, such as mercury, cadmium, lead, copper and zinc in the topmost sediments of the Gulf of Riga.

Production processes in different industrial sectors generate wastewater that is contaminated with both organic and inorganic substances.

Thus, heavy metals are naturally occurring component of the ecosystem. Metals could be found all over the earth (atmosphere, the Earth's crust, water bodies). Heavy metals can also accumulate in biological organisms (plants and animals). Under natural conditions, heavy metals are added to the soil during rock weathering. Under the influence of a complex of environmental conditions in the natural environment (humidity, temperature changes, erosion, etc.), rock decay and soil formation processes take centuries, so the HM is not locally concentrated, thus, the concentrations of metals in the soils remain low. Heavy metals are most often released into the environment by waste contaminated with oil products: transport waste (tires, used lubricants, filters, batteries), chemical waste (varnishes, paints, thinners) and household chemical products. Anthropogenic pollution by heavy metals is characterized by pollution in high concentrations of heavy metals, usually on a local or regional scale.

1.2. Health and environmental effects of heavy metals

Pollution of heavy metal is an important environmental problem due to the toxic effects of metals and their tendency to accumulate in food chains. Metals are essential minerals for all aerobic and anaerobic organisms, but high levels of many heavy metals, such as copper, lead, cadmium, chromium, or mercury, have been shown to have significant adverse effects on human health. The human body can't recycle and remove metals. As a result, heavy metals settle in various internal organs. Large amounts of sediment can cause adverse reactions and serious damage to the body (Mahurpawar, 2015).

Certain heavy metals such as chromium and nickel have been linked to cancer. HM have been shown to cause poisoning in humans or animals (Mahurpawar, 2015). Heavy metals can become toxic if they begin to accumulate in soft tissues (Jaishankar et al., 2014).

Heavy metals have toxic effects on soil microorganisms, resulting in changes in the diversity of soil communities, population size and overall activity. Increased Pb content in soil can reduce soil productivity and very low Pb concentrations can inhibit some vital plant processes, like photosynthesis, mitosis and water absorption. If compostable wastes such as sewage sludge, municipal solid waste and pig manure contain heavy metals, their presence can alter the composting process by inhibiting bacterial growth (Jiwan et al., 2011).

Heavy metal pollution is often encountered in developed industrial or very fast–growing economies.

Heavy metals can enter the body in several ways – with food or liquids, through direct contact and inhalation.

Soluble inorganic arsenic (As) may have direct toxic effects. Ingestion of large amounts may cause symptoms such as severe vomiting, blood and circulatory disorders, nervous system damage and, eventually, death. When doses are not yet lethal, such high doses can reduce blood cell production, break down red blood cells in the blood, enlarge the liver, cause tingling and sensory loss in the extremities or cause brain damage (Verma et al., 2016).

Adverse effects of cadmium (Cd) are particularly dangerous for the kidneys, lungs, brain and bones. Depending on the severity of the exposure, symptoms of exposure include nausea, vomiting, abdominal cramps, shortness of breath, and muscle weakness. Severe exposure can cause pulmonary odema or even human death. Exposure to cadmium and its compounds may occur in the lungs (emphysema, bronchiolitis, and alveolitis) and kidney (Jiwan et al., 2011). Prolonged exposure to cadmium and its compounds can cause headaches, dizziness, irritability, less frequently difficulty breathing, cough and chest pain. Health problems are caused by oxidative stress caused by cadmium in the body's cells. Long–term cadmium poisoning causes Fanconi syndrome (Martin et al., 2009).

Chromium (Cr) is detected in the environment as Cr (III) or Cr (VI). Cr (VI) is toxic to plants and animals, is a strong oxidizer, corrosive, soluble in alkaline medium and weakly acidic water, toxic and a potential carcinogen (Shekhawat et al., 2015). Cr (VI) toxicity results from its ability to diffuse across cell membranes and oxidize biological molecules (Jiwan et al., 2011).

Copper (Cu) is an important element in the nutrition of mammals as a component of metal enzymes. Conversely, high levels of Cu can cause many negative health effects. Human exposure to Cu occurs primarily through food and drinking water. Humans can be poisoned by copper heavy metal if the metal enters the human body through the mouth (Araya, 2007). Excessive consumption of Cu can lead to severe extensive capillary damage, central nervous system irritation or even depression. This metal can cause problems for the liver or stomach (Jiwan et al., 2011). Like iron, copper contributes to the production of red blood cells and the formation of the circulatory system. In cells, copper binds to proteins, an element important for oxidation and reduction, and oxygen metabolism (Yang et al., 2002).

Copper is found in several forms in the soil. In the soil solution as copper chloride, copper nitrate, copper sulfate and its concentration is low and depends on the immobilization of copper with organic compounds. The soil of this heavy metal also contains an exchange form that can be displaced from the complex by an excess of another cation (Carvalho et al., 2015).

Acute lead poisoning (Pb) can lead to impaired renal, reproductive and cerebral function. The teratogenic effects of lead are particularly pronounced. Lead poisoning also inhibits hemoglobin synthesis, characteristic of the cardiovascular system and acute and chronic damage to the central nervous system (CNS) (Debnath et al., 2019). Other chronic effects include anemia, fatigue, gastrointestinal problems and anoxia. Lead can cause difficulties during pregnancy, high blood pressure, muscle and joint pain (Jiwan et al., 2011).

People with elevated levels of lead complain of constipation, nausea , vomiting, abdominal pain attacks. To avoid these and the unpleasant symptoms listed above, it is possible to seek to replace lead with other non–toxic substances. It is also possible to use personal protective equipment – respirators, gloves, special headgear. Workers with lead should take vitamin C: this would help remove accumulated lead from the body (Wani et al., 2015).

People can be exposed to nickel (Ni) by inhaling air, eating food, drinking water or even smoking cigarettes. Excessive levels of nickel have the following consequences: higher chances of lung cancer, nasal cancer, laryngeal cancer and prostate cancer. The following diseases are characteristic: respiratory failure, pulmonary embolism, malformations, asthma and chronic bronchitis, allergic reactions, heart disorders. Nickel vapors irritate the respiratory tract and can cause pneumonitis (Das et al., 2019).

Zinc (Zn) is considered relatively non – toxic, but excessive amounts can disrupt growth and reproduction processes. Clinical signs of zinc toxicosis: vomiting, diarrhea, bloody urination, hepatic failure, renal failure and anemia (Chasapis et al., 2012).

Inorganic forms of mercury (Hg) cause spontaneous abortion, congenital malformations and gastrointestinal disorders. Poisoning by its organic forms causes erection (abnormal irritation of the organ or body part or sensitivity to stimulation), acrodynia (a rosacea characterized by a rash on the hands and feet), gingivitis, stomatitis. It is also characterized by neurological disorders, complete brain and CNS damage, which are also associated with congenital malformations (Rice et al., 2014).

The toxicity of mercury depends on its form (elemental mercury, inorganic mercury or organic mercury). Accordingly, the exposure scenarios for these different forms of mercury are very different and complicate the assessment of toxicity. Approximately 80 % of inhaled mercury vapor is trapped in the lung tissue where it penetrates the blood – brain barrier. Inhalation of mercury vapor has been reported to cause the following symptoms: tremor, insomnia, memory loss, nerve and muscle changes, headaches and effects on the kidneys and thyroid gland. The International Agency for Research on Cancer considers methylmercury to be potentially carcinogenic (Vejrup et al., 2013).

Due to toxicity and effects on living organisms, heavy metals must be controlled. Most of the researchers pay attention to the monitoring of concentrations of heavy metals in humans.

The effects of heavy metals on the human body are very different: the magnitude of the effect depends on the concentration of the metal and the duration of action. The most common disorders are: central nervous system disorders, respiratory disorders, nausea, vomiting and abdominal cramps.

1.3. Physical, chemical and biological properties of yeast

Yeast – unicellular fungi, which can be ovoid, circular or cylindrical shape. Yeast could be divided into 2 categories:

1) fermented yeast: yeasts are mainly used in the bread and wine industry;

2) oxidized yeast: a type of yeast with strong oxidation potential mainly used in the oil refining industry and wastewater treatment process (Qadir, 2019).

Brewer's yeast is made from a unicellular fungus called *Saccharomyces cerevisiae*. *Brewer's* yeast is a rich source of minerals, especially chromium. It could be used as trace element that helps the body maintain normal blood sugar, selenium, protein, and B – complex vitamins.

Yeast usually grows in an acidic environment with pH of 5.0 to 6.0 and an optimal growth temperature of 25 to 30 °C. They are resistant to acids, resistant to osmotic pressure, high temperatures and highly metabolic efficient. In addition, yeast has a good enzyme system, can adapt to a variety of environments and is widespread in soil, light water, the sea, the human body surface and inside the body. Different yeast populations are distributed in different environments and community changes reflect changes in environmental conditions. Trichosporon sp., Rhodotorula sp., Candida sp. and Cryptococcus sp. can be used as indicators of water pollution. Studies have shown that yeast can degrade various macromolecular substances such as phenol and glyceride (Qadir, 2019).

Yeast can convert organic matter into non – toxic unicellular proteins. If wastewater enters water bodies without treatment, it would cause significant environmental pollution. Yeast treatment technology can reduce the amount of oil in wastewater from 10.000 mg/l to 100 mg/l, which is not currently implemented with other biological treatment methods (Qadir, 2019).

Yeast identification involves the identification of both morphological and cultural traits. From the morphological features, it is necessary to determine the relative size and shape of vegetative cells, as well as whether they reproduce by division or buds. If the propagation process takes place in buds, it is necessary to identify whether the buds are formed anywhere in the cell or only at the ends of the elongated cells. It is important to recognize whether the buds are separated from the stem cell by abstraction or by the formation of a transverse wall. In addition, it is necessary to determine whether the buds separate quickly after their formation or whether they tend to form groups. In the latter case, cells, if elongated, can form a branched structure very similar to fungus (Reis et al., 2013).

Nowadays, yeast exploration has a major impact on the supply of renewable energy because they can ferment carbohydrates and thus produce ethanol. Significant progress has been made in the field of medicine in the production of human therapeutic proteins using yeast genetic engineering (Silva et al., 2009).

The word 'Saccharomyces' comes from the Greek and means 'sugar mold' and 'cerevisiae' comes from the Latin and means 'beer'. This is probably the most useful species of yeast, as it has been used in baking and cooking.

This eukaryotic model is one of the most intensively studied model in the molecular and cell biology of organisms, similar to E. coli as a model prokaryote. The shape of *Saccharomyces cerevisiae* cells may be round or oval with diameter of 5 – 10 µm. Typically, yeast cells have those parts: cell wall, cytoplasm and inclusions, cytoplasmic membrane, single nucleus, mitochondria, Golgi apparatus, vacuoles, cytoskeleton (Stanila, 2013).

This type of yeast can withstand stressful conditions. They are characterized by high fermentation efficiency, rapid growth, efficient sugar consumption, the ability to produce and consume ethanol. This type of yeast is also characterized by tolerance to high ethanol concentrations, low oxygen levels and cellular activity in an acidic environment, which is a major potential for its industrial application (Reis et al., 2013).

Yeast S. cerevisiae is not difficult to grow in large quantities. They can be easily grown using simple fermentation methods. The biomass of these yeast could be obtained from food and/or beverage industries. For example, it is easy to obtain *S. cerevisiae* from the fermentation industry compared to other types of microbial biomass waste. *S. cerevisiae* is generally considered as a safe type of yeast, so biosorbent made from *S. cerevisiae* can be easily applied in research, especially in the study of metal – yeast interactions at the molecular level (Wang et al., 2006). Using this type of yeast, lead, cadmium, copper, zinc, cobalt, silver, strontium and cesium can be removed from aqueous solutions (Can et al., 2010).

Over the last two decades, scientific research has shown that not only *Saccharomyces cerevisiae*, but also other methylotrophic yeasts, can grow in a culture medium where methanol is the only source of carbon and energy, can be adapted to remove heavy metals from contaminated water solutions. The following genera are distinguished: Candida and Pichia (Can et al., 2010). The Candida yeast species is used to remove copper, iron and zinc from aqueous solutions (Anaemene, 2012). Meanwhile, the species of Pichia yeast originated in the kingdom of fungi; subtype *Saccharomycotina*; from the class *Saccharomycetes*; from the order of *Saccharomycetales*; from the family Sacchamomycetaceae; from the genus Pichia and the species P. pastoris. Some yeasts of the genus Pichia are found in soil, freshwater, and insects (Silva, 2009). Psyche, as eukaryotic fungal organism, is easy to grow (Goncalves et al., 2013). These species of yeast are used to remove palladium and gold from aqueous solutions (Elahian et al., 2019).

The focus was on the yeast species of *Saccharomyces cerevisiae* because this species captures the widest range of heavy metals to be removed.

1.4. Technologies for the removal of heavy metals from aqueous solutions

The food and water are often contaminated with a variety of chemicals and HM such as arsenic, lead, cadmium, chromium or mercury, which are linked to many diseases. Although the impact of heavy metals on the population is not a new problem, the important question remains – what is the best way to reduce the amount of HM in the environment remains. Many technologies are inefficient and others are too expensive to use in practice. This has led researchers to look for alternative solutions (Qadir, 2019).

Heavy metals are hazardous to the environment, so different technologies are used to remove HM from aqueous solutions. Table 1.2 presents heavy metal removal technologies.

Table 1. 2. Methods for removing heavy metals from aqueous solutions (Bilal et al., 2013)

Methods						
Chemical precipitation	Ion exchange	Membrane filtration	Flotation	Electrochemical separation	Coagulation	Adsorption
Hydroxide		Ultrafiltration	Dissolved air flotation	Electroplating		Carbon nanotubes
Sulfide		Nanofiltration	Ionic flotation	Electrocoagulation		Activated charcoal
Chelated		Reverse osmosis	Particle flotation	Electroflotation		Bioadsorbents
		Electrodialysis				Nanoparticles

Chemical precipitation

Chemical deposition is an effective heavy metal removal technology that is simple and inexpensive. During precipitation, chemical solutions react with heavy metal ions to form insoluble hydroxide (OH^{-}), carbonate (CO^{3-}) or sulfide (S^{2-}) precipitates (Mahmood et al., 2011). The main types of chemical precipitation are hydroxide, sulfide and chelate precipitates. Hydroxide deposition is most commonly used in industry. The reaction proceeds best in an alkaline medium when the pH ranges from 8 to 11 (Bilal et al., 2013).

Ion exchange

Ion exchange reactions can be applied not only to the removal of heavy metals but also to the purification of precious metals from aqueous solutions (Gaikwad, 2010). The reaction takes place between the liquid (metal solution) and solid (ion exchange resins) phases. Ion exchange resins are capable of absorbing positive or negative ions from electrolyte solutions, replacing them in solution with an equivalent amount of other ions with the same charge.

Membrane filtration

Membrane filtration is applied to remove heavy metals from wastewater. Membrane filtration is based on the separation of particles of different sizes using different membranes or pressures (Bilal et al., 2013).

Depending on the size of the pollutant particles in the solution, four types of membrane filtration can be distinguished: reverse osmosis, ultrafiltration, nanofiltration and electrodialysis. The efficiency of membrane filtration can be increased by additional treatment of membranes with chemical reagents (Khulbe et al., 2018).

Flotation

This decontamination technology is based on the separation of heterophases using air bubbles: the contaminated sample is saturated with air, then reduced by pressure, from which air bubbles are released, which float the dirt. Contaminants are collected on the surface of the water and removed from it. Three main types of flotation are used to remove heavy metals from contaminated water: flotation of dissolved air, ions and particles (Ahmed et al., 2013).

Electrochemical separation

Electrochemical separation is the movement of ions or complex ions under the action of a direct current towards electrodes and their subsequent discharge (Qodah et al., 2017). The application of this technology requires high investment and operating costs (especially high electricity costs) and is therefore not widely used (Bilal et al., 2013). The main types of electrochemical disposal used are: electroplating, electroflotation, electrocoagulation.

Coagulation

Coagulation is a method of cleaning aqueous solutions (wastewater) from heavy metals. Coagulation technology is based on the adhesion of colloidal particles to larger formations and their sedimentation. Various materials (aluminum or ferrous sulphate, ferric chloride, etc.) are often used to improve adhesion efficiency – coagulants and constant mixing of the mixture. The efficiency of the process is highly dependent on the temperature and pH of the medium (Un et al., 2015). Molecular electric traction forces play a major role in coagulation. The particles stick together and swell due to gravitational forces, inertial forces, Brownian motion or gravitational forces. When agglomerates form, the process of disintegration of larger particles also takes place.

The intensity of coagulation depends on the probability of the particles colliding: the more often the particles collide, the more likely they are to stick together. Coagulation rate depends on particle size, particle electric charge distribution, temperature and pressure (Saied et al., 2016).

Adsorption

The phenomena associated with changes in concentrations at the phase contact point are called sorption phenomena. Sorption – the ability of solids to absorb dissolved substances, vapors or gases from their environment (Lietuvninkas, 2012).

The biosorption process involves a solid phase and a liquid phase containing a dissolved type of substance to be sorbed (sorbate, metal ion). The process continues until balance between the amount of solid bound sorbate species and the proportion remaining in the solution. Soluble (sorbate) molecules predominate in the solution, they are not present in the sorbent particles. This imbalance between the two environments creates a driving force for soluble species.

The solid on the surface of which the adsorption takes place is called the adsorbing surface, the adsorbable material is called the adsorbent, the part of it that has already adsorbed is called the adsorbate. Solids can adsorb gases, dissolved molecules and ions. The adsorbent does not adsorb to the entire surface, but only to certain active sites. The extent of adsorption is expressed as the number of moles of adsorbed material per unit mass of adsorbent (mol/kg) (Edet et al., 2020).

It has been mentioned that the active centers on the surface of the adsorbent adsorb. Each active site connects to a single molecule and a saturated monomolecular adsorption layer is formed. The adsorbed molecules are bound to the active sites for some time and then cleaved – the desorption process takes place. At equilibrium, part of the adsorbent surface is coated with the adsorbent and the other part is free (Edet et al., 2020).

The adsorption process consists of 3 stages: diffusion to the surface of the adsorbent, diffusion of molecules into pores, adsorption of molecules on the walls. The following adsorbents are most widely used: activated carbon, silica gel, zeolite or ion exchange resin.

Activated carbon is specially treated carbon from which resinous substances have been removed from the pores and thus the adsorption surface has been increased. It is derived from a variety of organic raw materials, solid fuels: peat, coal, anthracite or wood and its waste. Activated carbon is hydrophobic and flammable. According to the size and shape of the particle, activated carbon is divided into granular carbon and carbon in powder form. Granular carbon is used in adsorbers with a fixed layer of adsorbent and powder is used for water purification (Kassem, 2014).

Silica gel is hydrophobic, can adsorb large amounts of adsorbent. Coarse, medium porosity and low porosity silica gel are distinguished. The latter is used for adsorption of gases and vapors, the other two – vapors of organic compounds. Because the regeneration temperature of silica gel is low, lower energy consumption is required and, therefore, the cost of mass production is lower (Yan et al., 2018).

Zeolites are aluminosilicates that contain alkali and alkaline earth metal oxides. Natural zeolites include siobesite, natrolite, gesnite and others. Meanwhile, among the synthetic zeolites it can assign aluminosilicates of sodium, calcium and other metals. In terms of structure, zeolites belong to a group of scaffolds in which the tetrahedra join at all four vertices to form an infinite, three–dimensional scaffold, with the voids within it. About half of the volume of zeolites consists of cavities, voids and channels. The spaces of many zeolites are interconnected into long and broad–shaped channels and vary according to the shape of the minerals (Corner et al., 2015).

Ionites are macromolecular and insoluble but swelling in water, relatively strong substances. They can adsorb positive and negative ions from electrolytic solutions in exchange for an equivalent amount of other ions containing the same charge (Ahmad et al., 2015).

The adsorption process depends on the adsorbate concentration, the total surface area of the adsorbent, the temperature of the gas and the adsorption layer, the characteristics of the adsorbate molecules, the porosity (size and shape) of the adsorbent microstructure and the chemical activity of the adsorbent (polarity and reactivity). The rate of adsorption depends on the rate of diffusion into the pores of the adsorbent, which depends on the size of the adsorbent particles, the degree of saturation of the layer (Edet et al., 2020).

Thus, all adsorbents except activated carbon adsorb polar molecules better than non–polar ones. For this reason, activated carbon is mainly used: it is not expensive, after activation it is stored in airtight containers.

The adsorption process ends when the maximum amount of adsorbate accumulates on the surface of the adsorbent and equilibrium is reached. By lowering the temperature, the process can start again and continue for some time before saturation.

Numerous studies have been conducted to develop cheaper and more efficient adsorbents. It is proposed to use a variety of natural materials, biosorbents, industrial and agricultural waste. These materials could be used as sorbents to remove heavy metals. Sorbents can be clay minerals such as bentonite, kaolinite, montmorillonite, other minerals (zeolite, vermiculite, pumice), agricultural waste (coconut shells, walnut husks, corn bran), biosorbents (lichens, algae, bacteria) (Hlihor et al., 2009).

Biosorption could be considered as one of the alternative method which can be used in water treatment plants (Abbas et al., 2014).

HM are adsorbed on the biomass surface, thus the biosorbent is enriched in metal ions and bioaccumulates sorbate. This mode of accumulation of active living cells (bioaccumulation) depends on the metabolic activity of the cell (Hlihor et al., 2009).

Some types of biosorbents are broad – spectrum, binding and collecting most HM that lack specific activity, while others are specific for certain metals (Ahalya et al., 2003).

Depending on cellular metabolism, biosorption mechanisms can be divided into:

1) dependent on metabolism;
2) independent of metabolism.

The differences between bioaccumulation and biosorption are important when using biomass for metal separation/concentration purposes. Biosorption has some inherent advantages over the bioaccumulation processes listed in Table 1.3.

Table 1. 3. Comparison of biosorption and bioaccumulation (Hlihor et al., 2009)

Feature	Biosorption	Bioaccumulation
Price	Usually low. Costs mainly include transportation and other simple handling fees.	Usually large. The process involves living cells; cell maintenance is expensive.
pH	The pH of the solution has a significant effect on the uptake of biomass. However, the process can be performed under various pH conditions.	The process can be performed under various pH conditions.
Temperature	Because the biomass is inactive, temperature does not affect the process.	Temperature strongly affects the process.
Maintenance, storage	Easy to store and use.	Additional energy is required.
Selectivity	Weak.	Greater opportunities than biosorption.
Versatility	High.	Low.
Degree of absorption	Very high.	Uptake is usually low.
Absorption rate	Fast.	Slower than biosorption.
Toxicity	High favorable conditions.	Depends on the toxicity of the pollutant.
Regeneration and reuse	High potential for biosorbent regeneration by reusing many cycles.	The possibilities – very limited.
Return of toxic substances	Acidic or alkaline solutions have proven to be an effective medium for the recovery of toxic substances.	Biomass cannot be used for another cycle.

The biosorption process begins with the selection of different types of biomass. Immobilization is performed to increase the efficiency of metal uptake. The adsorbed metal is removed by desorption and the biosorbent can be used for further processing. Below, Figure 1.1 shows a generalized biosorption process for heavy metal removal.

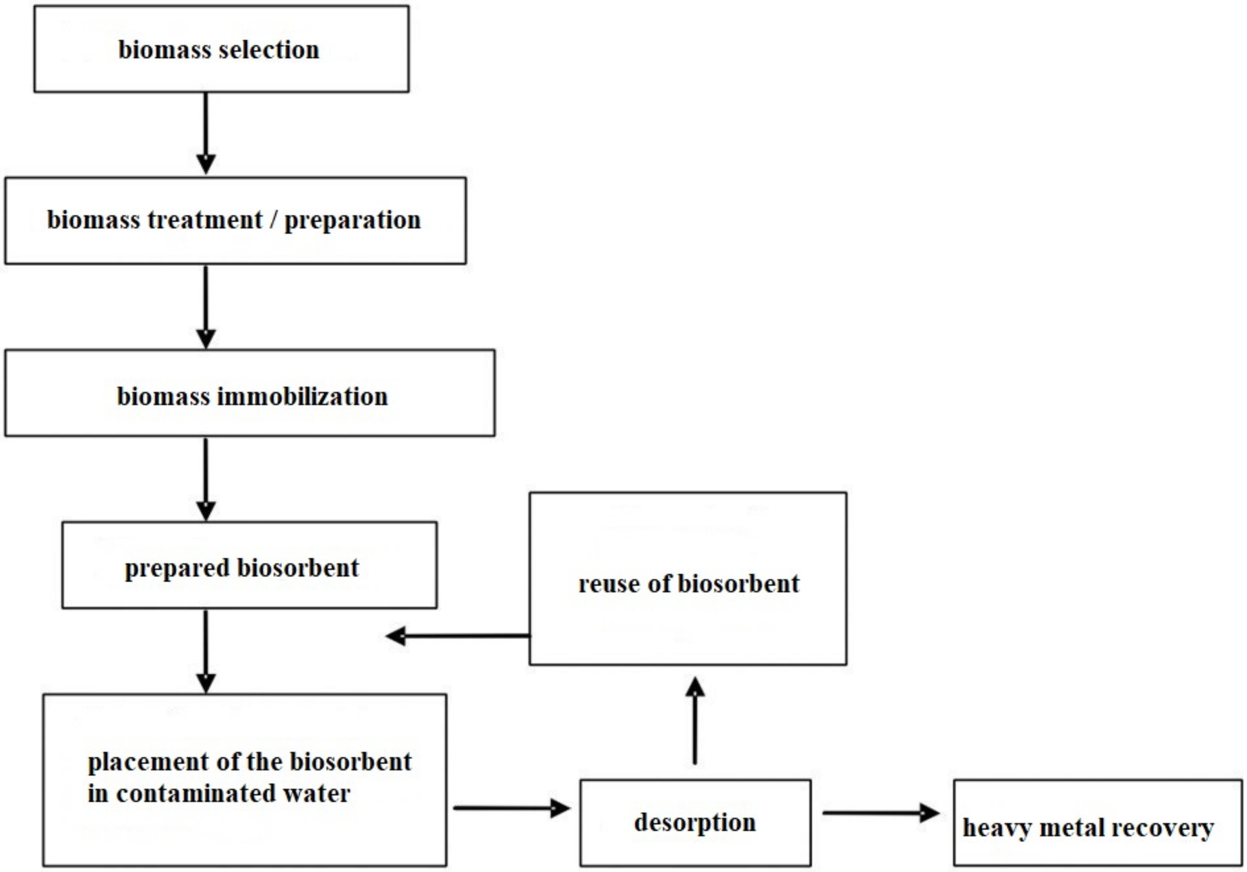


Fig. 1. 1. Schematic diagram of the biosorption process (Hlihor et al., 2009)

The efficiency of metal uptake from biomass is essential for industrial biosorption applications as it provides information about the process equilibrium that is necessary for design of the equipment. The biosorption process is affected by temperature, which affects biosorption rates, activity of functional groups in biomass and competition for metal ions. Increased biomass concentrations cause interference at the junctions.

In addition, biosorption can be classified as additional cell accumulation, cell surface sorption, and intercellular accumulation (Ahalya et al., 2003).

An important feature of biosorption is the ability to sorb metal ions when the cell is no longer metabolically active i.e., dead. Residual cell debris, such as cell walls, can still be an effective biosorbent.

Biomass can be:

1. industrial waste, which should be collected free of charge;
2. organisms which may accumulate in large quantities in nature;
3. fast–growing organisms, in particular those grown or propagated for biosorption purposes.

At the molecular level, adsorption occurs due to the interaction between the surface and the sorbed material. Two types of molecular adsorption are distinguished: physical and chemical adsorption.

Physical adsorption

This is the result of the attraction of intermolecular forces between the adsorbent and the adsorbate. In this case, physical forces are created, which are called Vander Wals connections. Due to these connections, the sorbed element is retained on the surface of the sorbent. The above process is reversible. The interaction energy between the sorbent and the adsorbate is usually higher than the condensation force, so no additional energy is required for process activation (Halnor, 2015).

Chemical adsorption

This chemical interaction, otherwise activated adsorption, is the interaction between the solid and the element to be sorbed. This process is irreversible. Both exothermic and endothermic processes are characteristic. A large amount of activation energy is usually required to initiate chemical sorption processes (Halnor, 2015).

Characteristics distinguishing chemical adsorption from physical:

1. Temperature dependence. The amount of physically adsorbed molecules in the adsorbent always decreases with increasing temperature. Meanwhile, the chemisorption capacity increases with increasing temperature (Mhemeed, 2018).

2. Process activation energy magnitude. Physical adsorption is characterized by low activation energy, as the adsorption rate is proportional to the number of collisions of the adsorbent molecules with the adsorbent surface. Chemisorption is characterized by an activation energy that is close to the reaction’s energy. The adsorption process accelerates as the temperature increases (Halnor, 2015).

3. Magnitude of the thermal effect of adsorption. The physical adsorption heat is close to the heat of condensation of the adsorbent and usually does not exceed 10 – 30 kJ/mol, and the heat of chemical adsorption reaches up to 80 – 600 kJ/mol. In both cases, the heat of adsorption depends on the degree of filling of the adsorbent (Rani et al., 2015).

4. Process equilibrium parameters. Physical adsorption is an equilibrium process. The balance stabilizes very quickly. Chemisorption can be at equilibrium and be irreversible (Halnor, 2015).

5. Process selectivity. Physical adsorption is nonspecific and chemical adsorption is specific and occurs only when the adsorbate and adsorbent can form a chemical bond (Mhemeed, 2018).

Adsorption kinetics studies are performed to determine the uptake time of metals from a liquid. The aforementioned studies are based on mathematical models (Olaofe et al., 2015). Adsorption kinetics can provide information on the mechanisms occurring between the adsorbate and the adsorbent and help to understand the adsorption process. Lagergren's first and second order kinetics and internal particle diffusion models are most commonly used in process modeling (Yadla et al., 2012).

During adsorption, the concentration of metals on the surface of the sorbent increases until dynamic equilibrium is reached (Halnor, 2015). It is assumed that the sorption material has a finite number of sorption sites, so when the maximum limit of sorption capacity is reached, the concentration in the solution stops decreasing. This dependence is well represented by the function of metal concentration and sorption capacity, which shows how metal ions are distributed between liquid phase and the surface of the adsorbent at constant pH and temperature. The graph of the function is called the adsorption isotherm (Foo et al., 2010).

Many isotherm equations have been developed, such as Langmuir, Freundlich, Toth, Redlich – Peterson, Dubinin – Radushkevich, Temkino and others. Langmuir and Freundlich isotherms are most commonly used to model the adsorption process.

Langmuir isotherm

The adsorption isotherm of Langmuir was developed in 1916. This isotherm is used to quantitatively compare the efficacy of various biological sorbents.

It is important to mention that not all surfaces of the adsorbent are adsorbed, but only the active centers in it, which bind the adsorbent molecules by valence or intermolecular forces. Each active center binds to one molecule and forms monomolecular adsorption layers (Dada et al., 2012).

The adsorbed molecules are attached to the active sites for some time, then detached – the desorption process begins. Equation of Langmuir isotherm:

$$\Gamma = \Gamma_{\infty} \frac{c}{k + c} \tag{1.1}$$

where

Γ – adsorption

$\Gamma\infty$ – marginal adsorption

k – empirically determined constant

C – is the concentration of the solute (if the equation applies to solutions).

Langmuir's theory is based on a monomolecular layer of adsorbed material and is only valid if the surface of the adsorbent is smooth.

Freundlich isotherm

The Freundlich isotherm differs from the Langmuir isotherm in that the Freundlich model does not have a saturation zone of the adsorbent surface: the amount of adsorbed material still increases even at high concentrations, albeit less than at the beginning of the adsorption process (Fig. 1.2) (Czikkely et al., 2018).

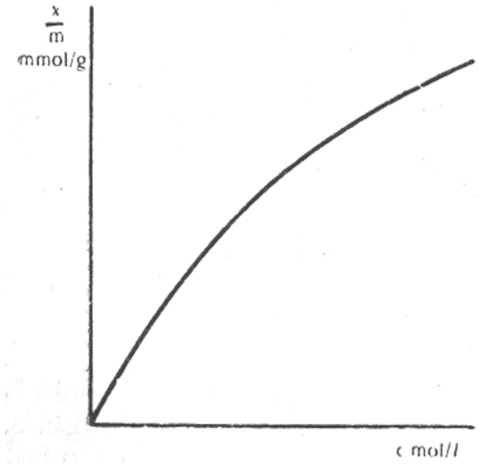


Fig. 1. 2. Freundlich isotherm

Freundlich isotherm equation:

$$\Gamma = \frac{x}{m} = k \cdot C^{\frac{1}{n}}, \qquad \Gamma = \frac{x}{m} = k \cdot p^{\frac{1}{n}} \tag{1.2}$$

where

x – amount of adsorbed material, mg

m – mass of the adsorbent, mg

C – equilibrium concentration of the adsorbent, mg/l

k – constant, the value of which is determined empirically (this is the amount of substance adsorbed on 1 g of adsorbent at an equilibrium concentration of 1)

n – empirically determined constant.

The Freundlich adsorption isotherm equation is only valid at mean adsorbent concentrations. At low or high concentrations, the Langmuir equation is used to calculate adsorption.

Graphically, the Langmuir and Freundlich isotherm curves look like this (Fig. 1.3):

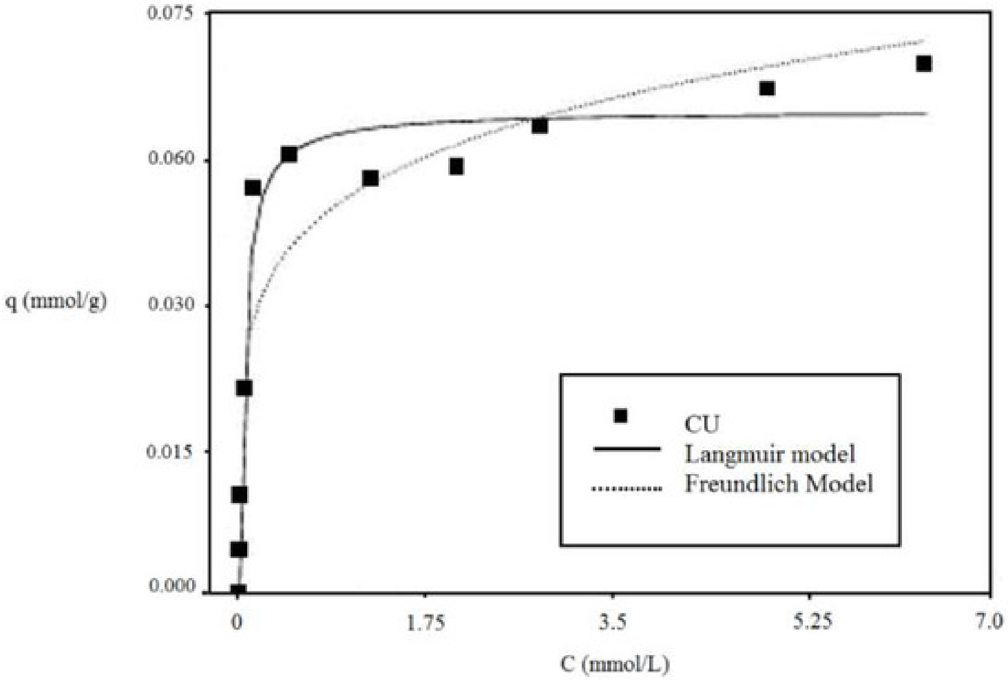


Fig. 1. 3. Langmuir and Freundlich isotherms (Czikkely et al., 2018)

The Langmuir isotherm can be described by the following equation (Dada et al., 2012):

$$q_{qe} = \frac{k_L Q_m C_{eq}}{1+k_L C_{eq}} \tag{1.3}$$

where

q_{qe} – amount of accumulated metal per gram of biosorbent material, mg/g

C_{eq} – initial concentration of the pollutant in the solution, mg/l

k_L – Langmuir constant, l/mg

Q_m – maximum adsorption capacity, mg/g.

The Freundlich isotherm can be described by the following equation (Salam et al., 2011):

$$q_{eq} = k_F C_{eq}^{\frac{1}{n}} \tag{1.4}$$

where
q_{eq} – amount of accumulated metal per gram of biosorbent material, mg/g
C_{eq} – initial concentration of the pollutant in the solution, mg/l
k_F, n – constant.

There are many methods which could be usable to reduce the concentration of heavy meals in solutions. In order to decide which method is the best, would be great to identified the problem and the aim of the research.

1.5. Technologies for the removal of heavy metals from contaminated water using yeast

Analysis of literature data has shown that yeast biomass can be successfully be used for biosorption of metals such as arsenic, silver, gold, cadmium, chromium, copper, lead, nickel, mercury and zinc. Yeasts of the genera *Saccharomyces*, *Candida*, *Pichia* are effective metal's biosorbents. Most yeast can sorb a variety of metals or be specific for only one heavy metal.

The water used by the population, together with industrial and surface wastewater, is collected and travels to sewage treatment plants, where it is treated. Physical (mechanical), biological and chemical purification processes are distinguished (Demirbas et al., 2017).

The inflowing wastewater enters the receiving chamber, where it flows through the gratings, thus trapping and removing large sediments. The wastewater then travels to an aerated sand trap. It is constantly supplied with air in order to keep the organic matter in the wastewater on the surface and to prevent it from settling together with sand or other minerals. After aerated sand traps, the leaked effluent enters the primary precipitators. Mechanically treated wastewater travels to aero tanks where biological treatment is performed.

During biological treatment in aero tanks, bacteria remove nutrients from wastewater. Blowers provide an extra amount of warm air, which stimulates the growth of nutrient–fed bacteria. The effluent then enters secondary precipitators where activated sludge is deposited.

It can also assign the adsorption process to the tertiary, chemical and wastewater treatment process.

Yeast, in addition to mold and fungus, has great practical significance for the biosorption of heavy metals. Due to their high growth rate, they are better biosorbent for removing heavy metal ions.

Yeast cells are much larger than bacterial cells, so size may be one of the indicators to differentiate these species (Hlihor et al., 2009).

Yeast, used in biosorption, has metal separation properties and can be used to reduce the concentration of heavy metal ions in solution from ppm to ppb. Yeast can release dissolved metal ions from diluted complex solutions (Stanila, 2013). The main advantages of biosorption over traditional wastewater treatment methods are cheapness, high efficiency, biosorbent regeneration and the ability to recover metals.

Concentrations of hazardous chemicals in sewage sludge are limited by the "Requirements for the Use of Sewage Sludge for Fertilization and Reclamation" LAND 20 – 2005. Table 1.4 shows the categorization of sewage sludge according to heavy metal concentrations.

Table 1. 4. Categorization of sludge according to heavy metal concentrations (LAND 20 – 2005)

Sludge category	Concentration of heavy metals, mg/kg						
	Pb	Cd	Cr	Cu	Ni	Zn	Hg
I	< 140	< 1,5	< 140	< 75	< 50	< 300	< 1,0
II	140 – 750	1,5 – 20	140 – 400	75 – 4000	50 – 300	300 – 2500	1,0 – 8,0
III	> 750	> 20	> 400	> 4000	> 300	> 2500	> 8,0

As can be seen from Table 1.4, sludge belonging to sludge class I has the lowest pollution with heavy metals. Meanwhile, class III sludge identifies as having the highest pollution with heavy metals.

Göksungur et al. performed experiments on biosorption of cadmium and lead ions from aqueous solutions using yeast (*S. cerevisiae*) biomass. First of all, yeast cells were treated with ethanol. Secondly, cells were heated in order to increase their biosorption capacity. The highest adsorption capacity (15.63 and 17.49 mg/g Cd (II) and Pb (II), respectively) was obtained in ethanol – treated yeast cells. Lastly, the effect of initial metal concentration and pH on biosorption using ethanol – treated yeast was investigated. The Langmuir model and the Freundlich equation were applied to the experimental data. It was found out that the Langmuir model correlated better with the experimental data. The maximum adsorption values (q_{max}, mg/g) of Cd (II) and Pb (II) were determined at 31.75 and 60.24. Other biosorption experiments were performed with Cd (II) and Pb (II) in combination with Cu (II), and the biosorption capacity of yeast biomass for all metal ions was lower than under non – competitive conditions (Göksungur et al., 2005).

Mapolelo and Torto evaluated the sorption properties of yeast cells characterized by *Saccharomyces cerevisiae*. Metal (Cd and Pb) concentrations were determined using flame atomic absorption spectrometry (FAAS). Parameters which can affect metal uptake are: pH, incubation time, yeast biomass content and effects of glucose concentration (Mapolelo et al., 2004).

Table 1.5 below provides summary information on the ability of different yeast species to sorb cadmium and lead (Table 1.5).

Table 1. 5. Biosorption of cadmium and lead using different yeast species (Hlihor et al., 2009)

Metals	Yeast species	pH	Temp. °C	Adsorption	
				mg/g	%
Cd (II)	*S. cerevisiae*	5,0	25	6,81	–
Cd (II)	*S. cerevisiae*	9,2	30	20	75
Cd (II)	A. pullulans	–	28	51,8	4,1
	Cr. laurentii	–	18	2757,8	51,8
	Cy. capitatum	–	18	732,8	45,8
	H. anomala	–	28	2175,3	33,3
	P. fermentans	–	28	109,9	6,7
	R. rubra	–	18	38,1	0,8
	S. cerevisiae	–	28	62,3	5,6
	Sp. roseus	–	18	362,8	15,4
Cd (II)	S. cerevisiae entrapped in polyurethane foam	4,5 – 8,0	–	2,7	66
Cd (II)	S. cerevisiae modified by crosslinking cystine with glutaraldehyde	< 6,0	–	11,63	86
Pb (II)		< 6,0	–	47,87	99,5
Cd (II)	*S. cerevisiae*	5,0	–	35	≈ 90,0
	K. fragilis	5,0	–	40	≈ 90,0
Cd (II)	*S. cerevisiae*	6,0	18	–	88
Cd (II)	Streptomyces sp. K33	6,0	28	38,49	70
	Streptomyces sp. HL–12	6,0	28	24,24	70
Cd (II)	*S. cerevisiae*	7,3	25	36,32	60

The results showed that the sorption of the tested metals using yeast depends on the yeast biomass content, pH and incubation time. Cadmium is a toxic agent to microorganisms, but there are yeast strains that are resistant to this metal. The mechanisms of resistance depend on the ability of the yeast to convert the adsorbed metal into composite polymeric compounds that are non – toxic to cells.

Trivalent chromium (Cr (III)) could be found in natural water. Almost all hexavalent chromium (Cr (VI)) compounds are of anthropogenic nature. Cr (VI) is more important than Cr (III) in controlling water pollution. Normal chromium treatment technologies include reduction/precipitation, chemical sorption and ion exchange.

Yeast biomass has been shown to be useful in biosorption studies in which Cr have been removed from contaminated water. Liu et al. studied the biosorption of Cr (VI) by the yeast strain SPSC01. Based on a preliminary experiment, the equilibrium time for Cr (VI) absorption was found to be 48 hours. Optimal pH, initial Cr (VI) concentration, initial biosorbent concentration and temperature conditions were also identified at 2.50 mg/l, 5.0 – 10.0 g/l (dry weight) and 30 ºC, respectively. The absorption capacity has been measured to be about 14 mg/g under optimal conditions (Liu et al., 2008).

Hlihor et al. conducted a study to evaluate *Saccharomyces cerevisiae* as a Cr (III) and Cr (VI) biosorbent. Yeast cells were immobilized on a porous glass (CPG), packed in a mini – column and added to a flow injection system. The effects of chemical and physical factors influencing the biosorption process were evaluated to select optimal analytical conditions for S. cerevisiae to retain Cr. Cr (III) retained immobilized cells and Cr (VI) retained CPG. Table 1.6 provides summary information on the biosorption capacity of different types of yeast for chromium ions (Hlihor et al., 2009).

Table 1. 6. Chromium biosorption using different yeast species (Hlihor et al., 2009)

Metals	Yeast species	pH	Temp., ºC	Assimilation	
				mg/g	%
Cr (VI)	S.cerevisiae	–	25	32,6	–
Pb (II)		–	25	43,3	–
Ni (II)		–	25	270,3	–
Cr (VI)	*Candida* utilis	–	30	1,75	90,0
Cr (VI)	S. cerevisiae	4.5,…,5.5	–	120,0	99,5
Cr (III)	S. cerevisiae	4	25	12,3	74,0

Experimental data have shown that the efficiency of Cr uptake using *Saccharomyces cerevisiae* yeast decreases at lower pH.

Under optimal conditions for the adsorption of copper ions by yeast, Zu et al. found out that negative pressure cavitation can improve the bioadsorption potential of copper ions. However, pretreatment of yeast has a greater effect on bioadsorption. During adsorption, the intercellular pH of yeast gradually increases. These results could suggest that cavitation due to negative pressure can force heavy metals to migrate from the cell surface to the interior of the cell and render the surface of the yeast rough (Zu et al., 2006).

Padmavathy investigated the biosorption of nickel (II) ions at different initial concentrations of metal ions. The effect of temperature on sorption was more significant at lower concentrations of nickel (II) ions compared to higher ones. Protonated yeast biomass has the highest adsorption of nickel (II) ions at 27 ºC, when the initial concentration of nickel (II) ions is 400 mg/l and the initial pH is 6.75. At an initial nickel (II) ion concentration of 400 mg/l, the biosorption capacity decreased from 9.8 to 9.3 mg/g, while at a lower initial concentration of 100 mg/l it decreased from 8.2 to 4.9 mg/g as the temperature was raised from 27 ºC to 60 ºC. The results showed that the biosorption of nickel (II) ions on food yeast was spontaneous and exothermic in nature. Biosorption in yeast is highly dependent on parameters such as pH, initial metal ion ratio and initial biomass concentration, growth conditions, the presence of various ligands and competitive metal ions in solution and to some extent temperature (Padmavathy et al., 2008).

The adsorption method can be used when the concentrations of HM in the water are low or when a low concentration of suspended solids (about 10 – 15 mg/l) prevails (so as not to clog or cover the adsorbent layer).

In 2016, Irawati and other researchers conducted experiments with activated sludge to determine the ability of yeast (a biosorbent) to remove mercury, copper and lead compounds from contaminated water.

Yeast isolate was taken from sludge (which was activated) at industrial wastewater treatment plants in Rungkut, Surabaya, Indonesia. The yeast isolate was grown in broth consisting of 2 % peptone, 1 % yeast extract and only 1% dextrose. Agar was prepared by adding 2 % pure agar. The cells were incubated at 37 °C on a shaker at 200 rpm. Growth was observed by measuring the optical density at 600 nm. The biosorption of copper, cadmium and lead was determined by AAS, the biosorption of mercury by SMEs (mercury evaporator).

It was found out that the prepared isolate was resistant to copper, lead, mercury and cadmium. Copper and lead resistance in isolated was 13 mM and 17 mM. It was concluded that isolate ES10.4 was resistant to copper, cadmium, lead and mercury (Irawati et al., 2016).

It was observed that the isolate felt best in a medium containing copper. Meanwhile the growth of the isolate in the presence of lead was slower than of copper. On the other hand, the growth of the isolate decreased in the presence of mercury and cadmium.

Massoud et al. 2019 analyzed the biological purification process of heavy metals using the yeast species *Saccharomyces cerevisiae*.

Studies have shown that the temperature is one of the most important parameters for bioremediation process. In the temperature range from 15 to 40 °C, the highest biosorption capacity of *S. cerevisiae* Pb, Ni and Cr ions was observed at 25 °C (Massoud et al. 2019).

Meanwhile, Rivas et al. examined the process of removing cadmium from aqueous solutions using the yeast *Saccharomyces cerevisiae*.

The biomass of yeast was inactivated by heating it in an autoclave at temperature around 121 °C for half an hour. After that it was frozen at minus 40 °C and lyophilized for about 48 hours. The lyophilized cells were stored in a freezer at minus 40 °C until encapsulation. Aqueous solutions of 2 concentrations were used in the experimental study: 5.0 and 10.0 mg/l. The resulting system of *S. cerevisiae* and alginate was characterized and analyzed based on particle size distribution and moisture content.

20 ml of concentration of 5 mg/l – 10 mg/l Cd^{2+} working solutions at pH 6.0 were used for biosorption experiments. They were separately mixed with 12 g of calcium alginate granules loaded with *S. cerevisiae* in 50 ml conical tubes. After incubation for 5, 15, 30 or 60 minutes at 25 °C, the beads were separated by gravity. The separated solution was acidified with HNO_3 acid to analyze the amount of unadsorbed residual Cd^{2+} by atomic absorption spectroscopy (AAS).

During 15 minutes of contact time, the yeast reached maximum adsorption efficiency and equilibrium was reached within 30 minutes. The removal efficiency of aqueous solutions containing 5.0 mg/l Cd^{2+} was 51.1 % ± 1.8 % and that of solutions containing 10.0 mg/l Cd^{2+} 51.2 % ± 1.8 %.

In 2020, Zinicovscaia and others published an article in Materials magazine on an efficient way to remove metals from wastewater containing synthetic and true galvanic zinc using the yeast species *Saccharomyces cerevisiae*.

Analysis of the information presented in the article revealed that using inactive S. cerevisiae biomass, the highest purification efficiency was recorded during the Pb (II) ion sorption process, followed by Ni (II) and Cr (VI). The S. cerevisiae yeast species was used to remove Cu^{2+}, Zn^{2+} and Cd^{2+} from solution. The bioadsorption capacity of Cu^{2+}, Zn^{2+} and Cd^{2+} was found to be 8.0, 7.1 and 14.0 mg/g, respectively.

Laura Žorža, Alexander Rapoport and Olga Muter were investigating activated sludge stimulation by adding yeast biomass. As we know, yeasts have different applications in industry: yeasts can be used in food manufacture or even for the biodegradation of xenobiotics (Žorža et al., 2019).

Metal removal has been studied mainly using a single metal solution. On the other hand, effluents can be described as system of multi – metal in which the metal removal efficiency will differ from a single metal solution due to the competitive binding site of metal ions on biosorbent surface.

1.6. Parameters determining the removal of heavy metals from contaminated water by yeast and their influence

S. cerevisiae, like many other microorganisms, accumulates various heavy metal ions in two different processes. The first step involves the association of the metal with cell surfaces and intercellular matrices (i.e., biosorption). This initial process is independent of temperature and metabolism, followed by slower uptake into cells by active or passive processes that depend on metabolism (Abbas et al., 2014).

Isolated S. cerevisiae cell walls can bind a variety of heavy metal ions. The common negatively charged cell wall facilitates cation exchange and coordination of metal ions with negatively charged groups. Binding of these cations to the cell wall is rapid and reversible (Abbas et al., 2014). The cell wall of S. cerevisiae is composed of many polymers, including glucan, proteins, lipids, and chitin/chitosan. These components are arranged in two – layer structures surrounding the cell. Table 1.7 provides summary information on the components that make up yeast cells.

Table 1. 7. Chemical composition of the walls of yeast, *Saccharomyces cerevisiae* (Duncan et al., 1994)

Component	Dry weight of cell wall, %
Nitrogen	2,10
Phosphate	0,31
Proteins	13,0
Ash	3,21
Lipids	8,50
Glucan	29,0
Chitin	1,00
Chitosan	1,00

The glucan microfibril layer protects the cell from osmotic lysis and mechanical degradation (Duncan et al., 1994).

The walls of yeast cells consist of both alkali – soluble and alkali – insoluble forms of glucan. Microscopic observation showed that the glucan component is aggregated into microfibrils.

The third sugar polymer, chitin, is found in most yeast cell walls only in small amounts (1 – 2 %). These polymers are highly insoluble in water. Chitin is thought to be associated with the glucan component of the cell wall due to the unavoidable degradation of glucan observed during chitin extraction (Duncan et al., 1994).

The biosorption process is affected by the following factors: pH, temperature, yeast concentration and duration of the sorption process.

The indicator of hydrogen ions, pH, is the most important parameter of the biosorption process: it influences the activity of functional groups in biomass. Yeast has the highest adsorption capacity at pH 5 – 6, so the absorption of heavy metals is most intense in a weakly acidic environment.

Parvathi et al. wanted to investigate the effect of pH on the biosorption process, so they performed experimental studies with the pH of the wastewater of pH 1, 2, 3, 4, 5 and 6 using 0.05 mol/l H_2SO_4 and 1 mol/l NaOH with a biosorbent concentration of 2 %. The experiments were not performed above pH 6, because of lead deposition. The effluent was diluted with distilled water to give solutions containing 25, 50, 75 and 100 mg/l lead. They were subjected to biosorption while maintaining a constant concentration of 2 % biosorbent. The experiments were performed by varying the stirring speed of the biosorption mixtures from 0, 50, 100, 150 – 200 rpm (Parvathi et al., 2007).

Lead uptake increased gradually when pH increase from 1 to 5, with a maximum value of 2.109 mg/g at pH 5. pH affects both the binding sites of cells on the cell surface and the availability of the metal in solution. At low pH, cell surface sites are closely related to H^+ ions. However, an increase in pH increases the result of negatively charged ligands, resulting in an increase in cation binding. However, at pH 6, lead uptake decreased to 1.78 mg/g due to partial precipitation.

According to Bejar and other scientists, the concentration of biomass in solution affects specific consumption: lower values of biomass concentrations increase specific consumption.

Goksungur et al. have been performed experimental studies on yeast cells to purify aqueous copper solutions with a concentration of 10 – 250 mg/l. It was observed that at lower concentrations of Cu^{2+} (10 – 50 mg), biosorption was completed within 5 minutes, but at higher concentrations, the process took about 30 – 60 minutes.

Meanwhile, temperature does not significantly affect the biosorption process, but at a temperature of 20 – 35 °C, the fastest biosorption processes were recorded (Ahalya et al., 2003).

In 2015, an article by Farhan and Khadom was published in the International Journal of Industrial Chemistry in which researchers analyzed the biosorption process of heavy metal removal from aqueous solutions using the yeast *Saccharomyces cerevisiae*. The influence of temperature on the biosorption process was discussed in the article.

Temperature affects the biosorption of metal ions, but only within a certain temperature range. According to the scientists, the temperature indicating a decrease in sorption capacity is 27 °C. It is important to mention that the biosorption process is usually not performed at high temperatures, as this can increase operating costs. The biosorption capacity was found to increase with decreasing temperature. A decrease in biosorption capacity between 27 and 62 °C could be observed due to damage to yeast active sites.

To sum up, it can point out that the pH has the highest impact on the process of heavy metals removal from contaminated water. On the other hand, it is very important to understand, that different tasks require different alternatives.

1.7. Overview of adsorption process modeling programs

The simulation identifies the characteristic parameters (sorbent mass, pollutant concentration, pH, liquid flow rate) of process that affect the result. Numerical modeling helps to evaluate water resource management processes – to control the processes taking place in water, to forecast their effectiveness.

RASPA, PHREEQC, MacroModel, COMSOL, MatLab, ANSYS, FLUENT, ORCHESTRA, MINTEQ are some examples of modeling programs.

RASPA is used to model the adsorption and diffusion of molecules in the adsorbent nanopores.

MacroModel allows modeling of the interaction of organic matter with biosorbents based on chemical reactions.

COMSOL is a modeling program enables the study of the flow of liquids, the transfer of heat and mass or chemical reactions themselves.

ANSYS is software that can model flows, turbulence, heat transfer and chemical reactions in industry.

FLUENT is a computer fluid dynamics (CFD) code for modeling fluid flows, heat transfers, and chemical reactions.

These programs enable faster analysis and comparison of differences or similarities between different theoretical mathematical models and data sets.

PHREEQC is a program that is used to model chemical reactions that take place on the surface of an adsorbent. The operation of this program is based on the chemical transformations of aqueous solutions that interact with adsorbents. This computer program is written in C, C ++ programming languages. PHREEQC provides the ability to calculate saturation indices, help model reactions and perform one – dimensional transport with reversible/irreversible reactions (Leal et al., 2014).

MatLab software is designed to solve mathematical problems and graphically display results. The following calculations are possible with this program (just a few examples):

- solution of differential equations;
- Fourier and statistical analysis functions;
- operations on trigonometric and other mathematical equations.

The main advantage of this software is that if makes it possible to perform calculations with your own created functions. MatLab program is characterized by high calculation speed, visualization of the obtained results. Although this program is expensive, it can be used to create systems models, perform actions with matrices (Vaišis, 2020).

The ORCHESTRA program is designed for chemical modeling of the distribution of chemical state forms and mass transport processes. It is important to note that the definitions of this software are separate from the computational kernel. This means that model types are defined in text format using objects. This allows you to freely change or add model definitions without changing the underlying data.

The computational core does not have any information about chemical models, so it allows to create a general structure of objects that is based on a small set of basic object classes and can be used as building blocks for the implementation of specific models. This facilitates the introduction of new models (Araujo et al., 2020).

MINTEQ is free software designed to create chemical equilibrium models for calculating solubility equilibrium, sorption and more. This program combines state of the art sorption and reaction descriptions with easy to use data import/export options to/from Excel. The input data consists of the concentrations of the selected substances, in addition the following parameters can be entered: pH, pressure (Irunde et al., 2019).

Visual MINTEQ was developed based on the MINTEQA2 program, which was originally used by the US Environmental Protection Agency. The main task of this program is to simulate the balance and specificity of inorganic dissolved substances in natural waters.

This program helps to calculate the type of inorganic ions and complexes in water, to evaluate the effect of solid phase dissolution or precipitation on water chemistry, to investigate changes in the equilibrium of common redox pores, to simulate changes in water sample chemical composition by titration (Xie et al., 2016).

Visual MINTEQ is designed primarily to calculate the balance of inorganic ions and trace elements in water (Zhang et al., 2008).

There are many software programs, which can be used to calculate element's migration or distribution in aqueous solution. The most important thing is to determine the purpose of the experiment.

Conclusions of the first chapter

1. Heavy metals are most often released into the environment by waste contaminated with petroleum products: transport waste (tires, used lubricants, filters, batteries), chemical waste (varnishes, paints, thinners) and household chemical products. Anthropogenic pollution is characterized by high concentrations of heavy metals, usually on a local or regional scale.

2. Heavy metals have a negative effect on human or other living organisms. Their effects on the human body are very different and depend on the concentration of the metal and the duration of action. The most common disorders are: central nervous system disorders, respiratory disorders, nausea, vomiting and abdominal cramps.

3. *Saccharomyces cerevisiae* yeasts are characterized by high fermentation efficiency, rapid growth, efficient sugar consumption and the ability to produce and consume ethanol. This type of yeast is also characterized by tolerance to high ethanol concentrations and low oxygen levels and cellular activity in an acidic environment, allowing them to be widely used.

4. HM are hazardous to the environment, many different removal technologies from aqueous solutions are used (chemical precipitation, membrane filtration, electrochemical separation, ion exchange, sorption, etc.).

5. Langmuir and Freundlich isotherm models are most commonly used to model the adsorption process in water.

6. Yeast biomass can be successfully used as a biosorption material for the removal of cadmium, chromium, copper, lead, arsenic, silver, gold, nickel, mercury and zinc.

7. The biosorption process is affected by temperature, pH, yeast concentration and duration of the sorption process.

8. RASPA, PHREEQC, MacroModel, COMSOL, MatLab, ANSYS, FLUENT, ORCHESTRA, MINTEQ are software programs, which can be used to calculate element's migration or distribution in aqueous solution.

2. METHODOLOGY OF EXPERIMENTAL INVESTIGATIONS OF BIOSORPTION PROCESSES

2.1. Selection of sorbents and general test conditions

The aim of the study was to determine the ability of yeast (*Saccharomyces cerevisiae*) to adsorb selected heavy metals from aqueous solutions by measuring different pH levels of the solutions, the concentration of metals in the solution and the duration of adsorption.

The natural biological material chosen for the preparation of the adsorbent was the yeast species *Saccharomyces cerevisiae* obtained from the Vilnius Nature Research Center. The best practice method saves resources and determines the optimal conditions for achieving the goal (optimizing biosorption efficiency).

The first tests were performed using *Saccharomyces cerevisiae* yeast, but due to the working conditions under quarantine conditions, *Brewer's* yeast was used for subsequent studies (Fig. 2.1).

Fig. 2. 1. Example of *Saccharomyces cerevisiae* and *Brewer* yeast

During the research work, experiments were performed with artificially contaminated deionized water, in which the concentrations of metals (copper, lead and cadmium) ions exceeded the maximum permissible concentrations.

The aim of the experimental research was to determine the optimal conditions under which the highest efficiency of heavy metal ion removal from aqueous solutions using yeast would be recorded. Experimental studies were performed at different values of pH: pH 2, 3, 4, 5, 6, because some heavy metals, such as lead, settle in the sediment from about pH 6 (depending on its concentration in solution) (Fig. 2.2).

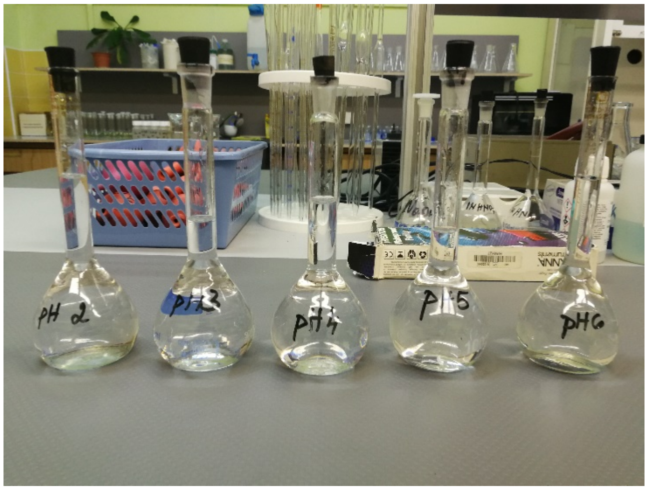


Fig. 2. 2. 100 ml volumetric flasks with aqueous solutions of different pH values

Based on the information provided in the scientific literature and the results of laboratory tests (No. 1 – 5), it was determined that the highest cleaning efficiency is achieved at pH value of 5. The remaining experiments were performed at this concentration of hydrogen ions in solution.

The dependence of the sorbed amount on the contact time was also investigated: the biosorbent prepared from yeast was in contact with the contaminated aqueous solution for 5 min, 30 min, 60 min, 4 h and 24 h (Fig. 2.3).

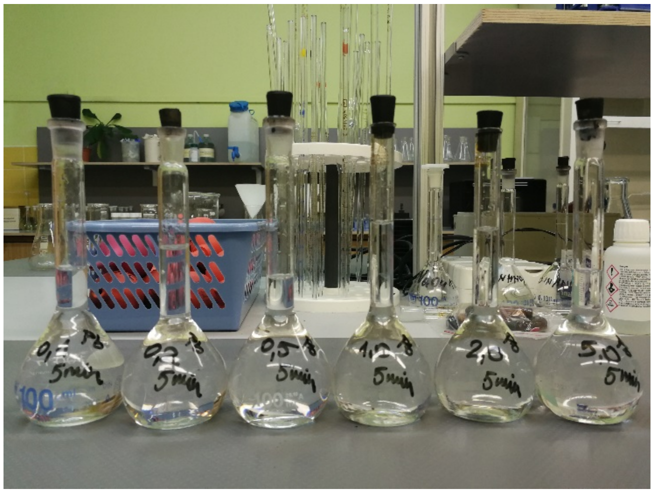


Fig. 2. 3. Solutions prepared for the 5 min biosorption process

Test substances, mixtures and chemical reagents: heat – treated *Saccharomyces cerevisiae* yeast species, sodium hydroxide (NaOH), deionized water (meeting the quality requirements of LST EN ISO 3696), nitric acid (HNO_3), standard solutions of copper, cadmium and lead (1000 mg/l). 0.1 N NaOH and 0.1 N HNO_3 solutions are used to adjust the pH of copper/cadmium/lead aqueous solutions.

2.2. Preparation of the contaminated water samples to be used in the test

Standard solutions (1000 mg/l) of different heavy metals (copper (Cu), cadmium (Cd) and lead (Pb)) were used for the tests.

The primary concentration of HM in the solution was an important parameter for the examination of adsorption process. Standard metal solutions and deionized water ware used to prepare solutions of different concentrations of the selected heavy metals in an Elenmeyer flask (100 ml) using.

Aqueous solutions of 2 concentrations were prepared: 5.0 mg/l and 10.0 mg/l. First of all, it was added 0.5 ml or 1.0 ml of the chosen heavy metal standard solution to 100 ml flasks. Then, it was taken needed volume of standard solution with a 1.0 ml graduated pipette (Fig. 2.4).

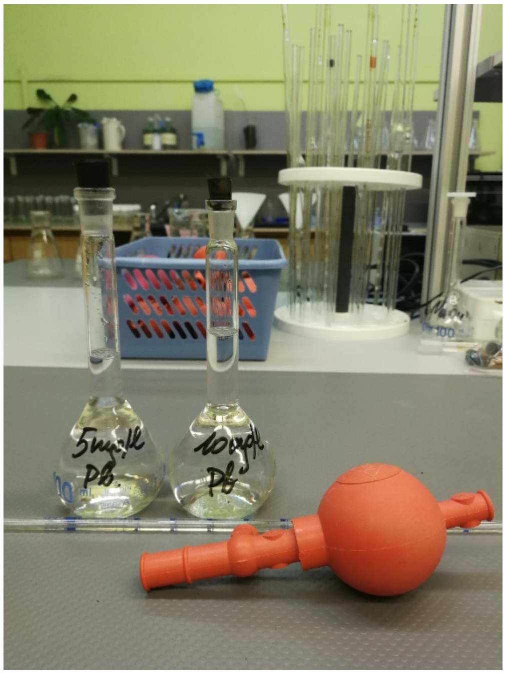


Fig. 2. 4. Measurements were performed with 5.0 mg/l and 10.0 mg/l solutions

After adding the required amount of heavy metal, the rest of the solution (up to 80 %) was prepared with deionized water (total volume about 80 ml). 0.1 N solution of nitric acid or alkali was then carefully added using a digital pipette, mixed and measured until the required pH was reached (Fig. 2.5).

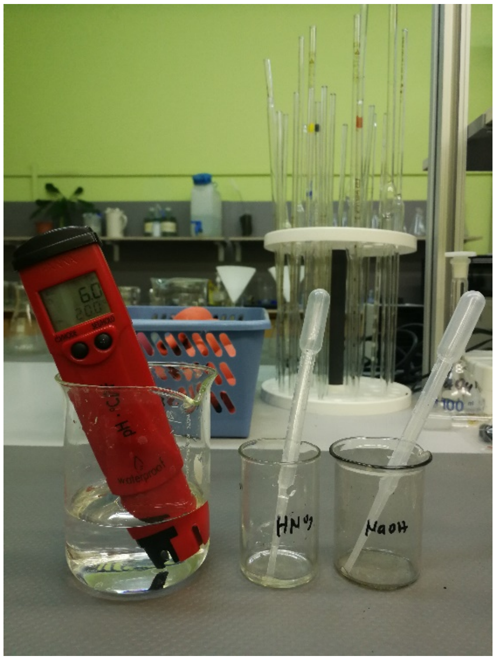


Fig. 2. 5. pH measuring device "pHep"

The pH of the solution was determined using a pHep meter. Before starting the experimental tests, the instrument was calibrated using two buffer solutions with different pH values, pH 4.0 and 7.0. The calibration process may need to be repeated until the meter readings match the pH values of the buffers. It is crucial that before the measurements with new solution of other pH values, the pH meter must be rinsed with deionized water, dried and immersed in the prepared buffer solution. The pH of the solution was adjusted with 0.1 M HNO_3 and 0.1 M NaOH.

2.3. Apparatus and instruments

Equipment and measuring instruments used for the research:

- Radwag analytical balance;
- “VWR Qualitative filter paper 413”;
- Buck Scientific 210 VGP atomic absorption spectrometer (AAS);
- pH meter "pHep";
- vacuum pump;
- funnels;
- 100 ml dishes (measuring flasks, glasses);
- 1, 2, 10 ml graduated pipettes.

2.4. The course of the investigation

After preparation of aqueous solutions of heavy metals of appropriate concentration, the required amount of yeast was added. 6 different amounts of yeasts were used for the studies: 0.1 g, 0.2 g, 0.5 g, 1.0 g, 2.0 g and 5.0 g (+/– 0.001 g) (Fig. 2.6). Then, the selected amount of yeast was transfer to each volumetric flask. To make the yeast active, the researcher should add 0.1 g of sugar or agar to each sample. The first tests were performed using agar, but due to the more complex filtration process, this solution was later abandoned and sugar was used instead.

Fig. 2. 6. Radwag scales

The prepared samples were then transferred to screw – on glass 100 ml volumetric flasks (Fig. 2.7), which were thoroughly mixed. Sample mixing was performed at the selected contact time.

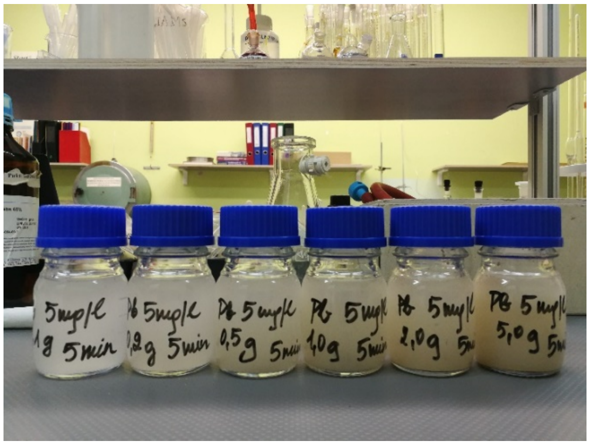


Fig. 2. 7. 100 ml glass vials with prepared HM – contaminated aqueous solutions

To avoid measurement errors, pre – filtration using “VWR Qualitative filter paper 413” filter paper was started before the end of the contact time, because the sorption process was not stopped during the filtration process (Fig. 2.8). After the primary filtration, a secondary one was performed using a vacuum pump (Fig. 2.9). Most of the yeast was removed using filter paper, but the residue amount was removed using a vacuum pump.

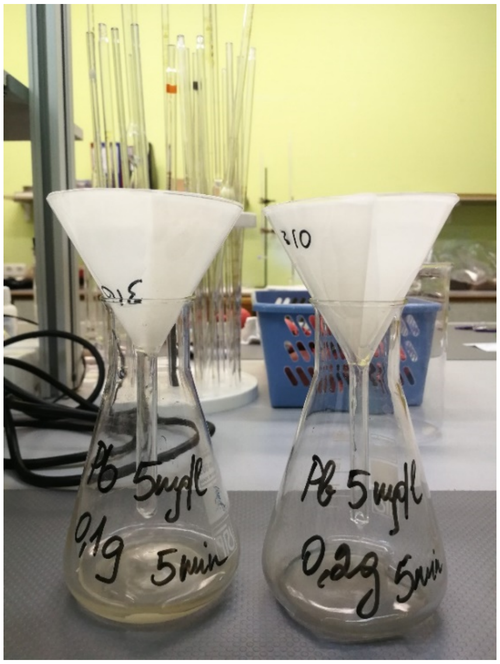


Fig. 2. 8. Filtration of aqueous solutions using “VWR Qualitative filter paper 413”

Fig. 2. 9. Vacuum pump

Filtered samples were then transferred to prepared (numbered) plastic bottles (Fig. 2.10). It was necessary to add 1.0 % by volume of concentrated nitric acid to each container. Acid preserves the samples. Until measurements, the samples were kept refrigerated at 5 °C.

Fig. 2. 10. Prepared samples for analysis with an atomic adsorption spectral analyzer

The rest concentration of HM in the solutions was determined by atomic adsorption spectral analysis using a Buck Scientific 210 VGP spectrometer with an air – acetylene flame and a graphite furnace (Fig. 2.11).

Fig. 2. 11. Atomic adsorption spectral analysis apparatus

Calibration curves, that are prepared for each heavy metal separately, were used to determine the concentrations of heavy metals. Solutions of the investigated HM (copper, cadmium and lead) prepared from standard metal solutions (~ 1000 mg/l metal, 2 % HNO_3) were used to form the data curves.

2.5. Statistical processing of results

The main objective of the experimental studies with yeast was to determine the biosorption efficiency.

Sorption capacity (Q) – the amount of metal ions per gram of sorbed biomass was calculated as follows:

$$Q = \frac{(C_i - C_f) \cdot V}{m} \quad (2.1)$$

where
C_i – initial concentration of heavy metal ions, mg/l
C_f – residual metal concentration after biosorption process, mg/l
V – the volume of the test solution, l
m – the mass of the sorbent, g.

Meanwhile, the biosoption efficiency (E) was determined according to the following formula:

$$E = \frac{(C_i - C_f)}{C_i} \cdot 100 \quad (2.2)$$

The results obtained in the study were statistically processed using MS Excel 2016. The quality of the measurements was ensured by the use of high purity chemical reagents, deionized water and a blank.

To estimate the strength of the relationship between the two values, the correlation coefficient has to be used (Table 2.1).

Table 2. 1. Values of correlation coefficient (Bilevičienė, 2011)

Value of correlation coefficient	Interpretation
From 0.9 to 1.0 or from -0.9 to -1.0	Very high
From 0.7 to 0.9 or from -0.7 to -0.9	High
From 0.5 to 0.7 or from -0.5 to -0.7	Medium
From 0.3 to 0.5 or from -0.3 to -0.5	Low
From 0.3 to -0.3	Very low

The correlation coefficient does not depend on the units of measurement of the variables. Coefficient varies from -1 to +1. Special points are: -1, 0, +1. A positive coefficient indicates a direct dependence (as the values of X increase, it is likely that the values of Y also increase); negative – inverse (as X values increase, Y values are likely to decrease) (Schober et al., 2018).

Conclusions of the second chapter

1. Two biological substances were selected for the preparation of the bioadsorbent – *Saccharomyces cerevisiae* and *Brewer's* yeast.

2. Standard solutions of different heavy metals (copper (Cu), cadmium (Cd) and lead (Pb)) ions (1000 mg/l) were used for the tests.

3. Experiments were performed with artificially contaminated deionized water with heavy metal (copper, lead and cadmium) ion concentrations of 5.0 mg/l and 10.0 mg/l.

4. Experimental studies were performed at different pH values of aqueous solutions: 2, 3, 4, 5, 6. After determining the optimal conditions for the biosorption process, further studies were performed at one pH value i.e., 5.

5. A biosorbent prepared from yeast was in contact with an aqueous solution contaminated with heavy metal ions for 5 min, 30 min, 60 min, 4 h and 24 h.

6. During experimental studies sorption capacity and biosoption efficiency were determined using MS Excel 2016.

3. RESULTS OF EXPERIMENTAL INVESTIGATIONS OF BIOSORPTION PROCESSES

3.1. Influence of pH of aqueous solutions on the process of heavy metal removal

Experimental trials of adsorption efficiency were performed with two types of yeast: food yeast, also known as *Brewer's* yeast, and *Saccharomyces cerevisiae* yeast.

The main unchanging condition of experiments was the type of bioadsorbent. Variable conditions include the pH of lead (Pb), copper (Cu) and cadmium (Cd) solutions, which ranged from 2 to 6, heavy metal concentration, contact time and yeast amount.

Aqueous solutions of 2 different concentrations (5.0 mg/l and 10.0 mg/l) of lead, copper and cadmium ions were prepared for experimental studies. Preparation was conducted by diluting standard lead/copper/cadmium solutions (~ 1000 mg/l) adding 0.1 g, 0.2 g, 0.5 g, 1.0 g, 2.0 g and 5.0 g of bioadsorbent (yeast).

pH played an important role in the adsorption of metal ions as it affected the degree of dissociation and the functional group. For the experimental work, the pH range was chosen from 2 to 6. The pH of the solution was adjusted with 0.1 M HNO_3 and 0.1 M NaOH solutions. The effect of pH on adsorption efficiency was studied at room temperature (21 – 23 °C). The efficiency of removal of lead, copper and cadmium ions from aqueous solutions was evaluated according to the residual metal concentration. It was compared to the concentration of HM ions in the solutions used for experimental studies before contact with the adsorbent and it was 5.0 mg/l or 10.0 mg/l.

Table 3.1 shows the influence of solution pH on the adsorption efficiency of the adsorbent. To study this, the tests (No. 1 – 5) were performed with an aqueous solution of lead ions, the contact time was 60 min.

Table 3. 1. Influence of aqueous solution pH on lead removal efficiency

Parameters	Initial pH level				
	2	3	4	5	6
Residual lead concentration, mg/l	2.94	1.74	0.21	0.21	0.26
Adsorption efficiency, %	41.10	65.30	95.83	95.91	94.93

Based on the data presented in Table 3.1, it can be concluded that with increasing pH values from 2 to 5, a significant increase in adsorption efficiency from 39.00 % (at pH 2) to 95.94 % (at pH 5) was observed. Meanwhile, when evaluating the adsorption efficiency values at pH 5 and pH 6, it was observed that at pH 6 the adsorption efficiency slightly decreased, from 95.94 % to 94.78 %.

Parvathi et al. investigated the effect of pH on the biosorption process, performed experimental studies with the pH of the wastewater 1, 2, 3, 4, 5. After experiments it was found out that lead uptake increased gradually with an initial pH increase from 1 to 5, with a maximum value at pH 5.

Based on the results performed experimental studies and the data presented in scientific publications, it was decided to perform further studies only at the pH value of 5.

3.2. Influence of sorbent content, initial concentration of metal solutions and time of sorbent presence in the solution on the efficiency of lead, copper and cadmium removal

Experiments on the removal of lead ions from aqueous solutions have shown that at lower concentrations of lead ions (5.0 mg/l) sorbent achieved a higher adsorption efficiency compared to 10.0 mg/l. The results of the residual lead concentration in the sample, sorbed amount and adsorption efficiency are given in Table 3.2.

Table 3. 2. Dependence of adsorption efficiency on sorbent amount at different lead concentrations (5 min)

Concentration Pb	Yeast amount / Contact time – 5 min					
5.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual lead concentration, mg/l	3.10	2.80	2.65	1.30	1.00	0.80
Sorbed amount, mg/g	1.90	1.10	0.47	0.37	0.20	0.08
Adsorption efficiency, %	38.00	44.00	47.00	74.00	80.00	84.00
10.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual lead concentration, mg/l	3.70	3.70	3.70	3.50	3.20	2.90
Sorbed amount, mg/g	6.30	3.15	1.26	0.65	0.34	0.14
Adsorption efficiency, %	63.00	63.00	63.00	65.00	68.00	71.00

The highest lead adsorption efficiency at 5.0 mg/l and 10.0 mg/l aqueous solutions was found at a yeast amount of 5.0 g. However, at a lower concentration of the solution, a higher adsorption efficiency was recorded – 84.00 %. At a concentration of 10.0 mg/l of lead ions, an adsorption efficiency of 71.00 % was recorded.

It should be noted that in solutions with a concentration of 10.0 mg/l of lead ions and at 0.1 g, 0.2 g and 0.5 g of yeast, the adsorption efficiency did not change, the same value of 63.00 % was recorded in all samples.

Studies of the adsorption of copper ions by yeast have shown that at higher concentrations of copper ions, i.e., 10.0 mg/l, higher adsorption efficiency was achieved compared to 5.0 mg/l concentration studies. Residual copper concentration in the sample, sorbed amount and adsorption efficiency results are presented in Table 3.3.

Table 3. 3. Dependence of adsorption efficiency on sorbent amount at different copper concentrations (5 min)

Concentration Cu	Yeast amount / Contact time – 5 min					
5.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual copper concentration, mg/l	5.00	4.30	4.20	4.00	4.00	3.80
Sorbed amount, mg/g	0.00	0.35	0.16	0.10	0.05	0.02
Adsorption efficiency, %	0.00	14.00	16.00	20.00	20.00	24.00
10.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual copper concentration, mg/l	7.00	7.00	7.00	6.00	5.00	5.00
Sorbed amount, mg/g	3.00	1.50	0.60	3.90	0.25	0.10
Adsorption efficiency, %	30.00	30.00	30.00	40.00	50.00	50.00

The highest adsorption efficiency was recorded in samples with 5.0 g of yeast. At 5.0 mg/l copper ion concentration, 24.00 % adsorption efficiency value was recorded and at 10.0 mg/l concentration, 50.00 % adsorption efficiency was observed.

At yeast amount of 0.1 g to 0.5 g, a slight change in sorption capacity was observed in the samples. For instance, at 5.0 mg/l, the residual concentration of copper ions in the sample was 5.0 mg/l. Thus, sorption capacity was 0.0 mg/g – adsorption efficiency 0,00 %. Moreover, sorption capacity of 0.35 mg/g and 0.16 mg/g was recorded at 0.2 g and 0.5 g of yeast amount.

Studies with samples containing 0.1 g, 0.2 g and 0.5 g of yeast with a solution concentration of 10 mg/l showed a uniform adsorption efficiency of 30.00 %. It can be assumed that at higher concentrations of heavy metal, a small amount of yeast in the sample is not sufficient to ensure larger changes in adsorption efficiency.

Studies on the adsorption of cadmium ions by yeast have shown that at lower concentrations of cadmium ions, i.e., 5.0 mg/l, higher adsorption efficiency was achieved compared to 10.0 mg/l. The results of the residual cadmium concentration in the sample, sorbed amount and adsorption efficiency are presented in Table 3.4.

Table 3. 4. Dependence of adsorption efficiency on sorbent amount at different cadmium concentrations (5 min)

Concentration Cd	Yeast amount / Contact time – 5 min					
5.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual cadmium concentration, mg/l	0.62	0.53	0.53	0.56	0.39	0.37
Sorbed amount, mg/g	4.38	2.24	0.89	0.44	0.23	0.09
Adsorption efficiency, %	87.60	89.40	89.40	88.80	92.20	92.60
10.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual cadmium concentration, mg/l	1.87	1.70	1.74	1.38	1.19	1.38
Sorbed amount, mg/g	8.13	4.15	1.65	0.86	0.44	0.17
Adsorption efficiency, %	81.30	83.00	82.60	86.20	88.10	86.20

The highest adsorption efficiency was observed with 2.0 – 5.0 g of yeast: at 5.0 mg/l, 92.60 % adsorption efficiency was recorded and at 10.0 mg/l 88.10 % adsorption efficiency was observed.

In studies of cadmium, more deviations from previously observed trends were recorded. Such as, an increase in adsorption efficiency from 0.1 g of yeast to 0.5 g of yeast at 5.0 mg/l, but in an aqueous solution of cadmium containing 1.0 g of yeast, a decrease, albeit slight, was observed in the adsorption efficiency compared to the first values in this order. Meanwhile, increasing the yeast content from 2.0 g to 5.0 g again showed an increased value of the adsorption efficiency.

The graphs below show the dependence of heavy metal adsorption efficiency on yeast content.

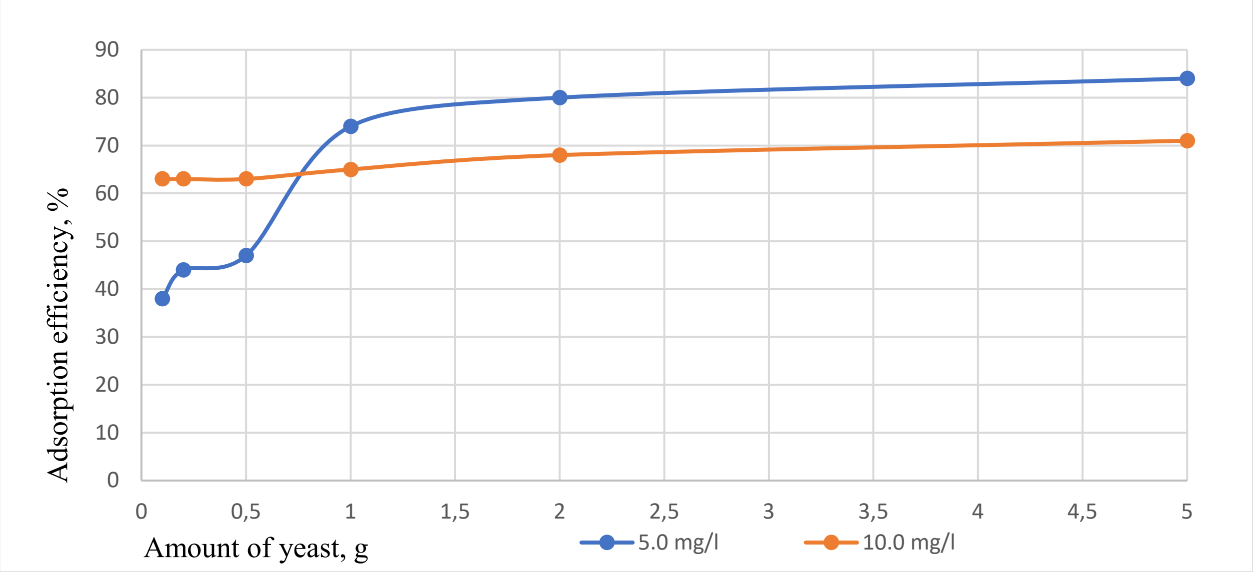


Fig. 3. 1. Graph of the dependence of lead adsorption efficiency on yeast content (5 min contact time)

Based on the results of the performed studies, it can be observed that in the case of using lead and cadmium (Fig. 3.1 and 3.3) ion solutions for adsorption, higher values of adsorption efficiency were recorded at lower concentations of heavy metal.

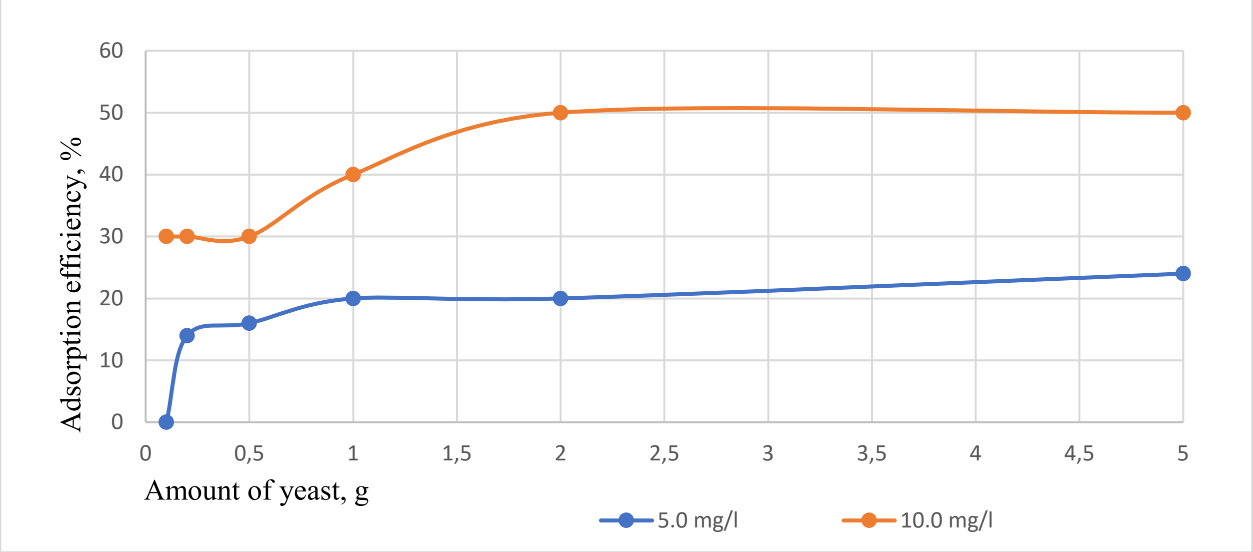


Fig. 3. 2. Graph of the dependence of copper adsorption efficiency on yeast content (5 min contact time)

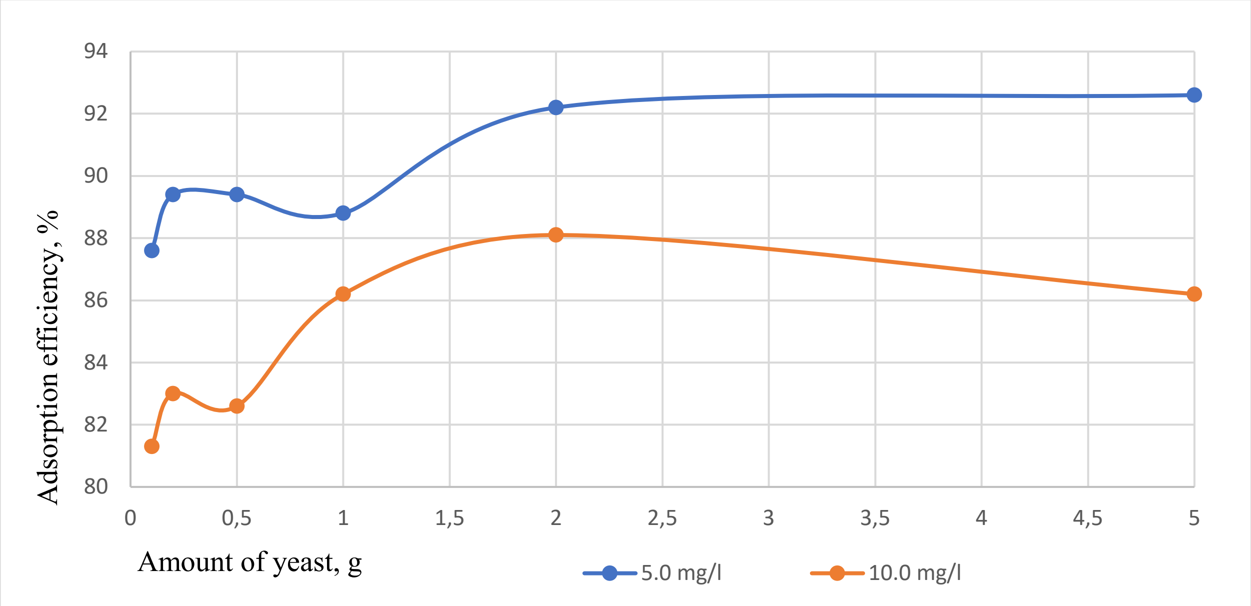


Fig. 3. 3. Graph of the dependence of cadmium adsorption efficiency on yeast content (5 min contact time)

The initial concentration of lead, copper and cadmium ions in the solutions was found to affect the adsorption efficiency of food yeast. The highest adsorption efficiency of lead at 5.0 mg/l and 10.0 mg/l aqueous solutions was recorded at a yeast amount of 5.0 g. At concentration of 5.0 mg/l with the samples of 5.0 g of yeast, the value of adsorption efficiency of 84.00 % was recorded and at the concentration of 10.0 mg/l, the adsorption efficiency of 71.00 % was observed (Fig. 3.4).

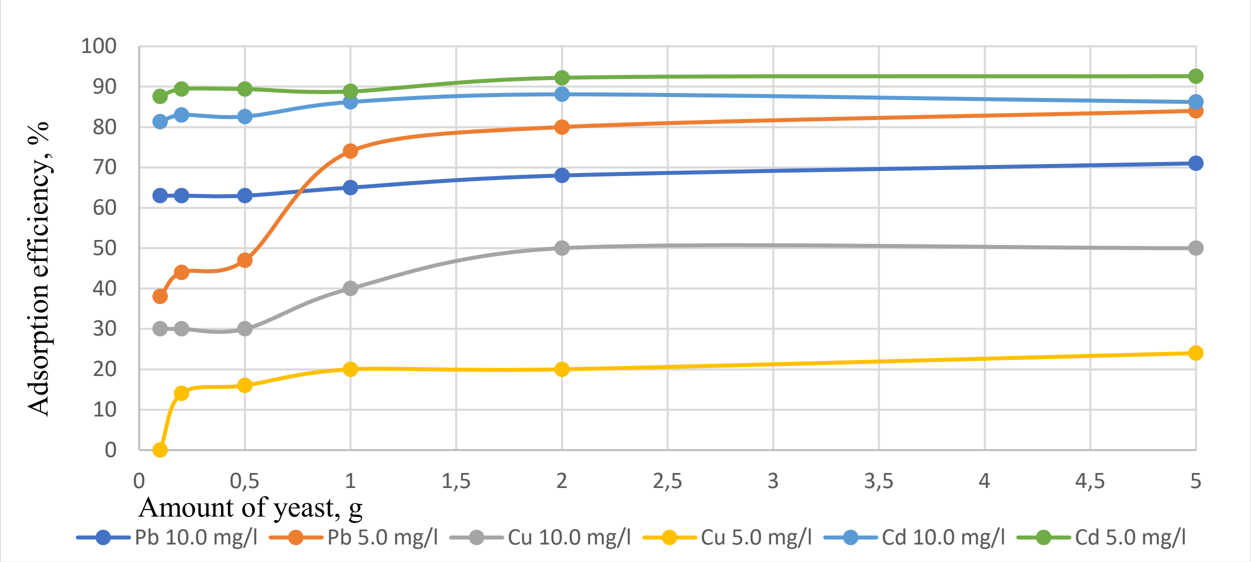


Fig. 3. 4. The dependence of lead, copper and cadmium adsorption efficiency on yeast amount (5 min contact time)

Based on the performed studies, it was observed that in cases of lead and cadmium ion solution use for adsorption, higher values of adsorption efficiency were recorded at lower concentrations of these heavy metal. Meanwhile, higher values of copper adsorption efficiency were recorded at a higher concentration of 10 mg/l.

At contact time of 30 min, sorption experiments of lead ions from aqueous solutions using yeast showed that at higher concentrations of lead ions, i.e., 10.0 mg/l, higher adsorption efficiency was achieved compared to 5.0 mg/l concentration studies. Residual lead ions concentration in the samples, sorbed amount and adsorption efficiency results are presented in Table 3.5.

Table 3. 5. Dependence of adsorption efficiency on sorbent content at different lead concentrations (30 min)

Concentration Pb	Yeast amount / Contact time – 30 min					
5.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual lead concentration, mg/l	2.05	2.05	2.05	3.65	1.65	1.50
Sorbed amount, mg/g	2.95	1.48	0.59	0.14	0.17	0.07
Adsorption efficiency, %	59.00	59.00	59.00	27.00	67.00	70.00
10.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual lead concentration, mg/l	4.20	4.10	4.10	3.80	3.50	2.90
Sorbed amount, mg/g	5.80	2.95	1.18	0.62	0.33	0.14
Adsorption efficiency, %	58.00	59.00	59.00	62.00	65.00	71.00

The highest lead adsorption efficiencies at 5.0 mg/l and 10.0 mg/l aqueous solutions were recorded at a yeast amount of 5.0 g. At a lower concentration of the solution, the adsorption efficiency of 70.00 % was observed, while at a concentration of 10.0 mg/l, the adsorption efficiency of 71.00 % was recorded (same as after 5 minutes of contact time).

It should be noted that in solutions of 5.0 mg/l and 10.0 mg/l at 0.1 g, 0.2 g and 0.5 g of yeast amount, the adsorption efficiency change was minimal, 58 – 59.00 % adsorption efficiency values were recorded in all of the samples tested.

Studies of the adsorption of copper ions by yeast have shown that at higher concentrations of copper ions, i.e., 10.0 mg/l, a lower adsorption efficiency was achieved compared to 5.0 mg/l. Residual copper concentration in the sample, sorbed amount and adsorption efficiency results are presented in Table 3.6.

Table 3. 6. Dependence of adsorption efficiency on sorbent content at different copper concentrations (30 min)

Concentration Cu	Yeast amount / Contact time – 30 min					
5.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual copper concentration, mg/l	1.85	1.46	1.17	1.17	1.14	0.75
Sorbed amount, mg/g	3.15	1.78	0.77	0.39	0.19	0.09
Adsorption efficiency, %	63.00	70.85	76.70	76.70	77.25	85.00
10.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual copper concentration, mg/l	4.50	4.40	3.25	3.25	2.95	2.85
Sorbed amount, mg/g	5.50	2.80	1.40	0.68	0.35	0.14
Adsorption efficiency, %	55.00	56.00	67.50	67.50	70.50	71.50

The highest adsorption efficiency was recorded at 5.0 g of yeast amount in samples: at concentration of 5.0 mg/l, the adsorption efficiency of 85.00 % was recorded and at concentration of 10.0 mg/l, the adsorption efficiency of 71.50 % was observed.

Comparing the results of copper sorption of 5 min and 30 min contact time, it was observed that yeast, which remained in the samples for a longer period of time, sorbed more copper ions. For example, at concentration of 10.0 mg/l with 5 min of contact time, the value of adsorption efficiency ranged from 30.00 % to 50. 00 %. When the contact time was extended to 30 min, the values of adsorption efficiency were recorded from 55.00 % to 71.50 %.

Studies on the adsorption of cadmium ions by yeast have shown that at lower concentrations of cadmium ions, i.e., 5.0 mg/l, maximum adsorption efficiency of 90.15 % was achieved. The results of the residual cadmium concentration in the sample, sorbed amount and adsorption efficiency are presented in Table 3.7.

Table 3. 7. Dependence of adsorption efficiency on sorbent content at different cadmium concentrations (30 min)

Concentration Cd	Yeast amount / Contact time – 30 min					
5.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual cadmium concentration, mg/l	0.85	0.79	0.57	0.50	0.53	0.76
Sorbed amount, mg/g	4.15	2.11	0.89	0.45	0.22	0.08
Adsorption efficiency, %	83.00	84.20	88.70	90.15	89.55	84.90
10.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual cadmium concentration, mg/l	2.63	3.55	2.11	1.82	1.18	1.04
Sorbed amount, mg/g	7.37	3.23	1.58	0.82	0.44	0.18
Adsorption efficiency, %	73.7	64.50	78.90	81.85	88.20	89.60

The highest adsorption efficiency was recorded at yeast amount of 1.0 g with samples with cadmium concentration of 5.0 mg/l. In cadmium 30 – min studies, a number of deviations from previously observed trends were also observed. For example, at cadmium concentration of 5.0 mg/l, an increase in adsorption efficiency from 0.1 g to 1.0 g of yeast was observed, but in cadmium aqueous solutions containing 2.0 g and 5.0 g of yeast, although a small, but a decrease in adsorption efficiency compared to the first values in this order was recorded.

Rivas et al. examined the process of removing cadmium from aqueous solutions using the yeast *Saccharomyces cerevisiae* (12.0 g). The removal efficiency of aqueous solutions containing 5.0 mg/l Cd^{2+} was 51.1 % ± 1.8 % and removal efficiency of solutions containing 10.0 mg/l Cd^{2+} 51.2 % ± 1.8 %. On the other hand, during this experimental work of 30 min sorption time between cadmium ions and yeast, it was observed that at the values of adsorption efficiency were higher. This example supports the idea that yeast is capable of purifying lower concentrations of heavy metal from solutions.

The graphs below show the dependence of the adsorption efficiency of heavy metals on the yeast amount, results were recorded after contact time of 30 min.

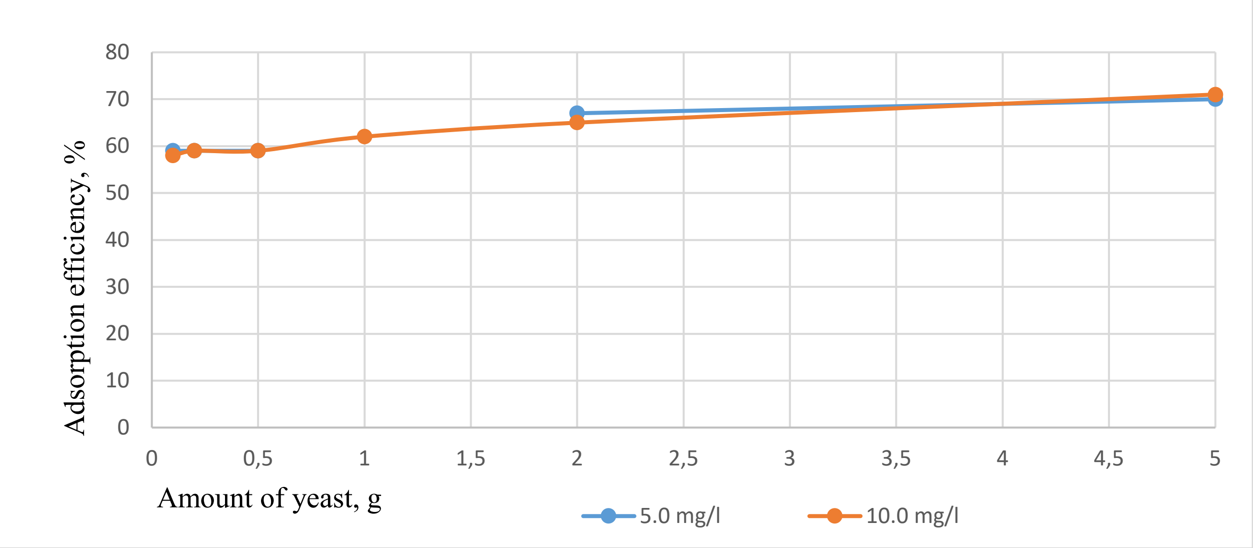


Fig. 3. 5. Graph of the dependence of lead adsorption efficiency on yeast amount (30 min contact time)

The highest efficiency of lead (Fig. 3.5) adsorption at concentration of 5.0 mg/l of aqueous solutions was recorded when the yeast amount ranged from 2.0 g to 5.0 g. At 5.0 mg/l with samples of 5.0 g of yeast, the value of adsorption efficiency of 70.00 % was recorded and at the concentration of 10.0 mg/l, the adsorption efficiency of 71.00 % was observed.

The graph of the 5.0 mg/l solution shows that the value of the samples containing 1.0 g of yeast was not involved in the curve. The inaccuracy of this measurement may have been resulted from poorly prepared aqueous solution (improperly measured yeast amount, no added sugar).

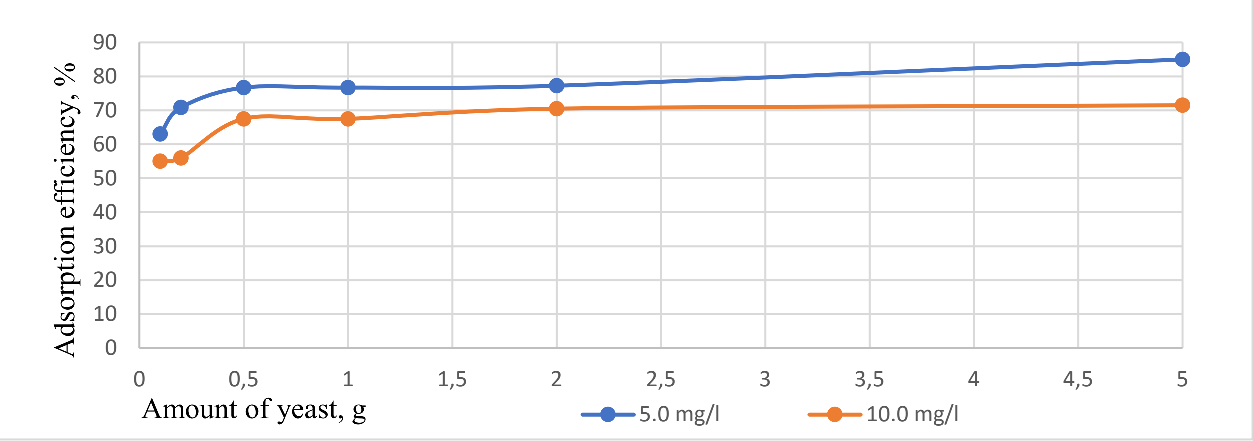


Fig. 3. 6. Graph of the dependence of copper adsorption efficiency on yeast amount (30 min of contact time)

It was found that higher values of adsorption efficiency were recorded at lower concentrations of copper (Fig. 3.6) in aqueous solution.

Based on Figure 3.7 it was observed that in the tests with cadmium higher values of adsorption efficiency were recorded at lower concentrations of heavy metal, but only up to 2.0 g of yeast. At 5.0 g of yeast, a higher value of adsorption efficiency was recorded with a higher concentration (10.0 mg/l) solution.

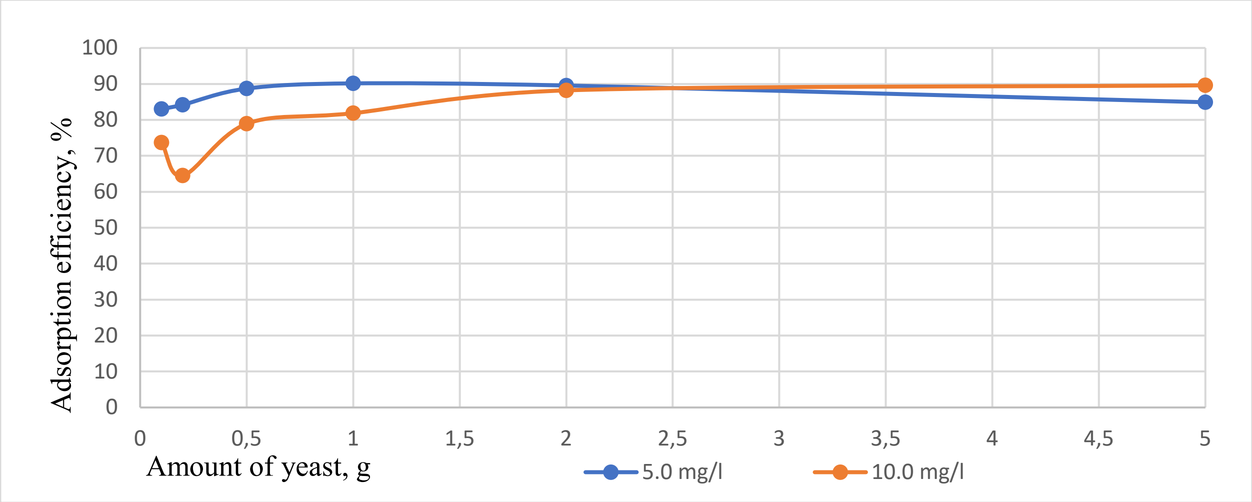


Fig. 3. 7. Graph of the dependence of cadmium adsorption efficiency on yeast amount (30 min of contact time)

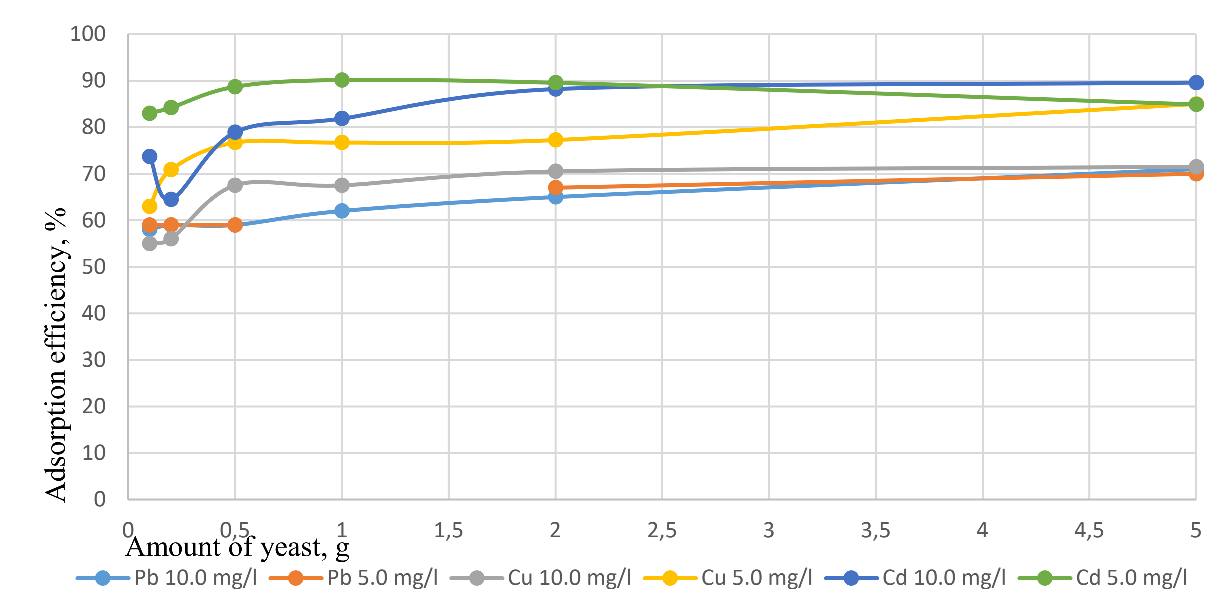


Fig. 3. 8. The dependence of lead, copper and cadmium adsorption efficiency on yeast amount (30 min contact time)

Studies have shown that with an increase of yeast amount in samples, higher values of adsorption efficiency were recorded (several exceptions were observed). Meanwhile, while comparing the different contact time of the sorption process of the same heavy metal, it was found that at 10.0 mg/l solutions after 30 min of yeast and heavy metal contact time higher sorption capacity values were recorded compared to the same concentration but 5 min contact time samples.

At contact time of 60 min, sorption experiments of lead ions from aqueous solutions using yeast showed that at higher concentrations of lead ions, i.e., 10.0 mg/l, higher adsorption efficiency was achieved compared to 5.0 mg/l concentration studies. Residual lead ions concentration in the samples, sorbed amount and adsorption efficiency results are presented in Table 3.8.

Table 3. 8. Dependence of adsorption efficiency on sorbent content at different lead concentrations (60 min)

Concentration Pb	Yeast amount / Contact time – 60 min					
5.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual lead concentration, mg/l	3.65	2.05	2.05	2.05	1.65	1.50
Sorbed amount, mg/g	1.35	1.47	0.59	0.29	0.16	0.07
Adsorption efficiency, %	27.00	59.00	59.00	59.00	67.00	70.00
10.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual lead concentration, mg/l	0.48	0.48	0.47	0.46	0.41	0.40
Sorbed amount, mg/g	9.51	4.76	1.90	0.95	0.47	0.19
Adsorption efficiency, %	95.12	95.20	95.25	95.35	95.90	96.00

The highest lead adsorption efficiency at 5.0 mg/l and 10.0 mg/l aqueous solutions was found at a yeast amount of 5.0 g. However, at a lower concentration of the solution, the highest adsorption efficiency was recorded – 70.00 %. On the other hand, at a concentration of 10.0 mg/l of lead ions, the highest adsorption efficiency was 96.00 %.

It should be noted that in solutions with a concentration of 10.0 mg/l of lead ions and at 0.1 g, 0.2 g, 0.5 g, 1.0 g and 2.0 g of yeast, the changes of adsorption efficiency were small, values fluctuated from 95.12 % to 95.90 %.

Studies of the adsorption of copper ions by yeast have shown that at higher concentrations of copper ions, i.e., 10.0 mg/l, a lower adsorption efficiency was achieved compared to 5.0 mg/l. Residual copper concentration in the sample, sorbed amount and adsorption efficiency results are presented in Table 3.9.

Table 3. 9. Dependence of adsorption efficiency on sorbent content at different copper concentrations (60 min)

Concentration Cu	Yeast amount / Contact time – 60 min					
5.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual copper concentration, mg/l	4.90	4.00	3.50	3.25	2.76	2.04
Sorbed amount, mg/g	0.10	0.50	0.30	0.10	0.11	0.05
Adsorption efficiency, %	2.00	20.00	30.00	35.00	44.80	59.20
10.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual copper concentration, mg/l	9.20	8.60	7.50	6.30	5.20	4.20
Sorbed amount, mg/g	0.80	0.70	0.50	0.37	0.24	0.11
Adsorption efficiency, %	8.00	14.00	25.00	37.00	48.00	58.00

The highest adsorption efficiency was recorded at 5.0 g of yeast amount in samples: at concentration of 5.0 mg/l, the adsorption efficiency of 59.20 % was recorded and at concentration of 10.0 mg/l, the adsorption efficiency of 58.00 % was observed.

Comparing the results of copper sorption of 5 min, 30 min and 60 min contact time, it was observed that yeast, which remained in the samples for a longer period of time, sorbed more copper ions, but not in all cases. For example, at concentration of 10.0 mg/l with 30 min of contact time, the value of adsorption efficiency ranged from 55.00 % to 71.50 % and when the contact time was extended to 60 min, the value of adsorption efficiency was recorded from 58.00 % to 59.20 %.

Studies on the adsorption of cadmium ions by yeast have shown that at lower concentrations of cadmium ions, i.e., 5.0 mg/l, maximum adsorption efficiency of 97.60 % was achieved. The results of the residual cadmium concentration in the sample, sorbed amount and adsorption efficiency are presented in Table 3.10.

Table 3. 10. Dependence of adsorption efficiency on sorbent content at different cadmium concentrations (60 min)

Concentration Cd	Yeast amount / Contact time – 60 min					
5.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual cadmium concentration, mg/l	0.76	0.60	0.50	0.51	0.29	0.12
Sorbed amount, mg/g	4.24	2.20	0.90	0.44	0.23	0.09
Adsorption efficiency, %	84.80	88.00	90.00	89.80	94.20	97.60
10.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual cadmium concentration, mg/l	1.55	2.00	1.12	1.23	0.86	0.65
Sorbed amount, mg/g	8.45	4.00	1.77	0.87	0.45	0.18
Adsorption efficiency, %	84.50	80.00	88.80	87.70	91.40	93.50

The highest adsorption efficiency was recorded at yeast amount of 5.0 g with samples with cadmium concentration of 5.0 mg/l. In cadmium 60 – min studies, a number of deviations from previously observed trends were also observed. For example, at cadmium concentration of 10.0 mg/l, an increase in adsorption efficiency from 1.0 g to 5.0 g of yeast was observed, but in cadmium aqueous solutions containing 0.1 g – 0.5 g of yeast, although a small, but a decrease was recorded.

The graphs below show the dependence of the adsorption efficiency of heavy metals on the yeast amount, results were recorded after contact time of 60 min.

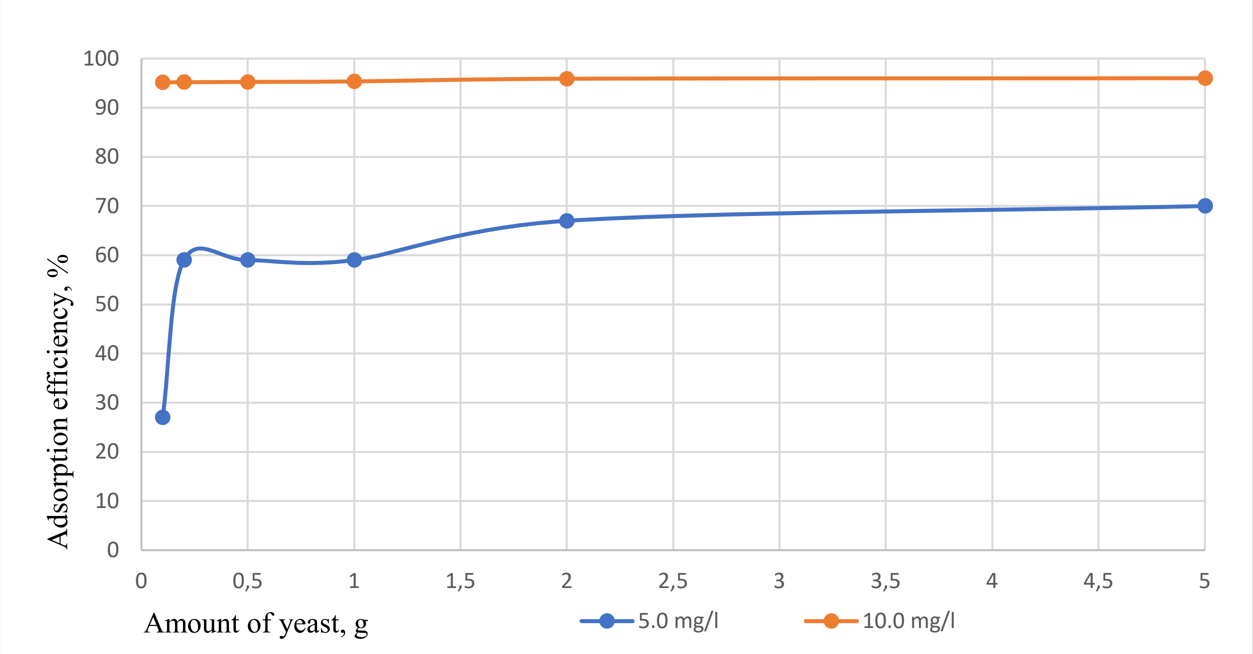


Fig. 3. 9. Graph of the dependence of lead adsorption efficiency on yeast amount (60 min contact time)

The highest efficiency of lead (Fig. 3.9) adsorption at concentration of 5.0 mg/l of aqueous solutions was recorded when the yeast amount ranged from 2.0 g to 5.0 g. On the other hand, the changes of adsorption efficiency were insignificant when measurements were made for 10.0 mg/l of aqueous solutions.

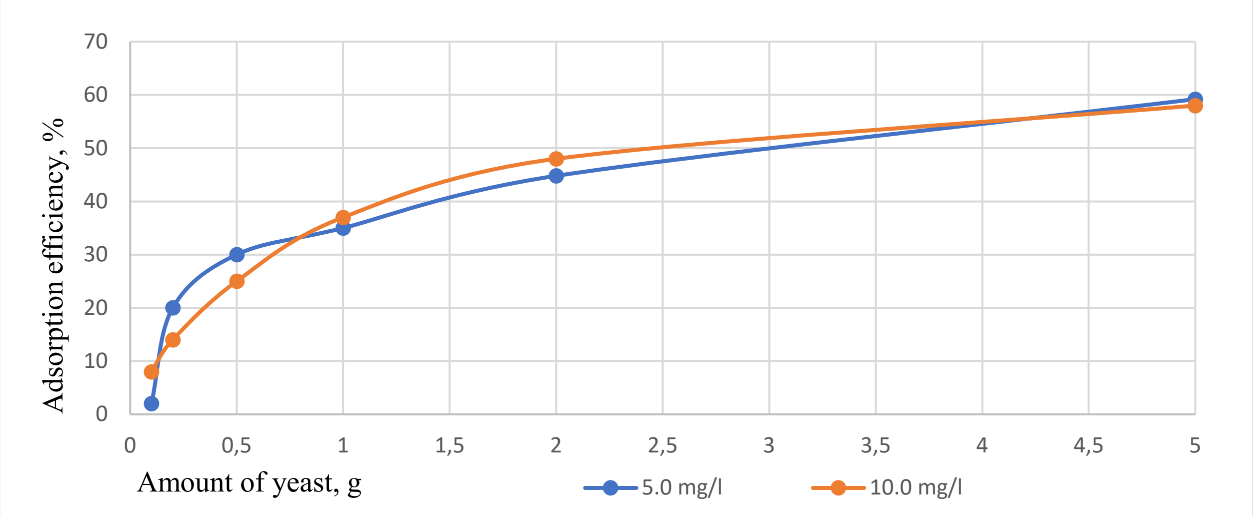


Fig. 3. 10. Graph of the dependence of copper adsorption efficiency on yeast amount (60 min of contact time)

Based on Figure 3.10 it was observed that in the tests with copper the values of adsorption efficiency were very variable. At 5.0 g of yeast, the highest value of adsorption efficiency was recorded at concentration of 5.0 mg/l.

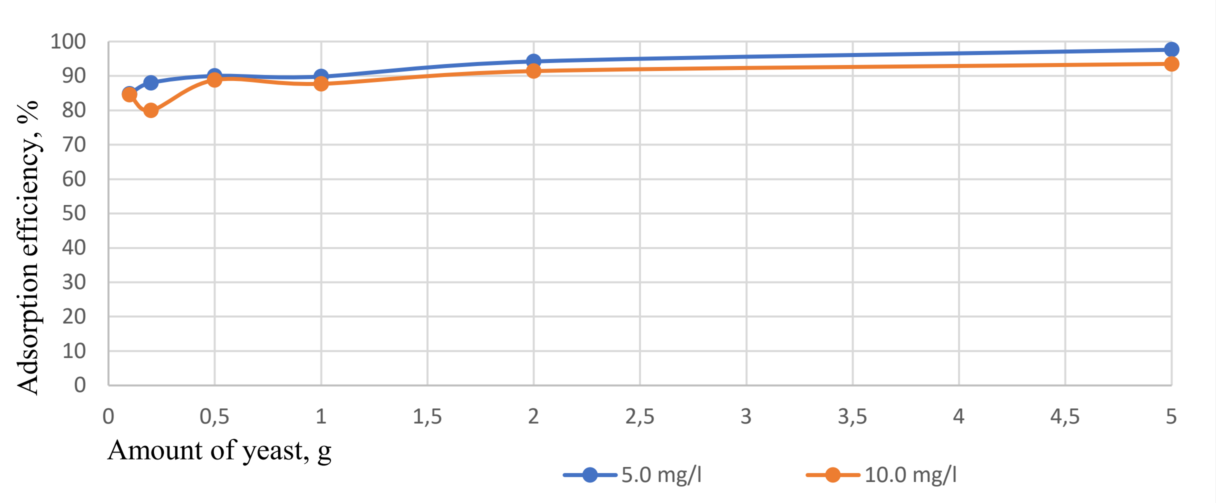


Fig. 3. 11. Graph of the dependence of cadmium adsorption efficiency on yeast amount (60 min of contact time)

Based on Figure 3.11 it was observed that in the tests with cadmium higher values of adsorption efficiency were recorded at lower concentrations of heavy metal. At 5.0 g of yeast, a higher value of adsorption efficiency was recorded with concentration of 5.0 mg/l.

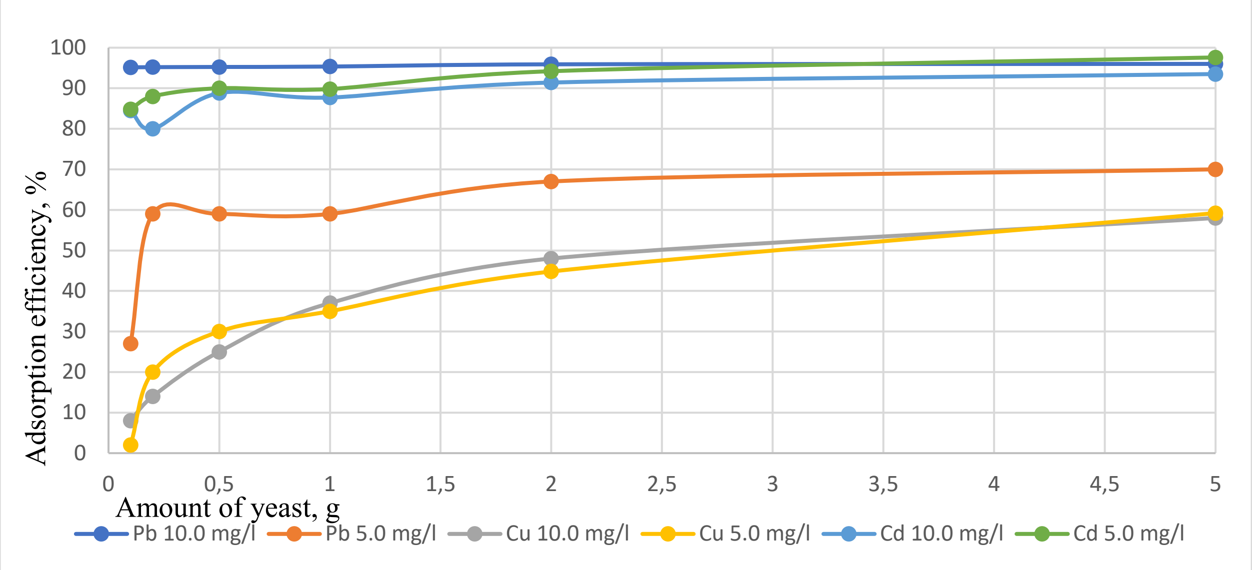


Fig. 3. 12. The dependence of lead, copper and cadmium adsorption efficiency on yeast amount (60 min contact time)

Studies have shown that with an increase of yeast amount in samples, higher values of adsorption efficiency were recorded (several exceptions were observed). Meanwhile, while comparing the different contact time of the sorption process of the same heavy metal, it was found out that at 5.0 mg/l solutions after 60 min of yeast and cadmium contact time, a higher sorption capacity values were recorded.

Studies of the adsorption of lead ions by yeast have shown that at higher concentrations of lead ions, i.e., 10.0 mg/l, higher adsorption efficiency was achieved compared to 5.0 mg/l. Residual lead concentration in the sample, sorbed amount and adsorption efficiency results are presented in Table 3.11.

Table 3. 11. Dependence of adsorption efficiency on sorbent content at different lead concentrations (4 h)

Concentration Pb	Yeast amount / Contact time – 4 h					
5.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual lead concentration, mg/l	0.30	0.28	0.23	0.215	0.17	0.15
Sorbed amount, mg/g	4.70	2.36	0.95	0.47	0.24	0.09
Adsorption efficiency, %	94.00	94.40	95.40	95.70	96.60	97.00
10.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual lead concentration, mg/l	0.41	0.35	0.34	0.28	0.26	0.08
Sorbed amount, mg/g	9.59	4.82	1.93	0.97	0.48	0.19
Adsorption efficiency, %	95.90	96.45	96.58	97.20	97.40	99.13

The highest lead adsorption efficiency at 5.0 mg/l and 10.0 mg/l aqueous solutions was found at a yeast amount of 5.0 g. However, at a lower concentration of the solution (5.0 mg/l), the highest adsorption efficiency was recorded – 97.00 %. Meanwhile at a concentration of 10.0 mg/l of lead ions, the highest adsorption efficiency was 99.13 %.

It should be noted that the changes of adsorption efficiency were small, values fluctuated from 94.00 % to 99.13 %. On the other hand, values of adsorption efficiency after 4 hours were quite higher than values after 5 min, 30 min or 60 min. Based on this information, it can assume that as the adsorption time increases, values of adsorption efficiency increase too.

Residual copper concentration in the sample, sorbed amount and adsorption efficiency results after 4 hours are presented in Table 3.12.

Table 3. 12. Dependence of adsorption efficiency on sorbent content at different copper concentrations (4 h)

Concentration Cu	Yeast amount / Contact time – 4 h					
5.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual copper concentration, mg/l	2.50	2.30	2.10	0.97	0.86	0.80
Sorbed amount, mg/g	2.50	1.35	0.58	0.40	0.20	0.08
Adsorption efficiency, %	50.00	54.00	58.00	80.60	82.80	84.00
10.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual copper concentration, mg/l	6.20	6.10	3.78	3.42	3.30	2.90
Sorbed amount, mg/g	3.80	1.95	1.24	0.65	0.33	0.14
Adsorption efficiency, %	38.00	39.00	62.20	65.80	67.00	71.00

The highest adsorption efficiency was recorded at 5.0 g of yeast amount in samples: at concentration of 5.0 mg/l, the adsorption efficiency of 84.00 % was recorded and at concentration of 10.0 mg/l, the adsorption efficiency of 71.00 % was observed.

Comparing the results of copper sorption at 5.0 mg/l, it was observed that from 0.1 g to 0.5 g of yeast values of adsorption efficiency were changed slightly: from 50.00 % to 58.00 %. On the other hand, at concentration of 10.0 mg/l with 4 hours of contact time, values of adsorption efficiency ranged from 38.00 % to 71.00 %.

Studies on the adsorption of cadmium ions by yeast have shown that at lower concentrations of cadmium ions, i.e., 5.0 mg/l, maximum adsorption efficiency of 94.80 % was achieved. The results of the residual cadmium concentration in the samples after 4 hours of adsorption time, sorbed amount and adsorption efficiency are presented in Table 3.13.

Table 3. 13. Dependence of adsorption efficiency on sorbent content at different cadmium concentrations (4 h)

Concentration Cd	Yeast amount / Contact time – 4 h					
5.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual cadmium concentration, mg/l	0.46	0.39	0.46	0.30	0.27	0.26
Sorbed amount, mg/g	4.54	2.30	0.90	0.47	0.23	0.09
Adsorption efficiency, %	90.80	92.20	90.80	94.00	94.60	94.80
10.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual cadmium concentration, mg/l	1.20	1.08	1.10	0.65	0.58	0.58
Sorbed amount, mg/g	8.80	4.46	1.78	0.93	0.47	0.18
Adsorption efficiency, %	88.00	89.20	89.00	93.50	94.20	94.20

The highest adsorption efficiency was recorded at yeast amount of 5.0 g. At cadmium concentration of 5.0 mg/l, slightly increase in adsorption efficiency from 0.1 g to 0.5 g of yeast was observed.

Comparing the results of cadmium sorption at 10.0 mg/l, it was observed that from 0.1 g to 0.5 g of yeast values of adsorption efficiency were changed slightly: from 88.00 % to 89.00 %. On the other hand, values of adsorption efficiency changed a lot, when amount of yeast reached 1.0 g.

The graphs below show the dependence of the adsorption efficiency of heavy metals on the yeast amount, results were recorded after contact time of 4 hours.

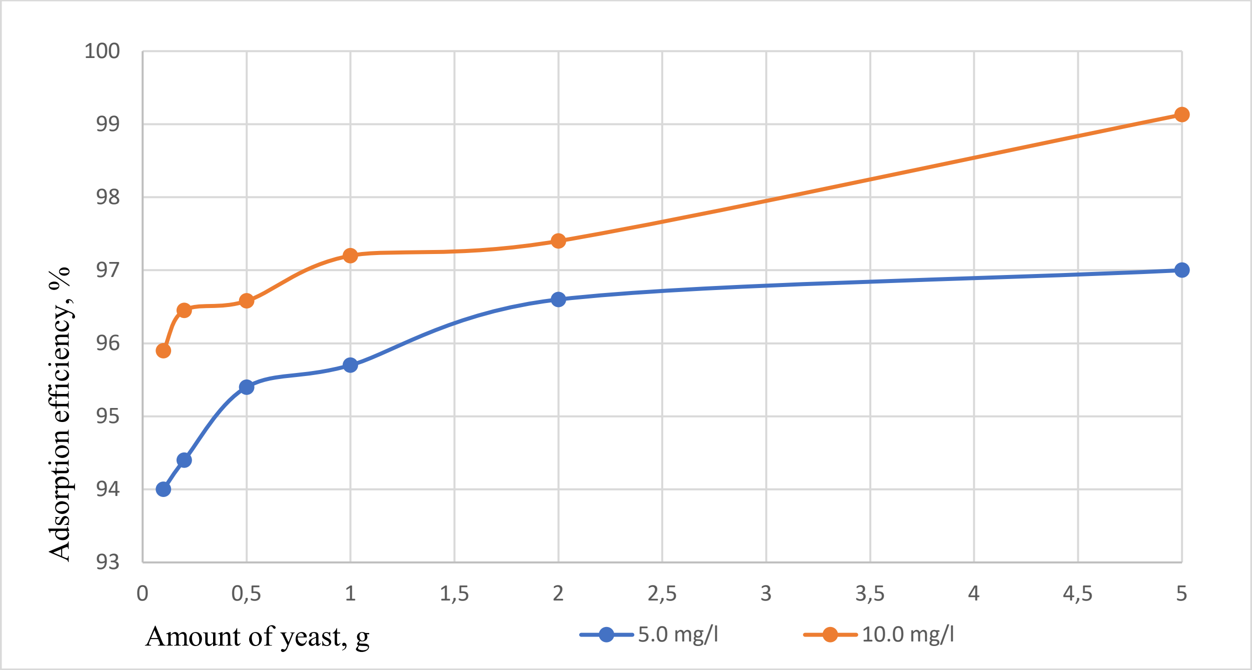


Fig. 3. 13. Graph of the dependence of lead adsorption efficiency on yeast amount (4 h contact time)

Based on the graph above (Fig. 3.13) it was concluded that higher values of adsorption efficiencywere typical for 10.0 mg/l of aqueous solutions of lead.

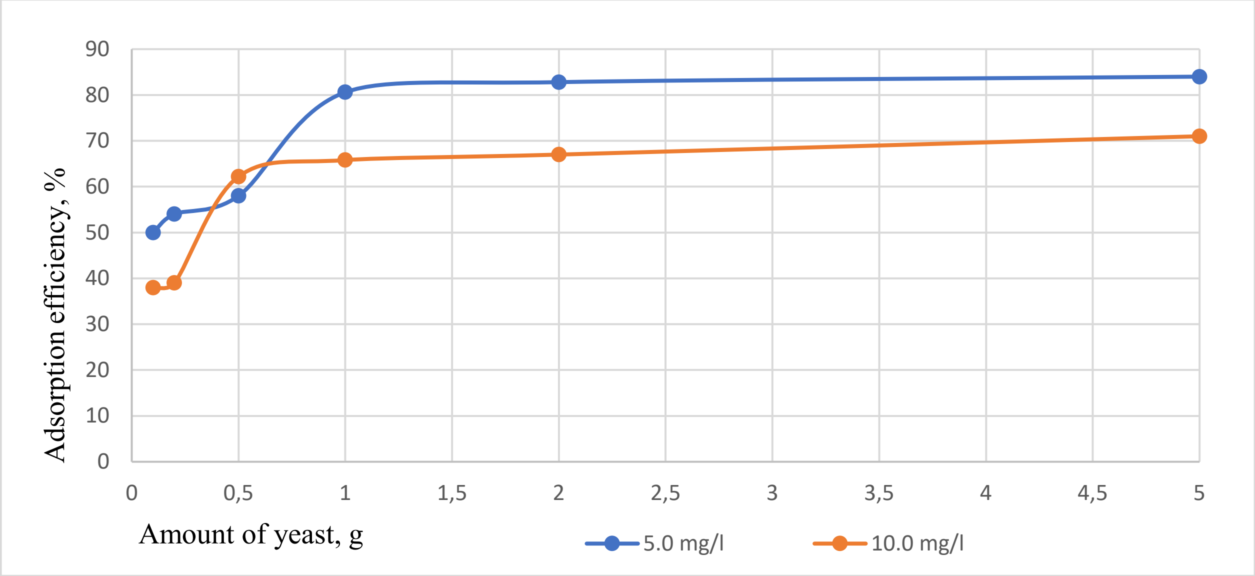


Fig. 3. 14. Graph of the dependence of copper adsorption efficiency on yeast amount (4 h of contact time)

Based on Figure 3.14 it was observed that in the tests with cadmium higher values of adsorption efficiency were recorded at lower concentrations of heavy metal, but only up to 0.5 g of yeast.

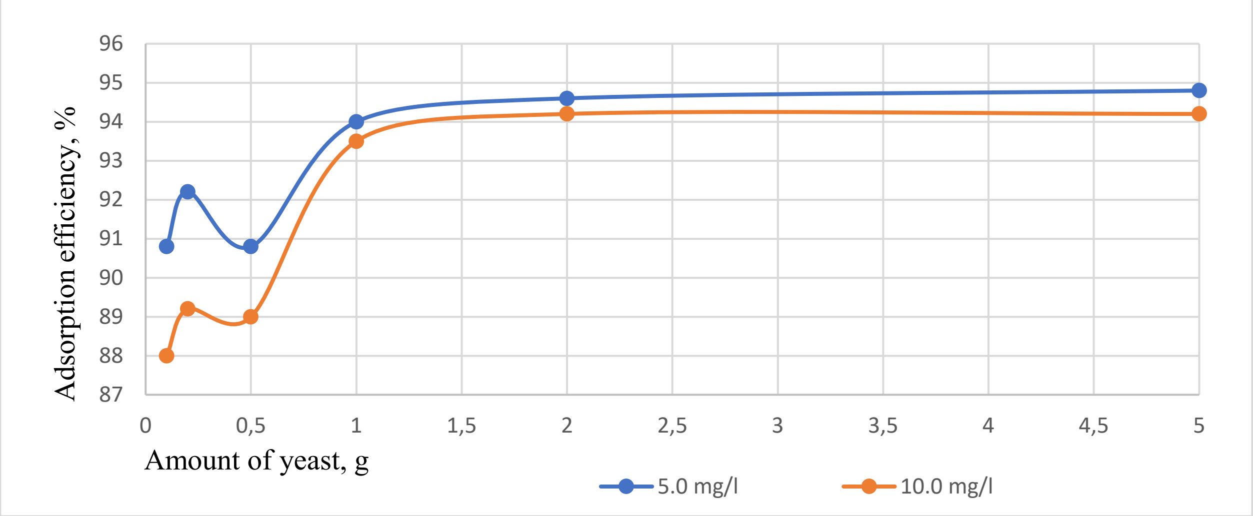


Fig. 3. 15. Graph of the dependence of cadmium adsorption efficiency on yeast amount (4 h of contact time)

Based on Figure 3.15 it was observed that in the tests with cadmium higher values of adsorption efficiency were recorded at lower concentrations of heavy metal. At 5.0 g of yeast, the highest value of adsorption efficiency was recorded with concentration of 5.0 mg/l.

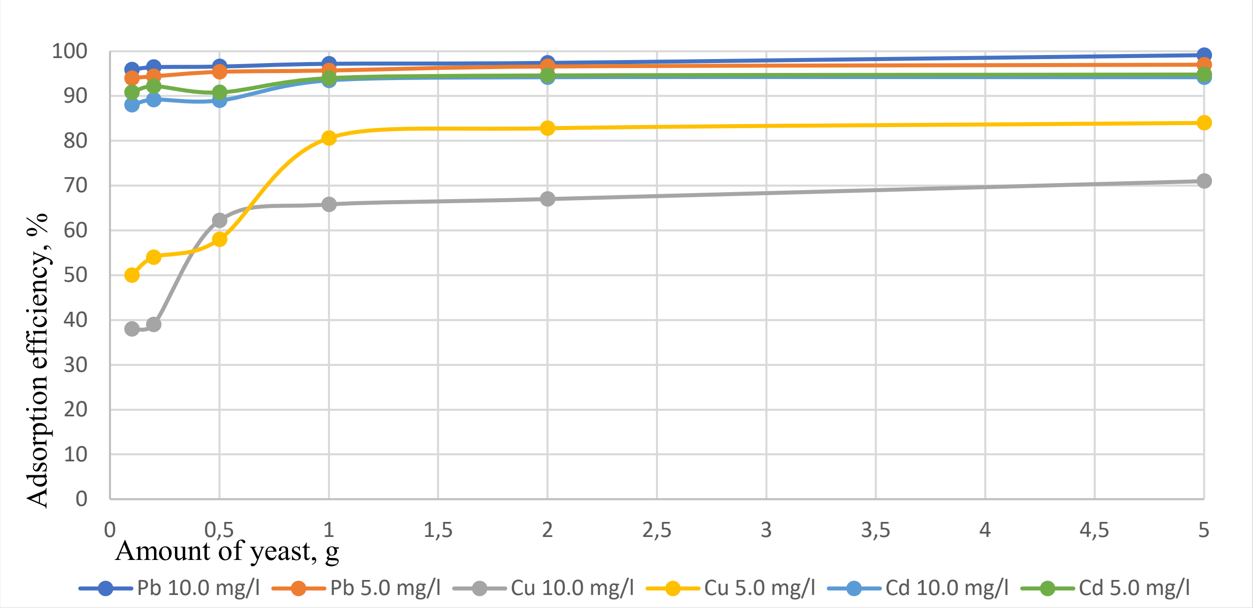


Fig. 3. 16. The dependence of lead, copper and cadmium adsorption efficiency on yeast amount (4 h contact time)

Studies have shown that with an increase of yeast amount in samples, higher values of adsorption efficiency were recorded (several exceptions were observed).

Based on the performed studies after 4 hours of contact time, it was observed that in cases of copper and cadmium ion solutions use for adsorption, higher values of adsorption efficiency were recorded at lower concentrations of these heavy metals.

Residual lead concentration in the sample, sorbed amount and adsorption efficiency results after 24 hours are presented in Table 3.14.

Table 3. 14. Dependence of adsorption efficiency on sorbent content at different lead concentrations (24 h)

Concentration Pb	Yeast amount / Contact time – 24 h					
5.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual lead concentration, mg/l	0.28	0.24	0.20	0.15	0.14	0.10
Sorbed amount, mg/g	4.72	2.38	0.96	0.48	0.24	0.09
Adsorption efficiency, %	94.40	95.20	96.00	97.00	97.20	98.00
10.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual lead concentration, mg/l	0.60	0.55	0.52	0.40	0.35	0.30
Sorbed amount, mg/g	9.40	4.72	1.89	0.96	0.48	0.19
Adsorption efficiency, %	94.00	94.50	94.80	96.00	96.50	97.00

The highest lead adsorption efficiency at 5.0 mg/l and 10.0 mg/l aqueous solutions was found at a yeast amount of 5.0 g. The highest adsorption efficiency at 5.0 mg/l was recorded – 98.00 %. Meanwhile at a concentration of 10.0 mg/l of lead ions, the highest adsorption efficiency was 97.00 %.

It should be noted that the changes of adsorption efficiency were small, values fluctuated from 94.00 % to 98.00 %.

Residual copper concentration in the sample, sorbed amount and adsorption efficiency results after 24 hours are presented in Table 3.15.

Table 3. 15. Dependence of adsorption efficiency on sorbent content at different copper concentrations (24 h)

Concentration Cu	Yeast amount / Contact time – 24 h					
5.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual copper concentration, mg/l	1.62	0.90	0.99	0.78	0.46	0.42
Sorbed amount, mg/g	3.38	2.05	0.80	0.42	0.22	0.09
Adsorption efficiency, %	67.60	82.00	80.20	84.40	90.80	91.60
10.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual copper concentration, mg/l	3.65	3.13	2.58	2.28	2.14	1.34
Sorbed amount, mg/g	6.35	3.43	1.48	0.77	0.39	0.17
Adsorption efficiency, %	63.50	68.70	74.20	77.20	78.60	86.60

Based on table 3.15. it was observed that in the tests with copper higher values of adsorption efficiency were recorded at lower concentrations of heavy metal. At 5.0 g of yeast, the highest value of adsorption efficiency was recorded with concentration of 5.0 mg/l (91.60 %).

The results of the residual cadmium concentration in the sample after 24 hours of adsorption time, sorbed amount and adsorption efficiency are presented in Table 3.16.

Table 3. 16. Dependence of adsorption efficiency on sorbent content at different cadmium concentrations (24 h)

Concentration Cd	Yeast amount / Contact time – 24 h					
5.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual cadmium concentration, mg/l	2.90	2.52	2.30	1.70	0.90	0.48
Sorbed amount, mg/g	2.10	1.24	0.54	0.33	0.20	0.09
Adsorption efficiency, %	42.00	49.60	54.00	66.00	82.00	90.40
10.0 mg/l	0.1 g	0.2 g	0.5 g	1.0 g	2.0 g	5.0 g
Residual cadmium concentration, mg/l	4.18	3.33	2.63	1.91	1.06	0.98
Sorbed amount, mg/g	5.82	3.33	1.47	0.80	0.44	0.18
Adsorption efficiency, %	58.20	66.70	73.70	80.90	89.40	90.20

The highest adsorption efficiency was observed with 2.0 – 5.0 g of yeast: at 5.0 mg/l, 90.40 % adsorption efficiency was recorded and at 10.0 mg/l 90.20 % adsorption efficiency was observed.

The graphs below show the dependence of heavy metal adsorption efficiency after 24 hours on yeast content.

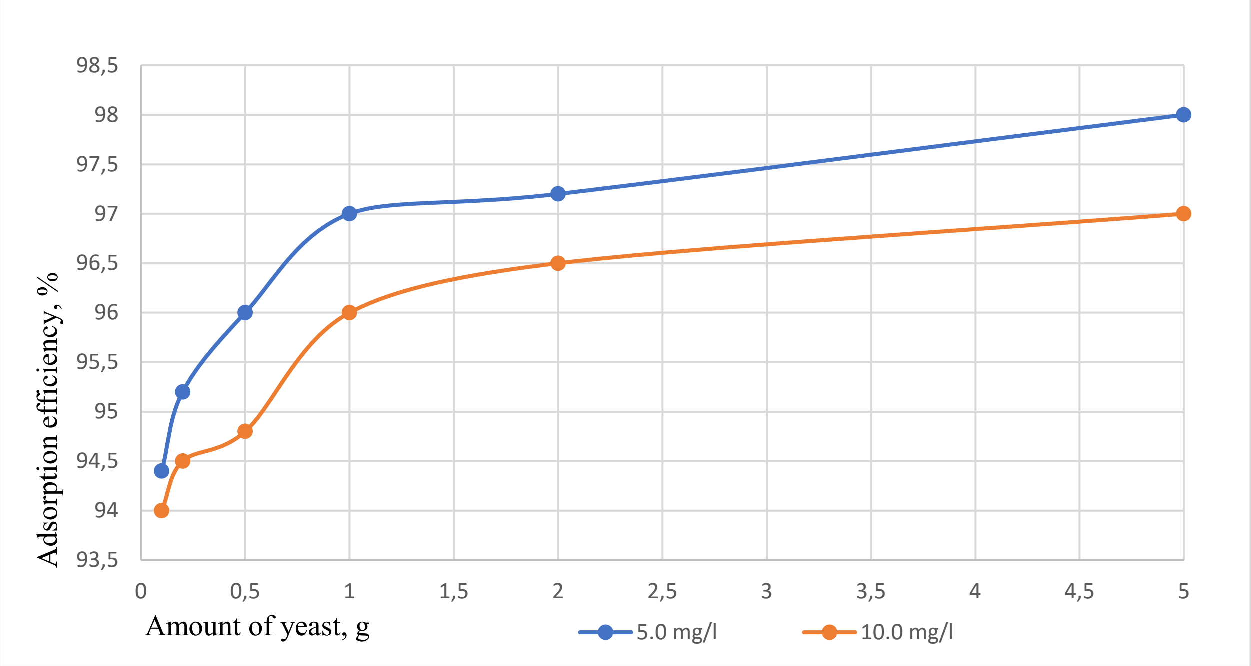


Fig. 3. 17. Graph of the dependence of lead adsorption efficiency on yeast amount (24 h contact time)

Based on the graph above (Fig. 3.17) it could be concluded that higher values of adsorption efficiencyare typical for 5.0 mg/l of aqueous solutions of lead.

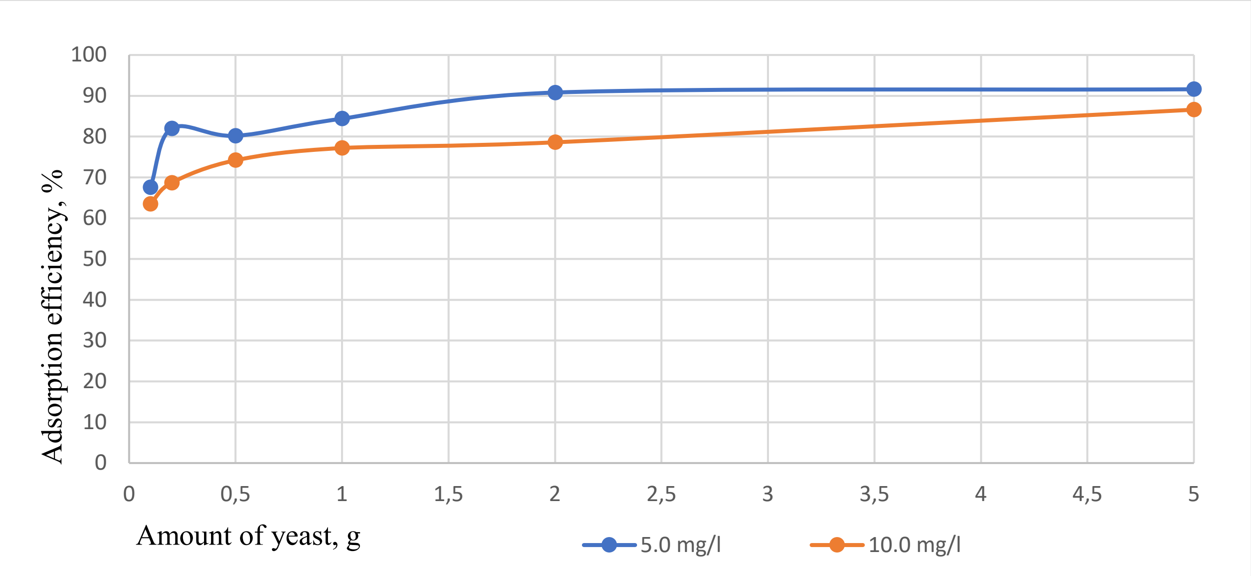


Fig. 3. 18. Graph of the dependence of copper adsorption efficiency on yeast amount (24 h of contact time)

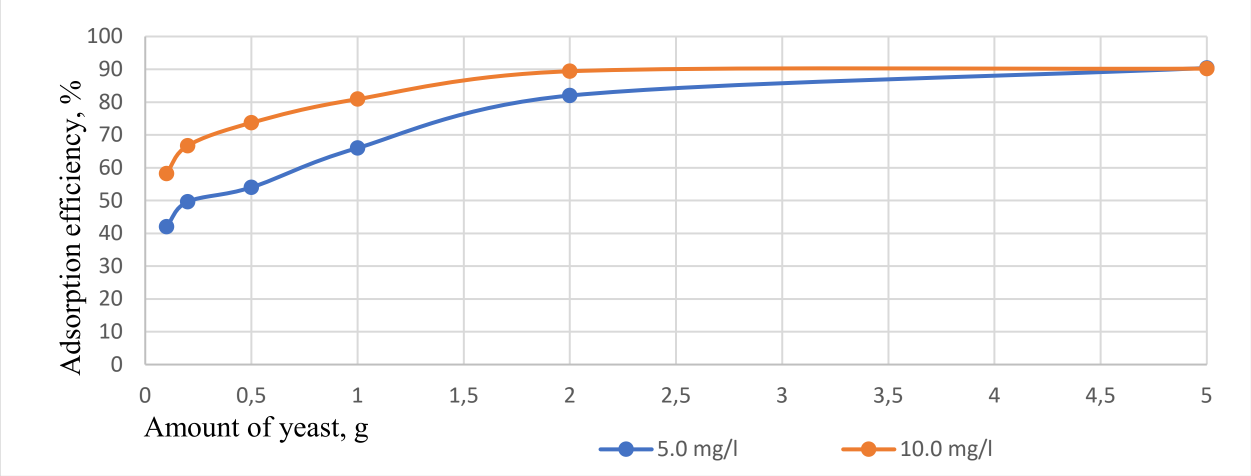


Fig. 3. 19. Graph of the dependence of cadmium adsorption efficiency on yeast amount (24 h of contact time)

The highest efficiency of copper (Fig. 3.18) adsorption at concentration of 5.0 mg/l of aqueous solutions was recorded when the yeast amount ranged from 1.0 g to 5.0 g. On the other hand, the changes of adsorption efficiency were insignificant when measurements were made for 10.0 mg/l of aqueous solutions.

Based on Figure 3.19 it was observed that in the tests with cadmium higher values of adsorption efficiency were recorded at higher concentrations of heavy metal. At 5.0 g of yeast, the values of adsorption efficiency were recorded almost the same.

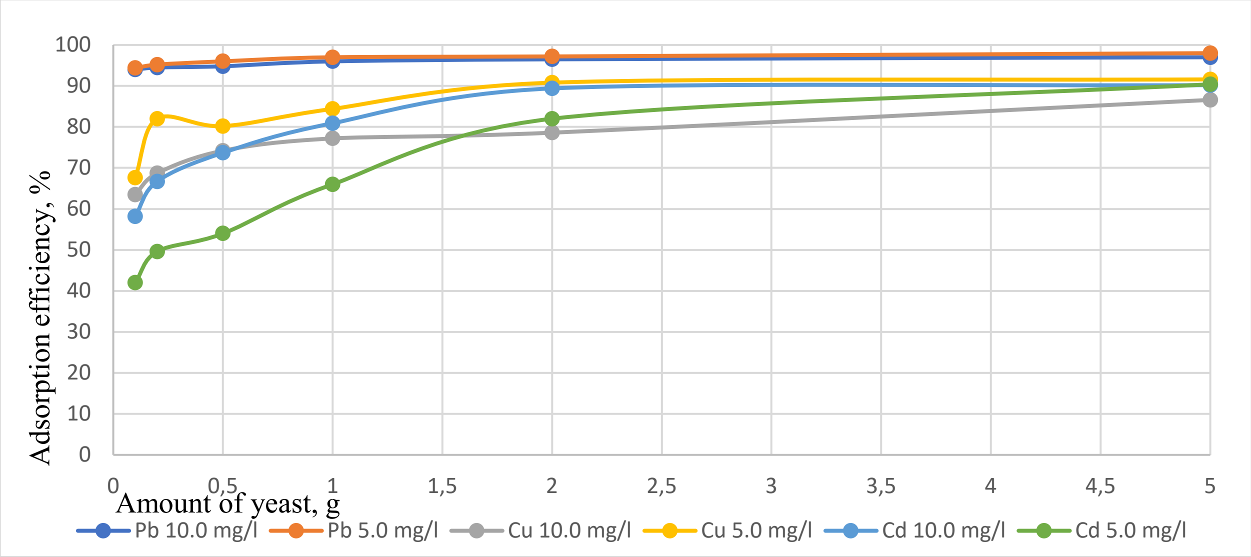


Fig. 3. 20. The dependence of lead, copper and cadmium adsorption efficiency on yeast amount (24 h contact time)

Based on the performed studies after 24 hours of contact time, it was observed that in cases of lead and copper ions solutions use for adsorption, higher values of adsorption efficiency were recorded at lower concentrations of these heavy metals.

Evaluating the values of measurements for the correlation coefficient (Table 3.17), it can be concluded that almost all relationships between parameters of amount of yeast and adsorption efficiency were very high or high. Although, the correlation coefficient of 5.0 mg/l of copper aqueous solution, was very low.

Table 3. 17. Correlation coefficient, arithmetic mean and standard deviation of measurements

	Values of correlation coefficient					Arithmetic mean
	5 min	30 min	60 min	4 h	24 h	
Pb						
5.0 mg/l	0.79	0.40	0.60	0.84	0.82	0.69
10.0 mg/l	0.96	0.98	0.90	0.97	0.85	0.93
Cu						
5.0 mg/l	0.84	-0.01	0.91	0.74	0.89	0.68
10.0 mg/l	0.61	0.76	0.78	0.74	0.78	0.73
Cd						
5.0 mg/l	0.67	0.81	0.86	0.74	0.72	0.76
10.0 mg/l	0.83	0.69	0.88	0.68	0.88	0.79

First of all, after experimental studies it can conclude that the longer the adsorption contact time was, the higher the adsorption efficiency values were recorded.

Secondly, the highest adsorption efficiency values were characteristic for lead and cadmium ions. On the other hand, studies with copper ions gave the lowest values of adsorption efficiency.

Based on literature review it can be concluded that yeast could be reused second time (it was not research during these experiments). It is very important because a small amount of waste is generated after the adsorption process.

We live in a modern world with a steadily growing population and expanding infrastructure. Unfortunately, this trend has its downsides: the amount of waste is increasing, pollution levels are constantly rising, so it is very important to promote the idea of circular economics. If we could re-use waste, that opportunity should be used.

Conclusions of the third chapter

1. The results of the study of the influence of the contact time between the adsorbent (*Saccharomyces cerevisiae* or *Brewer's* yeast) and the solutions of heavy metal ions (Pb^{2+}, Cu^{2+} and Cd^{2+}) on the adsorption showed that the adsorption process can be recorded after only 5 minutes of contact time.

2. Experimental studies have shown that the pH of the solution had a significant effect on the adsorption efficiency. Maximum values of adsorption efficiency were recorded when the pH of the solution was 5.0. At lower pH values, the adsorption of heavy metals was negligible, because the adsorption in the acidic medium does not occur intensively.

3. It was found out that with the increase of yeast amount in aqueous heavy metal ion samples, higher values of adsorption efficiency were recorded (several exceptions were observed).

4. Based on the obtained standard deviation values, it could be state that the results of the experimental studies can be considered reliable.

5. According to the information provided in the scientific articles and the results above, it can conclude that the removal of lead and cadmium ions has higher opportunity to be used in wastewater treatment plants than copper ions.

4. ADSORPTION MODELING USING VISUAL MINTEQ

4.1. Mathematical substantiation of modeling

The main purpose for Visual MINTEQ software program is to perform calculations of adsorption. Down below is provided the basic information which need to know every user before using this program:

1. mg/l, g/l, kg/l are the units of amount of solid in solution.
2. sites/m^2, sites/nm^2 – units for the concentration.
3. m^2/g – units for the specific surface area.
4. mg/g, mg/kg, mol/kg are the units for concentration of contaminant on the solid (Visual MINTEQ manual, 2021).

The main working unit for Visual MINTEQ is mol/l of solution. This fact allows all calculations to be performed in the exactly same manner as acid/base or complexation reactions (Visual MINTEQ manual, 2021).

Solid metal oxides and other surfaces often are strong adsorbers of aqueous species, such as Pb^{2+}, $PO4^{3-}$ etc. There are a few types of options for adsorption reactions. Types are divided into these groups:

1. Simple isotherms:
    - Linear isotherm;
    - Langmuir isotherm;
    - Freundlich isotherm.
2. Ion exchange adsorption of ions.

Electrostatic double layer models (DLM) are the simplest model in which both chemical and electrostatic contributions to surface complexation are estimated. Visual MINTEQ can be used to describe most heterogeneous reactions (Visual MINTEQ manual, 2021).

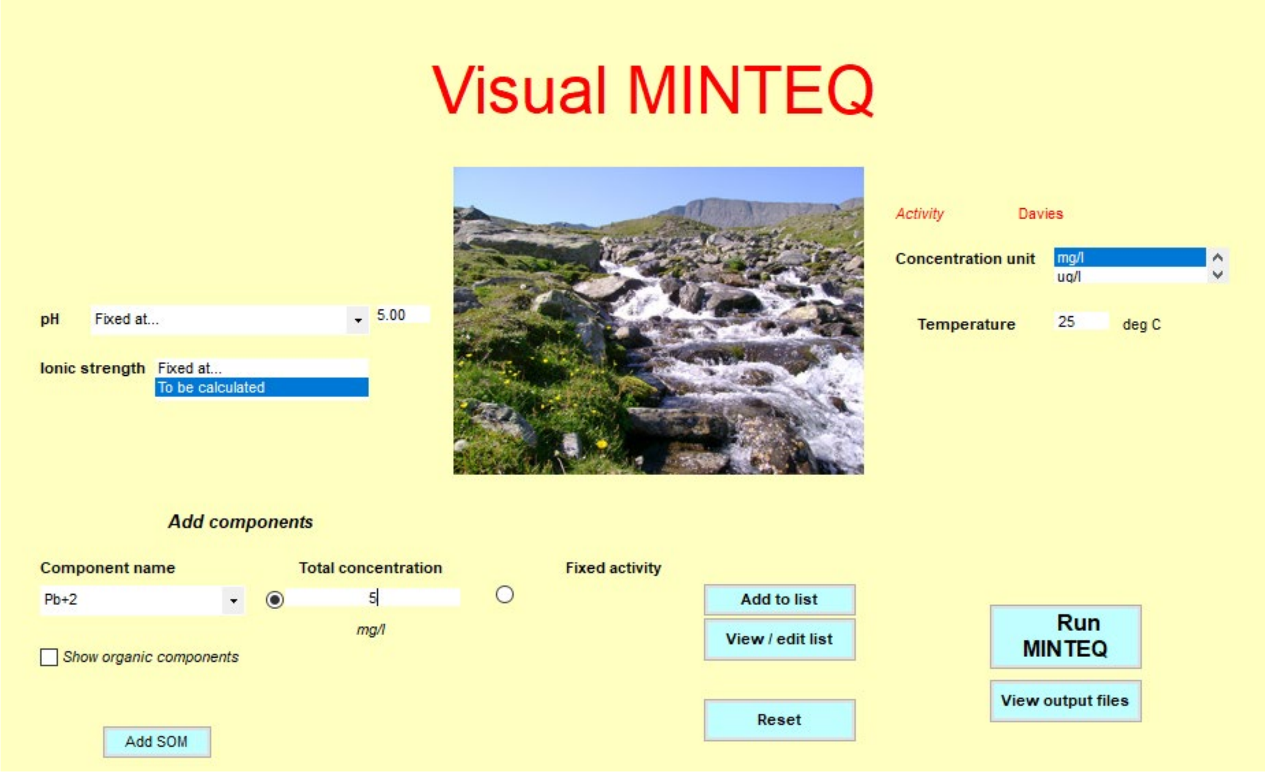
4.2. Methodology of modeling

In order to start working with software of Visual MINTEQ, the first thing which should be done – problem identification.

First of all, the user has to add the data (main menu). Data is shown only when the program is opened for the first time. If user know the value of pH, then it is fixed, so the user have to enter the pH value itself. If the value of pH has to be calculated, user could choose Calculated from mass and charge balance or Calculated from mass balance.

Then user need to choose the units of concentration for the data of input. On the other hand, the results will be shown in moles per liter (Visual MINTEQ tutorial, 2021).

Process mechanisms were investigated using the Visual MINTEQ program to model reactions between yeast of S. cerevisiae material and lead (II), copper (II), cadmium (II) ions. The temperature of the aqueous solution was chosen to be 25 °C, and the concentrations of dissolved chemicals were given in the selected dimensions (mg/l) (Fig. 4.1).



Activity Davies

Concentration unit: mg/l (ug/l)

pH: Fixed at... 5.00

Temperature: 25 deg C

Ionic strength: Fixed at... / To be calculated

Component name: Pb+2

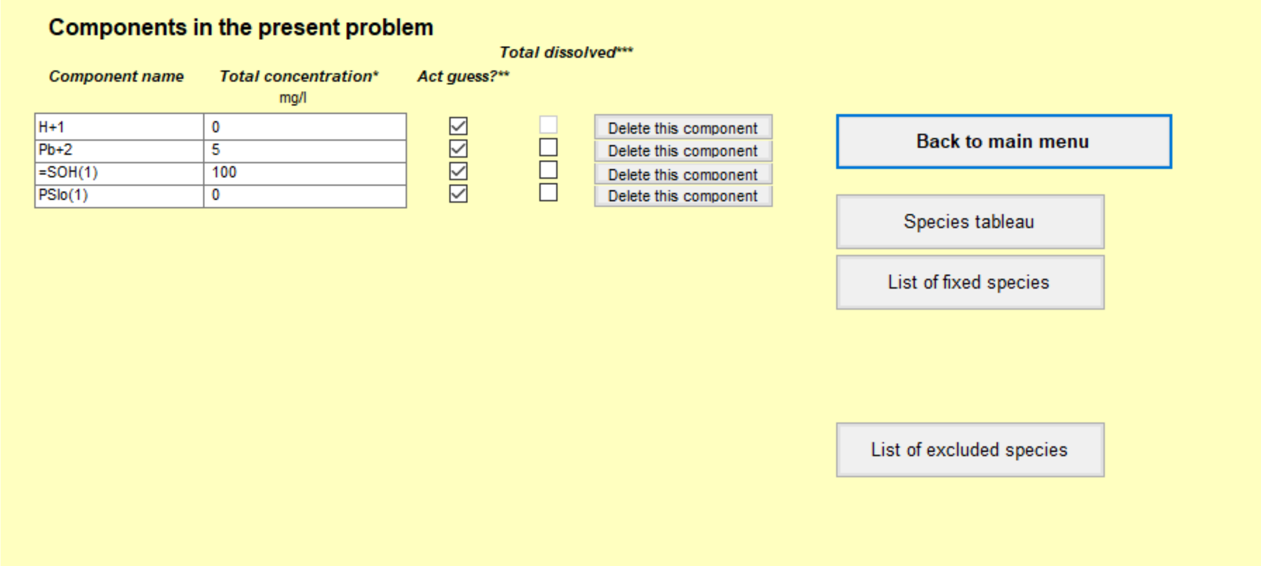
● Total concentration: 5 mg/l

○ Fixed activity

☐ Show organic components

Fig. 4. 1. Visual MINTEQ main window

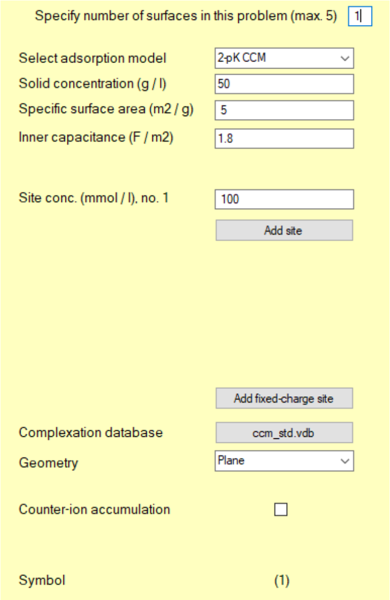
The simulation was performed 6 times when the initial introduced lead (Pb $^{2+}$) concentration in the solution was 5.0 mg/l and 10.0 mg/l. Respectively copper (Cu $^{2+}$) and cadmium (Cd $^{2+}$) concentrations in the solution – 5.0 mg/l and 10.0 mg/l (Fig. 4.2).



Component name	Total concentration* mg/l	Act guess?**	Total dissolved***	
H+1	0	☑	☐	Delete this component
Pb+2	5	☑	☐	Delete this component
=SOH(1)	100	☑	☐	Delete this component
PSIo(1)	0	☑	☐	Delete this component

Fig. 4. 2. Review of the concentrations of dissolved components used in Visual MINTEQ in solution when modeling the adsorption of lead ions

Modeling of the reaction of lead (II), copper (II) and cadmium (II) dissolved in aqueous solution with yeast of S. cerevisiae was performed using a commonly used surface complexation model – a constant volume model (2pK CCM) (Fig. 4.3).



Specify number of surfaces in this problem (max. 5) 1

Select adsorption model: 2-pK CCM
Solid concentration (g / l): 50
Specific surface area (m2 / g): 5
Inner capacitance (F / m2): 1.8

Site conc. (mmol / l), no. 1: 100

Complexation database: ccm_std.vdb
Geometry: Plane

Counter-ion accumulation ☐

Symbol (1)

Fig. 4. 3. Input data for calculations

The adsorption of lead, copper and cadmium from the aqueous solution was modeled separately. Other heavy metals that can compete for sorption sites were not included in the model. The aim was to determine the immobilization efficiency of individual heavy metal ions at different concentrations using only yeast of S. cerevisiae.

The simulation was performed using the following input conditions: pH 5 and amount of yeast (0.1 g, 0.2 g, 0.5 g, 1.0 g, 2.0 g and 5.0 g) as in the experimental studies. Although optimization condition was used: specific surface area of yeast was increased.

4.3. Analysis of mathematical modeling results

The results of modeling the dependence of lead (II) ions adsorption using different amount of *Saccharomyces cerevisiae* yeast are presented in Fig. 4.4 and 4.5.

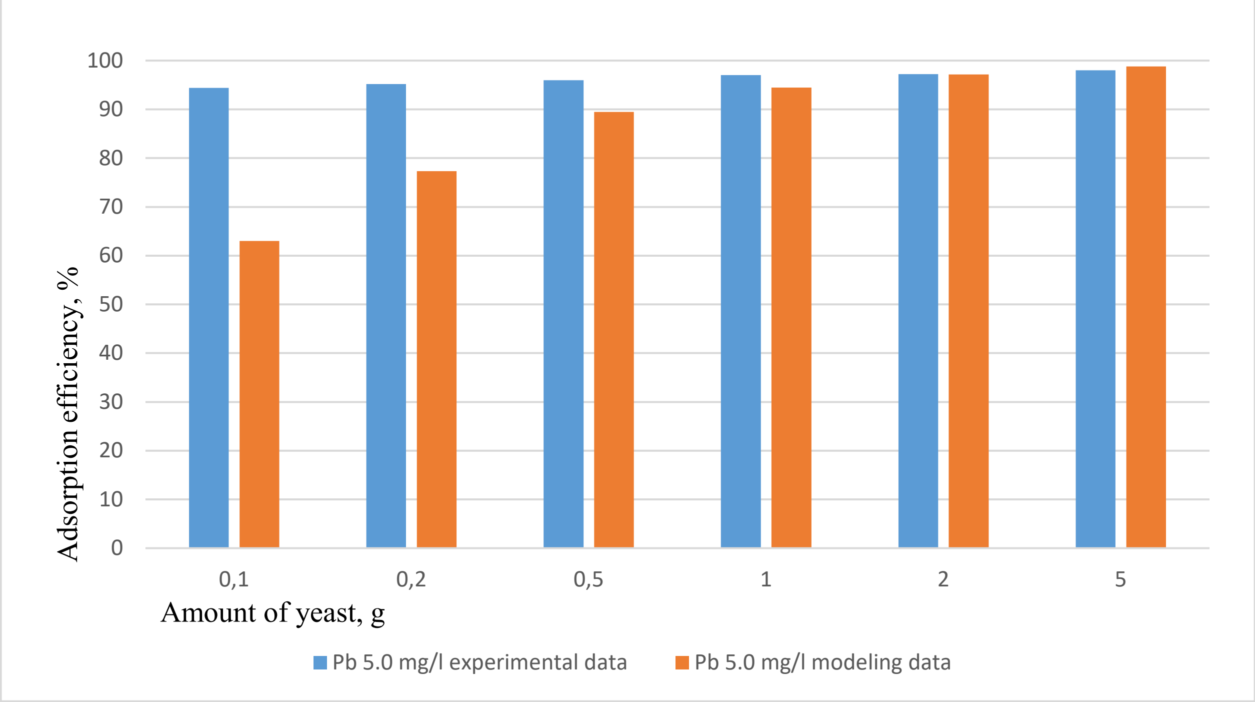


Fig. 4. 4. Experimental and modeling results of lead ions adsorption (5.0 mg/l)

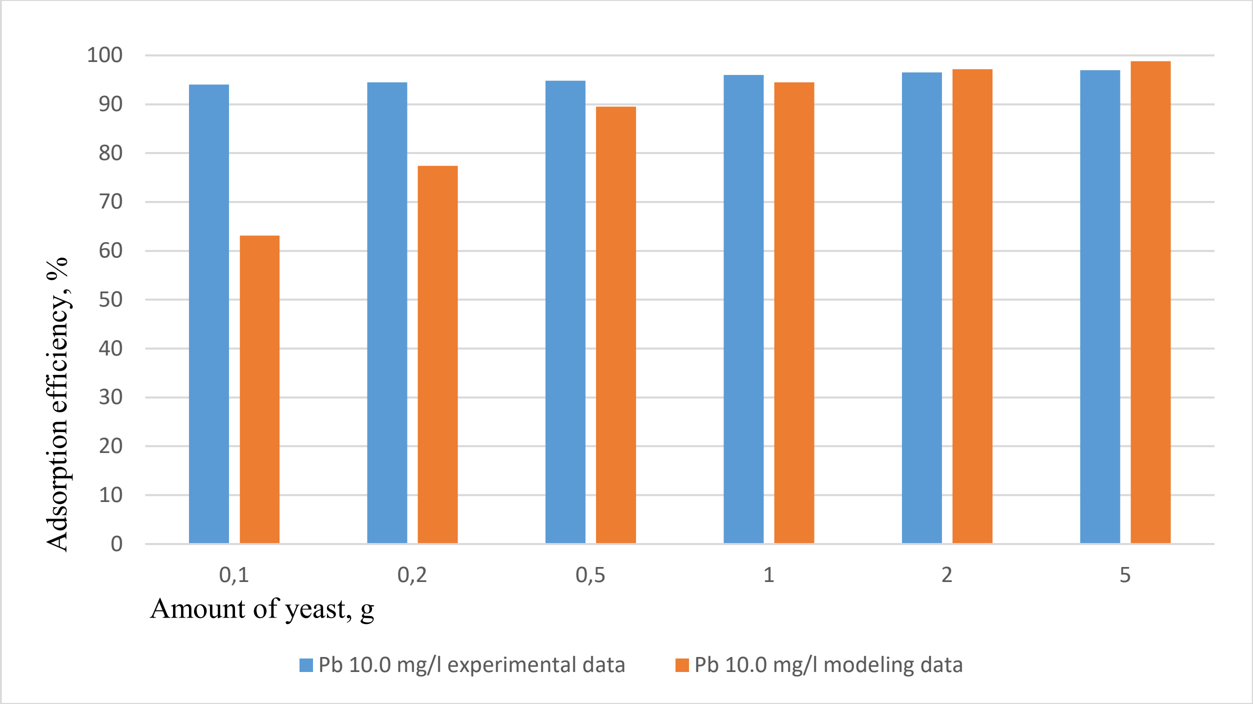


Fig. 4. 5. Experimental and modeling results of lead ions adsorption (10.0 mg/l)

It is necessary to mention that results of 24 h adsorption experimental studies were used in the modeling.

As it could be seen from figures 4.4 and 4.5 the highest adsorption efficiency was recorded at 5.0 g of yeast amount in samples: at concentration of 5.0 mg/l, the adsorption efficiency of lead was 98.83 % and at concentration of 10.0 mg/l the adsorption efficiency of 98.83 % was observed too.

Meanwhile, during experimental studies, the highest lead adsorption efficiency at 5.0 mg/l and 10.0 mg/l aqueous solutions was also found at yeast amount of 5.0 g. The highest adsorption efficiency at 5.0 mg/l was recorded – 98.00 % and at concentration of 10.0 mg/l of lead ions, the highest adsorption efficiency was 97.00 %.

It should be noted that the changes between experimental data and modeling data of adsorption efficiency were small, values fluctuated only a few percent.

The results of modeling the dependence of copper (II) ions adsorption using different amount of *Saccharomyces cerevisiae* yeast are presented in Fig. 4.6 and 4.7.

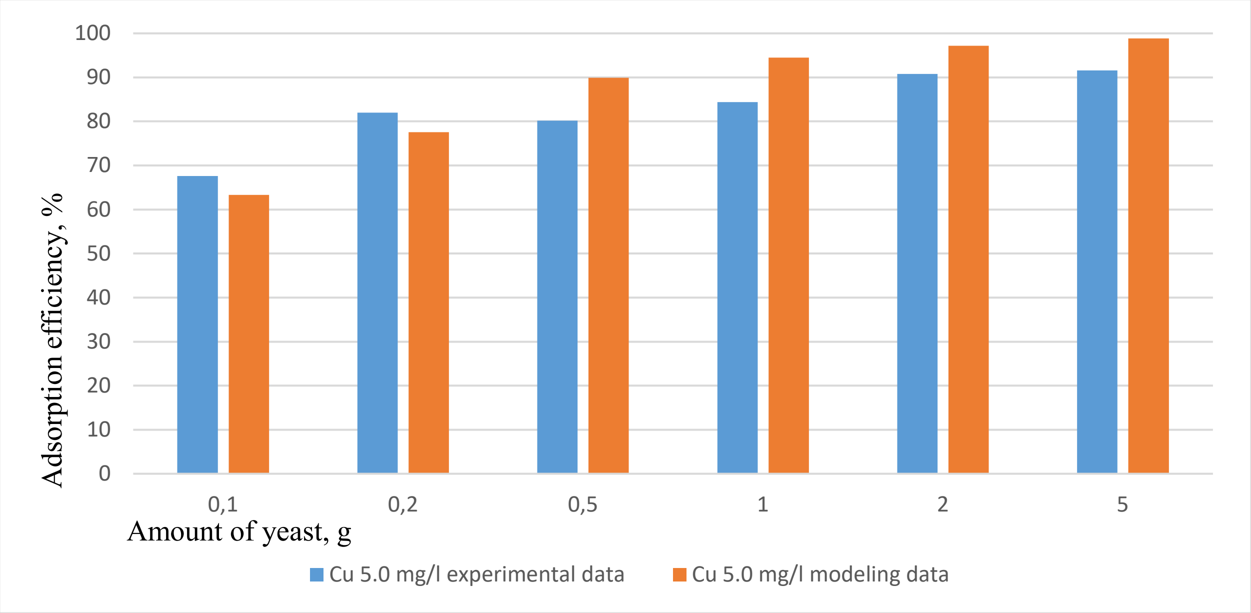


Fig. 4. 6. Experimental and modeling results of copper ions adsorption (5.0 mg/l)

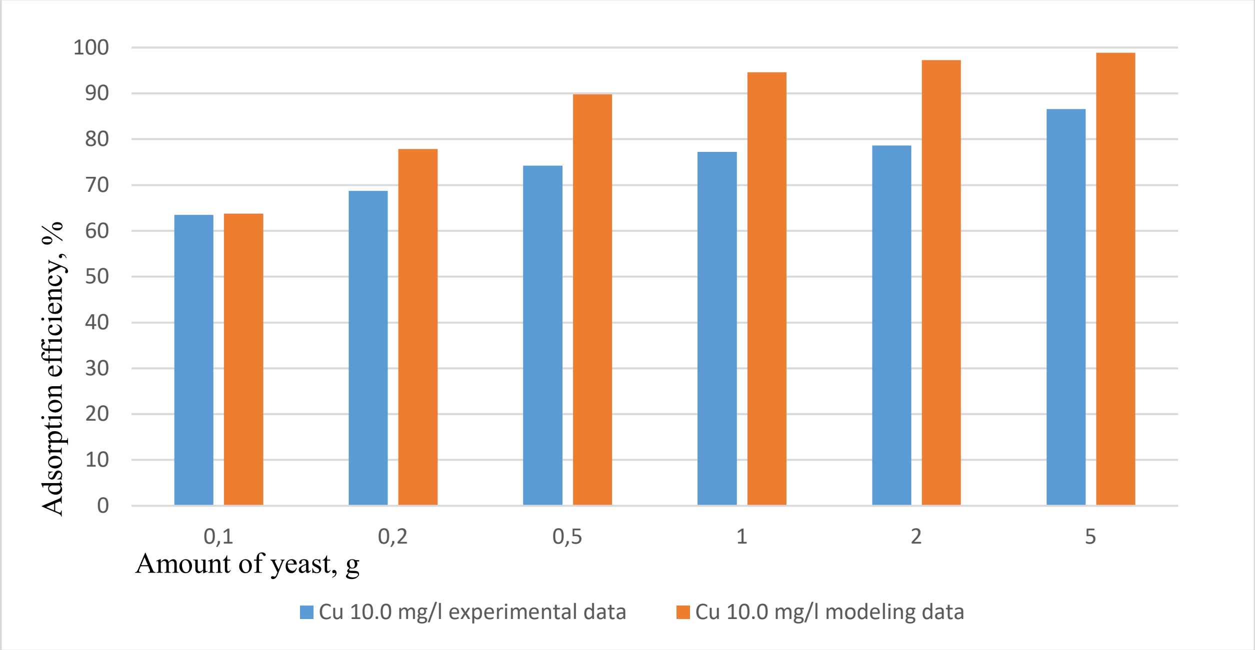


Fig. 4. 7. Experimental and modeling results of copper ions adsorption (10.0 mg/l)

As it could be seen from figures 4.6 and 4.7 the highest adsorption efficiency was also recorded at 5.0 g of yeast amount in samples: at concentration of 5.0 mg/l, the adsorption efficiency of copper was 98.85 % and at concentration of 10.0 mg/l the adsorption efficiency of 98.87 % was observed. The values of the modeling results were 9 – 20 % higher.

Based on modeling data it can conclude that the concentration of copper ions has negligible effect on adsorption efficiency using *Saccharomyces cerevisiae* yeast.

The results of modeling the dependence of cadmium (II) ions adsorption using different amount of *Saccharomyces cerevisiae* yeast are presented in Fig. 4.8 and 4.9.

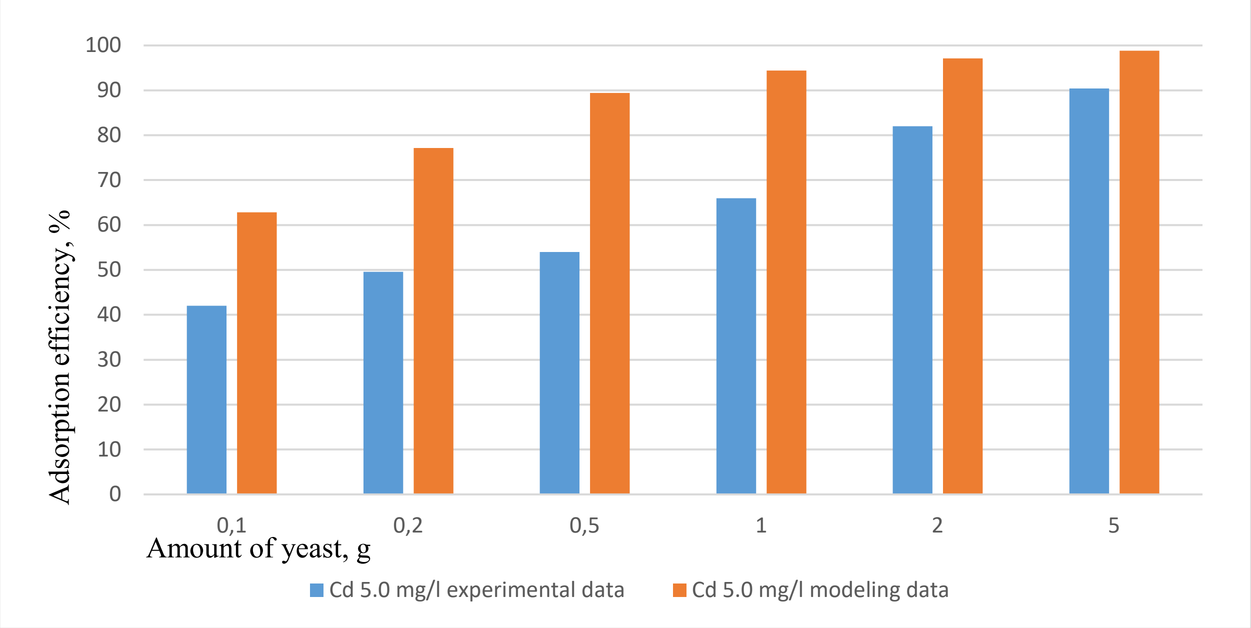


Fig. 4. 8. Experimental and modeling results of cadmium ions adsorption (5.0 mg/l)

The increase of cadmium ions adsorption efficiency values was consistent. At 5.0 mg/l, 98.82 % adsorption efficiency was recorded and at 10.0 mg/l 98.82 % adsorption efficiency was observed. Comparing modeling results with experimental data a similar trend was observed: values of the modeling results were 13 – 40 % higher.

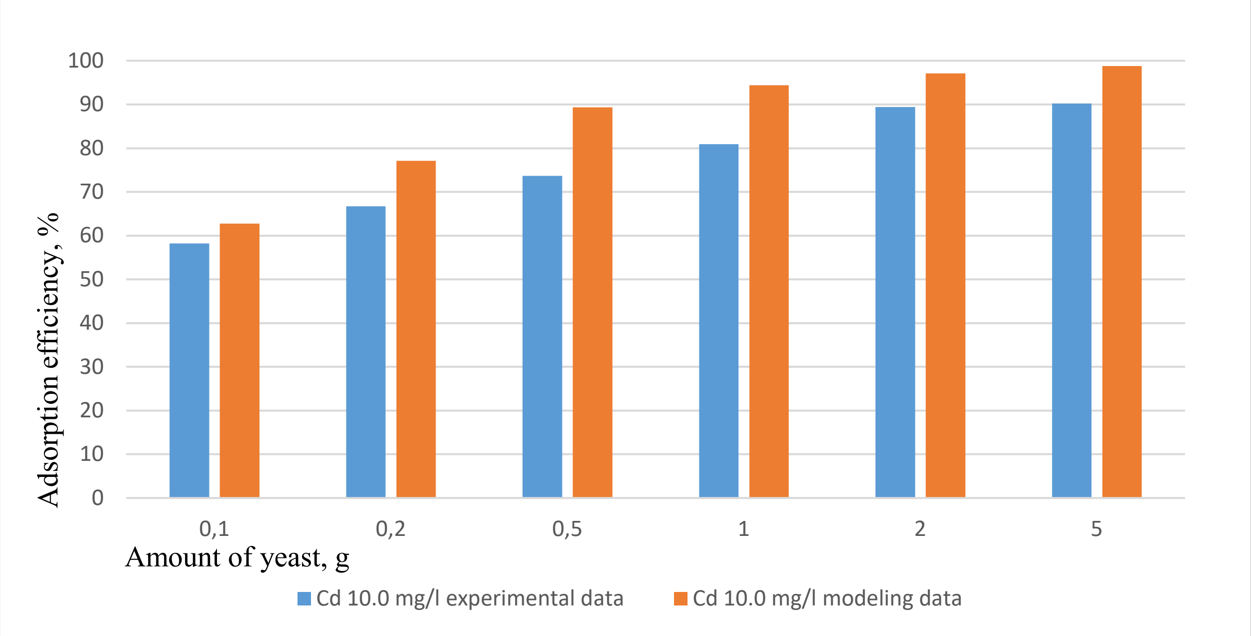


Fig. 4. 9. Experimental and modeling results of cadmium ions adsorption (10.0 mg/l)

Based on the graphs above (simulation data) it could be concluded that higher values of adsorption efficiency were typical for 10.0 mg/l of aqueous solutions of copper. On the other hand, values of adsorption efficiency were the same for both 5.0 mg/l and 10.0 mg/l of aqueous solutions of cadmium and lead.

Comparing all the results, it can be concluded that the applied mathematical modeling reflected the experimental data well enough.

Under real conditions, yeast of *Saccharomyces cerevisiae* would help reduce the negative environmental impact of contaminated waters by preventing the migration of immobilized heavy metals. This solution would be significantly more environmentally friendly than conventional wastewater treatment technologies because it would involve the secondary use of raw materials at the same time. It is important to evaluate this method using real conditions in wastewater treatment technologies.

Conclusions of the fourth chapter

1. The simulation was performed using Visual MINTEQ software and the same following input conditions, which were used in experimental studies: pH 5 and the amount of *Saccharomyces cerevisiae* yeast (0.1 g, 0.2 g, 0.5 g, 1.0 g, 2.0 g, 5.0 g).
2. Comparing all simulation data it was clear that higher values of adsorption efficiency were typical for 10.0 mg/l of aqueous solutions of lead; higher values of adsorption efficiency were typical for 5.0 mg/l of aqueous solutions of cadmium; higher values of adsorption efficiency were equal for both 5.0 mg/l and 10.0 mg/l of copper ions.
3. Comparing the results of experimental studies with modeling data, it was observed that the values of the results of experimental studies were higher than values of simulation.
4. In order to check the availability of this adsorption method using *Saccharomyces cerevisiae* yeast, it has to be done experiments under real conditions of wastewater treatment.
5. Applied mathematical modeling using Visual MINTEQ reflected the experimental studies.

GENERAL CONCLUSIONS

1. Heavy metals could be released into the environment by waste contaminated with petroleum products. They have a negative effect on human health. Heavy metal pollution is a major ecological problem worldwide, so eliminating it is particularly important.
2. The biosorption is one of the alternative methods which is used to remove heavy metals from polluted water. Biosorption process could be affected by temperature, pH and sorption time.
3. *Saccharomyces cerevisiae* yeasts can withstand stressful conditions. This type of yeast is not difficult to grow in large quantities.
4. Standard solutions of different heavy metals – copper (Cu), cadmium (Cd) and lead (Pb) ions (1000 mg/l) were used for the experimental tests. Experiments were performed with artificially contaminated deionized water with heavy metal (copper, lead and cadmium) ion concentrations of 5.0 mg/l and 10.0 mg/l. Experimental studies were performed at different pH values of aqueous solutions: 2, 3, 4, 5, 6. After determining the optimal conditions for the biosorption process, further studies were performed at one pH value i.e., 5. A biosorbent prepared from yeast was in contact with an aqueous solution contaminated with heavy metal ions for 5 min, 30 min, 60 min, 4 h and 24 h.
5. According to the information provided in the scientific articles and the results from experimental studies, it can conclude that the removal of lead and cadmium ions has higher opportunity to be used in wastewater treatment plants than copper ions.

RECOMMENDATIONS

1. It is recommended to use *Saccharomyces cerevisiae* yeasts as a sorbent for the removal of lead, copper and cadmium from aqueous solutions at low concentrations of heavy metals.
2. It is advisable to select the optimal process conditions for the removal of heavy metals from aqueous solutions: the adsorption process time should be more than 1 h, the pH of the solution – 5.
3. Adsorbents made from yeast of *Saccharomyces cerevisiae* may be re-used after a sorption process.

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Visual MINTEQ manual. 2021

Visual MINTEQ tutorial. 2021

ANNEX

List of author publications:

Stonkutė, M. 2021. Experimental Research on Application of Yeast in Heavy Metal Removal from Polluted Water. Proceedings of the 24 th Conference for Junior Researchers „Science – Future of Lithuania“, 19 March 2021, Vilnius, Lithuania

List of author presentations in the local and international conferences:

Proceedings of the 24 th Conference for Junior Researchers „Science – Future of Lithuania“, 19 March 2021, Vilnius, Lithuania

The Conference of Environmental and Climate Technologies „Conect 2021“, 12-14 May, 2021, Ryga, Latvia

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24-osios Lietuvos jaunųjų mokslininkų konferencijos „Mokslas – Lietuvos ateitis" teminė konferencija

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EXPERIMENTAL RESEARCH ON APPLICATION OF YEAST IN HEAVY METAL REMOVAL FROM POLLUTED WATER

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Annotation. Both surface and groundwater can be contaminated with a variety of chemicals, making it dangerous to use water for domestic usage. Water can be contaminated with heavy metals (HM), petroleum products, detergents, radioactive isotopes, mineral or organic fertilizers. Copper, cadmium and lead are some of the most commonly emitted heavy metals from various industries. Adsorption is considered to be one of the alternative methods of treatment of wastewater contaminated with heavy metals. The use of adsorbents of biological origin for the removal of heavy metals from wastewater is a promising method due to the low costs, rapid biodegradation and easy availability of adsorbents.

Key words: Saccharomyces cerevisiae, adsorption capacity, heavy metals, adsorption efficiency, lead, copper, cadmium.

Introduction

Both surface and groundwater can be contaminated with a variety of chemicals, making it dangerous to use water for domestic usage. Pollutants can enter the water with precipitation, sewage, transport exhaust gasses, fertilizers, industrial dust and snowmelt water. Contamination of surface and groundwater with oil products or landfill leachate is also possible (Ojo et al., 2012).

Water can be contaminated with heavy metals (HM), petroleum products, detergents, radioactive isotopes, mineral or organic fertilizers (Pazand et al., 2018). Heavy metals can enter the environment through natural processes, such as volcanic eruptions or weathering of rocks (Motuza, 2013).

Toxic metals are largely distributed in the environment through industrial effluents, organic waste, waste incineration and transportation and energy production. Heavy metals can disperse far from sources, depending on whether they are in the form of gaseous compounds or solid particles. These pollutants are leached from the air to land or water surfaces (Mahurpawar, 2015).

Heavy metal ions are non–biodegradable, toxic, carcinogenic even at very low concentrations and therefore generally pose a serious threat to the environment and public health (Liu et al., 2008). Heavy metals tend to accumulate in the environment, so they are termed "perpetual pollutants" and fall into the class of important environmental pollutants.

Copper (Cu), cadmium (Cd) and lead (Pb) are some of the most commonly emitted heavy metals from various industries. Copper is found in several forms in the soil. In the soil solution as copper chloride, copper nitrate, copper sulfate and its concentration is low and depends on the immobilization of copper with organic compounds (Carvalho et al., 2015). Health problems are caused by oxidative stress caused by cadmium in the body's cells. Long–term cadmium poisoning causes Fanconi syndrome (Martin et al., 2009). Increased Pb content in soil can reduce soil productivity and very low Pb concentrations can inhibit some vital plant processes, like photosynthesis, mitosis, and water absorption (Jiwan et al., 2011).

Heavy metals are characterized by carcinogenic, mutagenic and teratogenic effects, which manifest themselves not only in oncological diseases, but also in developmental disorders of the organism, weakened immunity and impaired reproductive functions (Jan et al., 2015). The negative effects of heavy metals are not only recorded in humans or animals, their toxic effects can also occur in plants.

Heavy metals tend to accumulate and migrate from one ecological niche to another. Heavy metal pollution is a major ecological problem worldwide, so eliminating it is particularly important (Bhat et al. 2019).

Adsorption is considered to be one of the alternative methods of treatment of wastewater contaminated with heavy metals. Adsorption has been shown to be a cheap and effective method to remove many heavy metals from water (Edet et al., 2020).

The use of adsorbents of biological origin for the removal of heavy metals from wastewater is a promising method due to the low costs, rapid biodegradation and easy availability of adsorbents (Halnor, 2015). The application of yeast (*Saccharomyces cerevisiae*) as a removal agent of heavy metals from contaminated aqueous solutions has been little studied.

Yeast usually grows in an acidic environment with a pH of 5.0 to 6.0 and an optimal growth temperature of 25 to 30 °C (Qadir, 2019). This type yeast can withstand stressful conditions; they are characterized by high fermentation efficiency, rapid growth, efficient sugar consumption, the ability to produce and consume ethanol (Reis et al., 2013). Yeast *S. cerevisiae* is not difficult to grow in large quantities. They can be easily grown using simple fermentation methods and inexpensive growth medium (Can et al., 2010).

The performed experimental studies and the results of those studies will allow to determine whether yeast can be used for the removal of heavy metals from contaminated water. The efficiency of yeast sorption properties at different concentrations of heavy metals in solution will be determined using different yeast and heavy metal contact times, sorbent content and pH.

The aim of the study was to investigate the application of yeast (*Saccharomyces cerevisiae*) to the removal of heavy metals from contaminated water and the factors influencing it‘s efficiency.

Methodology

The natural biological material chosen for the preparation of the adsorbent was the yeast species *Saccharomyces cerevisiae* obtained from the Vilnius Nature Research Center.

During the research work, experiments were performed with artificially contaminated deionized water, in which the concentrations of metals (copper, lead and cadmium) ions exceeded the maximum permissible concentrations.

The aim of the experimental research was to determine the optimal conditions under which the highest efficiency of heavy metal ion removal from aqueous solutions using yeast is recorded. Experimental studies were performed at different pH values: pH 2, 3, 4, 5, 6, as some heavy metals, such as lead, settle in the sediment from about pH 6 (depending on its concentration in solution).

The dependence of the adsorption capacity on the contact time was also investigated: the biosorbent prepared from yeast was in contact with the contaminated aqueous solution for 5 min, 30 min, 1 h.

Test substances, mixtures and chemical reagents: heat–treated *Saccharomyces cerevisiae* yeast species, sodium hydroxide (NaOH), deionized water (meeting the quality requirements of LST EN ISO 3696), nitric acid (HNO_3), standard solutions of copper, cadmium and lead (1000 mg/l). 0.1 N NaOH and 0.1 N HNO_3 solutions were used to adjust the pH of copper / cadmium / lead aqueous solutions.

The initial concentration of heavy metals in the solution was an important parameter for the examination of adsorption process. Standard metal solutions and deionized water were used prepare solutions of different concentrations of the selected heavy metals in an Elenmeyer flask (100 ml).

Aqueous solutions of 2 different metal concentrations were prepared: 5 mg/l and 10 mg/l. Added 0,5 ml or 1,0 ml of the chosen metal standard solution to 100 ml flasks.

After adding the required amount of heavy metal, the rest of the solution (up to 80 %) was prepared with deionised water. A 0,1 N solution of nitric acid or alkali is then carefully added using a digital pipette, mixed and measured until the required pH is reached.

The pH of the solution is determined using a pH-meter. Before starting the experimental tests, the instrument was calibrated using two buffer solutions with different pH values, pH 4.0 and 7.0. The pH of the solution was adjusted with 0.1 N HNO_3 and 0.1 N NaOH.

After preparation of aqueous solutions of appropriate heavy metals concentration, the required amount of yeast was added. 6 different amounts of yeasts were used for the studies: 0.1 g, 0.2 g, 0.5 g, 1.0 g, 2.0 g and 5.0 g (+/– 0.01 g). Then, the selected amount of yeast was transfered to each volumetric flask. To make the yeast active, 0,1 g of sugar or agar was added to each sample. The first tests were performed using agar, but due to the more complex filtration process, this solution was later abandoned and sugar was used instead.

The prepared samples were then transferred to screw–on glass 100 ml volumetric flasks, which were thoroughly mixed. Sample mixing was performed at the selected contact time.

To avoid measurement errors, pre–filtration using "VWR Qualitative filter paper 413" filter paper was started before the end of the contact time, as the sorption process is not stopped during the filtration process. After the primary filtration, a secondary one was performed using a vacuum pump.

Filtered samples were then transferred to prepared (numbered) flasks. It is necessary to add 1.0 % by volume of concentrated nitric acid to each container. This preserves the samples. Until measurements, the samples were kept refrigerated at 5 °C.

The residual concentration of metals in the solutions was determined by atomic adsorption spectral analysis using a Buck Scientific 210 VGP spectrometer with an air–acetylene flame and a graphite furnace.

Calibration curves, that are prepared for each heavy metal separately, were used to determine the concentrations of heavy metals. Solutions of the investigated heavy metals (copper, cadmium and lead) prepared from standard metal solutions (~ 1000 mg/l metal, 2 % HNO_3) are used to form the data curves.

Results

Based on the data presented in Table 1., it can be concluded that with increasing pH values from 2 to 5, a significant increase in adsorption efficiency from 41.10 % (at pH 2) to 95.91 % (at pH 5) is observed. Meanwhile, when evaluating the adsorption efficiency values at pH 5 and pH 6, it was observed that at pH 6 the adsorption efficiency slightly decreased.

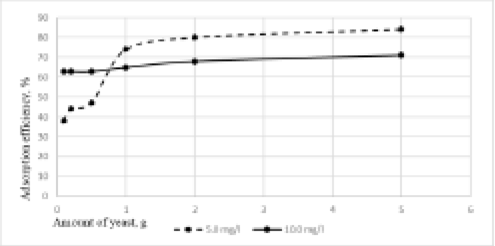
Table 1. Influence of aqueous solution pH on lead removal efficiency

Parameters	Initial pH level				
	2	**3**	**4**	**5**	**6**
Residual lead concentration, mg/l	2.94	1.74	0.21	0.21	0.26
Adsorption efficiency, %	41.10	65.30	95.83	95.91	94.93

Based on the results of the performed experimental studies and the data presented in scientific publications (Parvathi et al.), it was decided to perform further studies only at one pH value i.e., 5.0.

The highest lead adsorption efficiency at 5.0 mg/l and 10.0 mg/l aqueous solutions was found using yeast amount of 5.0 g. However, at a lower concentration of the solution, a higher adsorption efficiency was recorded – 84.0 % (Fig. 1). At a concentration of 10.0 mg/l of lead ions, an adsorption efficiency of 71.0 % was recorded.

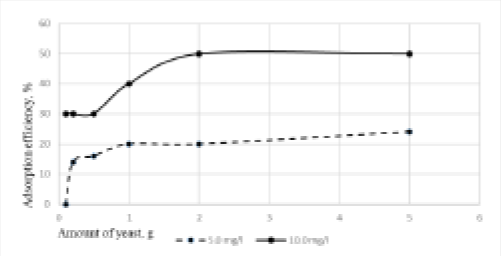
Fig. 1. Graph of the dependence of lead adsorption efficiency on yeast content (5 min)



It should be noted that in solutions with a concentration of 10.0 mg/l of lead ions and at 0.1 g, 0.2 g and 0.5 g of yeast, the adsorption efficiency did not change, the same value of 63.0 % was recorded in all samples.

On the other hand, the highest adsorption efficiency of copper was recorded in samples with 5.0 g. At 5.0 mg/l copper ion concentration, 24.0 % adsorption efficiency value was recorded, and at 10.0 mg/l concentration, 50.0 % adsorption efficiency was observed (Fig. 2). At yeast amount of 0.1 g to 0.5 g, a slight change in sorption capacity was observed in the samples. For instance, at 5.0 mg/l, the residual concentration of copper ions in the sample was 5.0 mg/l. Thus, sorption capacity was 0.0 mg/g – adsorption efficiency 0.0 %. Moreover, sorption capacity of 0.35 mg/g and 0.16 mg/g was recorded at 0.2 g and 0.5 g of yeast amount.

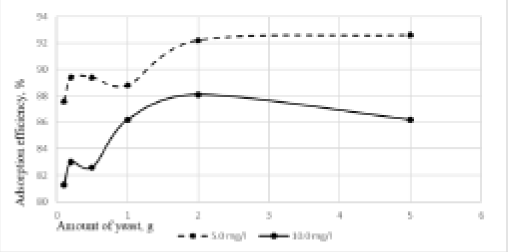
Fig. 2. Graph of the dependence of copper adsorption efficiency on yeast content (5 min)



Studies with samples containing 0.1 g, 0.2 g and 0.5 g of yeast with a solution concentration of 10 mg/l showed a uniform adsorption efficiency of 30.0 %. It can be assumed that at higher concentrations of heavy metal, a small amount of yeast in the sample is not sufficient to ensure larger changes in adsorption efficiency.

In studies of cadmium, more deviations from previously observed trends were recorded. Such as, an increase in adsorption efficiency from 0.1 g of yeast to 0.5 g of yeast at 5.0 mg/l, but in an aqueous solution of cadmium containing 1.0 g of yeast, a decrease, albeit slight, was observed in the adsorption efficiency compared to the first values in this order. Meanwhile, increasing the yeast content from 2.0 g to 5.0 g again showed an increased value of the adsorption efficiency (Fig. 3).

Fig. 3. Graph of cadmium adsorption efficiency dependency on yeast amount (5 min contact time)

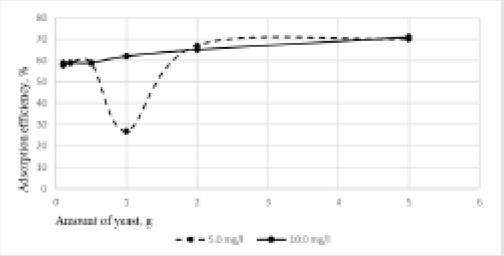


The initial concentration of lead, copper and cadmium ions in the solutions was found to affect the adsorption efficiency of *Saccharomyces cerevisiae* yeast. The highest adsorption efficiency of lead and copper at 5.0 mg/l and 10.0 mg/l aqueous solutions was recorded at a yeast amount of 5.0 g. At concentration of 5.0 mg/l with the samples of 5.0 g of yeast, the value of adsorption efficiency of 84.0 % was recorded, and at the concentration of 10.0 mg/l, the adsorption efficiency of 71.0 % was observed. Adsorption efficiency of 24.0 % was recorded in samples with 5.0 g of yeast and copper samples at a concentration of 5.0 mg/l, and adsorption efficiency of as much as 50.0 % was observed at a concentration of 10.0 mg/l.

At contact time of 30 min, sorption experiments of lead ions from aqueous solutions using yeast showed that at higher concentrations of lead ions, i.e., 10.0 mg/l, higher adsorption efficiency was achieved compared to 5.0 mg/l concentration studies.

It should be noted that in solutions of 5.0 mg/l and 10.0 mg/l at 0.1 g, 0.2 g and 0.5 g of yeast amount, the adsorption efficiency change was minimal, 58.0 – 59.0 % adsorption efficiency value was recorded in all of the samples tested (Fig. 4).

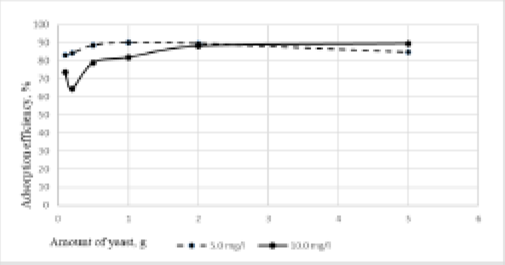
Fig. 4. Graph of the dependence of lead adsorption efficiency on yeast amount (30 min contact time)



The highest lead adsorption efficiencies at 5.0 mg/l and 10.0 mg/l aqueous solutions were recorded at a yeast amount of 5.0 g. At a lower concentration of the solution, the adsorption efficiency of 70.0 % was observed, while at a concentration of 10.0 mg/l, the adsorption efficiency of 71.0 % was recorded (same as after 5 minutes of contact time).

Comparing the results of copper sorption of 5 min and 30 min contact time, it was observed that yeast, which remained in the samples for a longer period of time, sorbed more copper ions (Fig. 5). For example, at concentration of 10.0 mg/l with 5 min of contact time, the value of adsorption efficiency ranged from 30.0 % to 50.0 %, and when the contact time was extended from 5 min to 30 min, the value of adsorption efficiency was recorded from 55.0 % to 71.5 %.

Fig. 5. Graph of the dependence of copper adsorption efficiency on yeast amount (30 min of contact time)

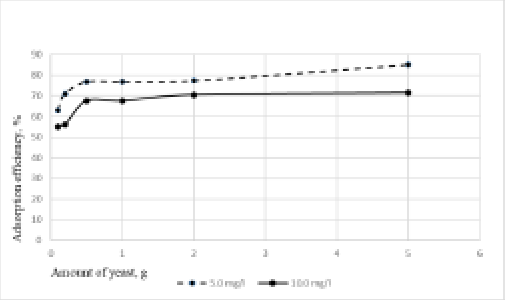


Studies on the adsorption of cadmium ions by yeast have shown that at lower concentrations of cadmium ions, i.e., 5.0 mg/l, maximum adsorption efficiency of 90.15 % was achieved.

The highest adsorption efficiency was recorded at of 5.0 g of yeast amount in samples: at concentration of 5.0 mg/l, the adsorption efficiency of 85.0 % was recorded, and at concentration of 10.0 mg/l, the adsorption efficiency of 71.5 % was observed.

The last, but not least cadmium: the highest adsorption efficiency was recorded at yeast amount of 1.0 g with samples with cadmium concentration of 5.0 mg/l (Fig. 6). In cadmium 30 min studies, number of deviations from previously observed trends were also observed. For example, at cadmium concentration of 5.0 mg/l, an increase in adsorption efficiency from 0.1 g to 1.0 g of yeast was observed, but in cadmium aqueous solutions containing 2.0 g and 5.0 g of yeast, although a small, but a decrease in adsorption efficiency compared to the first values in this order.

Fig. 6. Graph of cadmium adsorption efficiency as a function of yeast amount (30 min contact time)



Studies have shown that with an increase of yeast amount in samples, higher values of adsorption efficiency were recorded (several exceptions were observed). Meanwhile, while comparing the different contact time of the sorption process of the same heavy metal, it was found out that at 10.0 mg/l solutions after 30 min of yeast and heavy metal contact time a higher sorption capacity values were recorded compared to the same concentration, but 5 min contact time samples.

Conclusion

1. Experimental studies have shown that the pH of the solution has a significant effect on the adsorption efficiency. Maximum of adsorption efficiency was recorded when the pH of the solution was at 5.0.

2. After measurements with 5 min of contact time, it was observed that the highest values of adsorption efficiency were recorded for cadmium ions (88.1 – 92.6 %), and the lowest purification efficiency was typical for copper ions (24.0 – 50.0 %).

3. After the contact time of 30 minutes, evaluation of the residual concentration of heavy metal ions in the samples showed that cadmium ions have the highest values of adsorption efficiency (89.6 – 90.15 %). The lowest values of adsorption efficiency were found in aqueous lead solutions (70.0 – 71.0 %).

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MIELIŲ TAIKYMO SUNKIŲJŲ METALŲ ŠALINIMUI IŠ UŽTERŠTO VANDENS EKSPERIMENTINIAI TYRIMAI

M. Stonkutė

Santrauka

Tiek paviršinis, tiek požeminis vanduo gali būti užterštas įvairiomis cheminėmis medžiagomis, tad vandens vartojimas buitinėms reikmėms tampa pavojingas. Vanduo gali būti užterštas sunkiaisiais metalais (SM), naftos produktais, detergentais, radioaktyviais izotopais, mineralinėmis arba organinėmis trąšomis. Varis, kadmis ir švinas – vieni iš dažniausiai su nuotekomis išleidžiamų sunkiųjų metalų iš įvairių pramonės šakų. Adsorbcija yra laikomas vienas iš alternatyvių nuotekų, užterštų sunkiaisiais metalais, valymo būdų. Biologinės kilmės adsorbentų panaudojimas sunkiųjų metalų šalinimui iš nuotekų yra perspektyvus metodas dėl adsorbentų pigumo, sparčios biodegradacijos bei lengvo prieinamumo.

Raktiniai žodžiai: Saccharomyces cerevisiae, adsorbcijos pajėgumas, sunkieji metalai, adsorbcijos efektyvumas, švinas, varis, kadmis.

Experimental research on application of yeast in heavy metal removal from polluted water

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Introduction

Water can be contaminated with heavy metals (HM), petroleum products, detergents, radioactive isotopes, mineral or organic fertilizers [1]. Heavy metal pollution is a major ecological problem worldwide, so eliminating it is particularly important [2].

Adsorption is one of the alternative methods of treatment of wastewater contaminated with heavy metals. Adsorption has been shown to be a cheap and effective method to remove lead (Pb^{2+}), copper (Cu^{2+}) and cadmium (Cd^{2+}) from water [3].

The application of yeast (Saccharomyces cerevisiae) as a removal agent of heavy metals from contaminated aqueous solutions has been little studied. Yeast usually grows in an acidic environment with a pH of 5.0 to 6.0 and an optimal growth temperature of 25 to 30 °C [4].

The aim of the study was to investigate the application of yeast (Saccharomyces cerevisiae) to the removal of heavy metals from contaminated water and the factors influencing it's efficiency.

Methodology

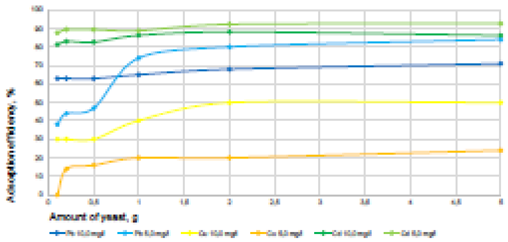
During the research work, experiments were performed with artificially contaminated deionized water, in which the concentrations of metals (**lead, copper and cadmium**) ions exceeded the maximum permissible concentrations.

Aqueous solutions of 2 different metal concentrations were prepared: 5 mg/l and 10 mg/l. 6 different amounts of yeasts were used for the studies: 0.1 g, 0.2 g, 0.5 g, 1.0 g, 2.0 g and 5.0 g (+/– 0.01 g).

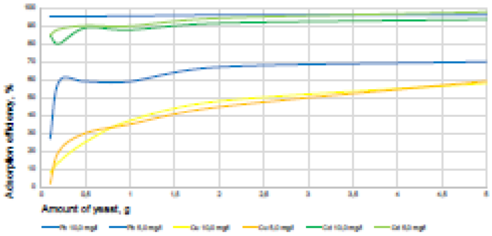
The residual concentration of metals in the solutions was determined by atomic adsorption spectral analysis using a Buck Scientific 210 VGP spectrometer with an air–acetylene flame and a graphite furnace.

Results

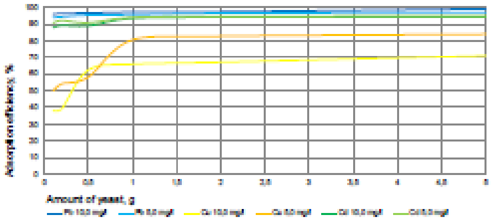
The dependence of lead, copper and cadmium adsorption efficiency on yeast amount (5 min contact time)



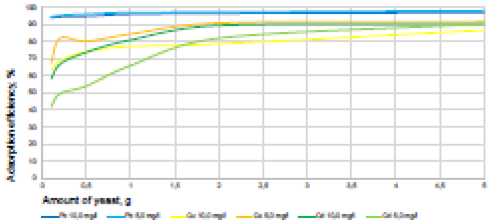
The dependence of lead, copper and cadmium adsorption efficiency on yeast amount (1 h contact time)



The dependence of lead, copper and cadmium adsorption efficiency on yeast amount (4 h contact time)



The dependence of lead, copper and cadmium adsorption efficiency on yeast amount (24 h contact time)



Discussion and conclusion

After measurements of 5 min, 1, 4 and 24 h of contact time, it was observed that the highest values of adsorption efficiency were recorded for Cd ions (after 5 min and 60 min) and for Pb ions (after 4 h and 24 h). The lowest adsorption efficiency was typical for Cu ions (after 5 min and 60 min) and for Cu – Cd ions (after 4 h and 24 h).

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