UDC 622.765:542.61:546.571
DOI: 10.15587/2706-5448.2022.256750
Article type «Original research»

Tetiana Obushenko,
Nataliia Tolstopalova,
Olga Sanginova,
Yevhenia Yuzupkina

DETERMINATION OF THE INFLUENCE OF BASIC PARAMETERS ON THE SOLVENT SUBLATION OF ANIONIC DYE

The object of research is wastewater contaminated with anionic dyes. Traditional methods of wastewater treatment from dyes are imperfect and inefficient or non-existent. Therefore, the need to develop and implement effective and inexpensive to use and operate dye removal technologies is important. The biggest problem in dye removal is when large volumes of low concentration wastewater have to be treated. To purify just such effluents, a combined method, solvent sublation, has been proposed. It combines flotation and extraction methods and has the benefits of both. The essence of the method is the passage of gas bubbles through the aqueous phase and the transport of a hydrophobic complex (sublate) formed by a dye and a surfactant into the organic phase. The study used imitates of wastewater contaminated with an anionic dye, active bright blue in the concentration range of 5–50 mg/dm^3. The influence of the main parameters on the degree of dye removal was studied: the pH of the initial solution, the molar ratio of surfactant: dye, the size of air bubbles, the gas flow rate, the initial concentration of the dye, the duration of solvent sublation. Rational parameters of the process have been established, which are advisable to use in solvent sublation:

– *purification process must be carried out in the presence of a cationic collector hexadecyltrimethylammonium bromide;*
– *extractant – isoamyl alcohol;*
– *molar ratio Dye: surfactant=1:1.5;*
– *pH 5.5;*
– *generation of gas bubbles by a Schott filter with a porosity of 40 μm;*
– *gas flow rate – 127 cm^3/min.*

Under such conditions, the removal efficiency of active bright blue is 97 % at a process time of 10–25 min. The results obtained confirm the promise of the proposed method for the effective removal of dyes from low-concentration aqueous solutions. The method has a number of advantages: it requires a small amount of extractant compared to liquid extraction; ions are concentrated in small volumes of an organic solvent; the process proceeds without phase mixing, so no emulsions are formed.

Keywords: *solvent sublation of dyes, surfactants, sublate, active bright blue, hexadecyltrimethylammonium bromide.*

Received date: 01.03.2022
Accepted date: 11.04.2022
Published date: 30.04.2022

How to cite
Obushenko, T., Tolstopalova, N., Sanginova, O., Yuzupkina, Y. (2022). Determination of the influence of basic parameters on the solvent sublation of anionic dye. Technology Audit and Production Reserves, 2 (3 (64)), 17–24. doi: http://doi.org/10.15587/2706-5448.2022.256750

1. Introduction

Pollution of water areas is an important environmental problem on a global scale. Therefore, the issue of purification, regeneration and disposal of wastewater is very acute. Among the many pollutants, special attention should be paid to dyes, since most of them are toxic and dangerous to the environment.

Getting into the environment with wastewater, dyes not only violate the quality of water and the aesthetic perception of the aquatic environment, but also have a negative impact on the vital activity of ecosystems and the processes of self-purification of water bodies. Some dyes are almost not subject to biochemical degradation and remain in the environment for a long time [1].

The main sources of pollution with dyes are enterprises of the light, chemical, pulp and paper and pharmaceutical industries, since a significant proportion of these enterprises discharge waste water into water bodies without prior treatment. The annual volumes of environmental pollution with dyes are only increasing, as their production is also growing, which, according to preliminary estimates, is about 1 million tons/year [2].

The textile industry is the biggest consumer of high quality water. The water consumption rate is 100–200 liters of water per kilogram of textile. Therefore, as a result of various processes, significant volumes of polluted water enter the reservoirs. Considering the annual production of 40 million tons of textile fibers, wastewater discharge is estimated at more than 4–8 billion m^3/year [3].

The imperfection of existing technologies for the treatment of wastewater contaminated with dyes necessitates the search for such methods that would make it possible to

ISSN 2664-9969

purify these waters to the maximum permissible concentration (MPC) (0.05–0.5 mg/dm^3). Such an actual method of water purification is solvent sublation. Solvent sublation is a combined method for extracting pollutants from an aqueous medium due to their adsorption on the surface of small gas flow bubbles that move up, cross the water-extractant phase distribution boundary, and then concentrate in an organic solvent layer on the surface of the aqueous phase.

2. The object of research and its technological audit

The object of research is wastewater contaminated with anionic dyes. Namely, active bright blue ($C_{23}H_{12}Cl_2N_6Na_2O_8S_2$). It is a water soluble dye. The water solubility of active dyes determines the sulfo group in the form of a sodium salt, the ability to chemically interact with the fiber is provided by various reactive groups. Due to their high durability and brightness, active dyes are widely used in printing and dyeing of cellulose fibers, natural silk and wool, and, to a lesser extent, polyamide fibers. Most active dyes are azo dyes. Active dyes are used to dye fibers containing a hydroxyl or amino group, with which the dye molecules enter into a chemical reaction, which leads to the formation of a color that is resistant to wet processing and abrasion. These fibers include cellulose, protein and polyamide. The choice of active dyes for research is due to the fact that they are widely used and therefore create a large amount of effluents that require purification.

The analysis of scientific and technical sources indicates that in modern conditions of painting and finishing enterprises, it is most expedient to use local purification immediately after the process of dyeing and washing textile materials. This will not only reduce the volume of wastewater, but will help to reuse wastewater after the treatment process in production [4].

3. The aim and objectives of research

The aim of research is to study the influence of the main parameters of solvent sublation on the efficiency of removing the anionic active bright blue dye from model aqueous solutions that simulate wastewater.

To achieve the aim, the following objectives must be completed:

1. Experimentally select a cationic surfactant and an extractant that provide the maximum degree of dye removal.
2. Investigate the dependence of the degree of dye removal on the surfactant concentration, i. e. from the molar ratio Dye:Surfactant.
3. Find out the effect of bubble size, gas flow rate and pH value of the initial solution on the degree of dye removal.
4. Set the change in the degree of dye removal from its initial concentration.

4. Research of existing solutions of the problem

To date, there is a wide range of technologies for wastewater treatment from dyes, involving their destruction or removal. They differ from each other in terms of economy, environmental friendliness and efficiency. Three categories of methods for removing dyes from the aquatic environment are common:

1) physical (sorption, membrane separation, ion exchange, radiation exposure);

2) chemical (coagulation and flocculation, oxidation: ozonation, photochemical reactions; electrochemical coagulation);

3) biological treatment [5].

Since synthetic dyes in wastewater cannot be removed with high efficiency by traditional methods, the adsorption of synthetic dyes on inexpensive and effective solid carriers is considered as a simple and economical way to remove them from water and wastewater. The distinctive adsorption properties of carbon-based substances have been used to decolorize dyes in industrial effluents [6]. The effectiveness of different types of charcoal was comparable for the removal of basic red 22 and acid blue 25 from textile production effluents. The data indicate that results obtained with fruit charcoal, pine and chestnut were better than those obtained with beech and oak charcoal [7, 8]. The process of adsorption on the surface of carbonized soil has been studied. Basic blue 3, methylene blue, acid blue, and reactive yellow 2 were adsorbed on this sorbent [9]. Good sorption characteristics of sulphated coal for the removal of synthetic dyes have also been demonstrated [10].

Adsorption methods have some disadvantages. Since adsorption processes are generally not selective, other wastewater components may also be adsorbed, and competition between adsorbates may affect the ability of sorbents to bind to dyes. In addition, the adsorption process removes synthetic dyes from wastewater, concentrating them on the surface, keeping their structure virtually unchanged. When regenerating the sorbent, a concentrated dye solution is obtained, which is a problem that cannot be properly solved.

Hydrogen peroxide is often used to bleach synthetic dyes in aqueous solutions. It can effectively purify wastewater from contaminants in the presence of Fe (II) sulfate with higher discoloration rates at higher concentrations of reagents [11]. Not only an iron catalyst was used, but also an ultraviolet (UV)/H_2O_2 oxidation process was used to decolorize reactive black in textile wastewater [12]. Iron powder and hydrogen peroxide are used in combination to decolorize Reactive Red 120, Direct Blue 160, and Acid Blue 40 in aqueous solutions. The orange azo dye II was efficiently mineralized by iron and hydrogen peroxide, while pH has a significant effect on the decomposition rate [13].

The use of microorganisms for the biological purification of synthetic dyes is an attractive method in operation. However, the biological mechanisms can be complex. A large number of species have been tested for decolorization and mineralization of different dyes. However, most of these compounds are chemically stable and resistant to the action of microorganisms. The study of new strains or the adaptation of existing dyes to the schedule is likely to increase the efficiency of dye biopurification in the near future.

The use of microorganisms to remove synthetic dyes from industrial wastewater has significant advantages. The process is relatively inexpensive, operating costs are low, and the end products of complete mineralization are non-toxic. Various aspects of the microbiological degradation of synthetic dyes were previously considered [14]. In addition to traditional wastewater treatment technologies, other methods are used in the microbiological purification of dyes. For example, an active sedimentation process has been developed to remove methyl violet and rhodamine B from effluents using microorganisms obtained from livestock rot [15].

Coagulation is the most common traditional cleansing method. During coagulation, flakes of colloidal size are formed, their electrical charge promotes repulsion and thus prevents their aggregation. During coagulation, an additional chemical load is placed on the wastewater, which increases the production of sludge and leads to incomplete removal of the dye.

The possibility of using a new coagulant-flocculant based on tannin for the treatment of surface and textile wastewater was tested [16]. The efficiency of water purification was noticeable in all cases, and filtration improved the removal of flocculation and the reduction of turbidity. For wastewater from the textile industry, about 95 % dye removal has been achieved.

Red mud, a by-product of bauxite processing by the Bayer process, has been investigated for its latest applications in gas and wastewater treatment [17]. The study showed promising results using red mud as a coagulant and adsorbent for both cases, as well as a catalyst for some industrial processes.

Decolorization of wastewater containing dyes using a mineral coagulant has been substantiated [18].

Adsorption separation methods such as ionic flotation and adsorption colloidal flotation have provided efficient removal (about 99 %) of the direct blue dye from wastewater [19].

Auramine O (basic yellow), a cationic dye, was recovered from wastewater by ionic flotation of the auramine-sodium lauryl sulfate complex. More than 98 % of the auramine was removed from the solution after 15 minutes [20].

Almost all available methods of wastewater treatment from dyes have certain shortcomings. Physical methods provide a high degree of wastewater treatment, however, they require preliminary mechanical and chemical treatment in order to remove insoluble impurities that are complex in instrumentation and have a high cost of treatment. The disadvantages of chemical methods are the low degree of purification, especially discoloration, the need to dispose of waste water treatment and their dehydration. When implementing destructive methods, when using these methods, an irretrievable loss of valuable components occurs.

All this necessitates the development and implementation of efficient and at the same time inexpensive to implement and operate technologies for wastewater treatment from dyes. The search for new, more advanced and cost-effective methods that allow not only to remove dyes from wastewater, but also to regenerate expensive components, is one of the main directions in the development of wastewater treatment technology.

One such purification method is the solvent sublation method. The essence of solvent sublation purification can be explained as follows. A collector (surfactant) is added to polluted water to form a sublate, a poorly soluble hydrophobic compound [21–23]. The rate of saturation of the aqueous phase with gas bubbles is less than in ionic flotation. But this is a necessary condition in order to avoid ruptures of the organic layer. At the bubble-liquid interface, the hydrophobic compound is adsorbed, and then transferred to the surface of the water column for removal. Initially, solvent sublation was limited to use only for the removal of various metal ions from an aqueous medium. The gradual introduction of this technology allowed expanding the limits of its use: this method was chosen for the removal of various dissolved organic compounds and the purification of a fleet of hydrophobic liquids [24]. At the present stage of development of water treatment technologies, solvent sublation is used in bioengineering and bioseparation, for analytical analyzes of water bodies, in the treatment of wastewater contaminated with organic and inorganic pollutants.

When analyzing the literature on the process of wastewater treatment by the solvent sublation method, a lack of information was found on certain parameters of the process, such as the influence of the acidity of the medium, the duration of the process, and the choice of the optimal extractant. These parameters are determined by the type of dye and may vary [25]. Therefore, there is a need for further research on this type of wastewater treatment.

5. Methods of research

The process of removing dyes from wastewater by solvent sublation was studied on the example of model solutions of the active bright blue (ABB) dye. Collectors and extractants were experimentally determined.

The main characteristic of the process was the degree of removal X – the ratio of the difference between the initial and residual concentrations to its initial concentration in percent:

$$X_D = \frac{C_{D\,in} - C_{D\,res}}{C_{D\,in}} \cdot 100\ \%,$$

where X_D – degree of dye removal; $C_{D\ in}$ – the initial concentration of the dye, mg/dm^3; $C_{D\ res}$ – the residual concentration of the dye in the test solution, mg/dm^3.

The research and description of the laboratory unit are presented in previous works [26–28].

6. Research results

6.1. Collector selection. Active bright blue in aqueous solutions is in the anionic form. The corresponding ionogenic surfactants, hexadecyltrimethylammonium bromide (HTAB) and hexadecylpyridinium bromide (HPB), were chosen to neutralize the anion charge and form a sublate. The results are shown in Fig. 1.

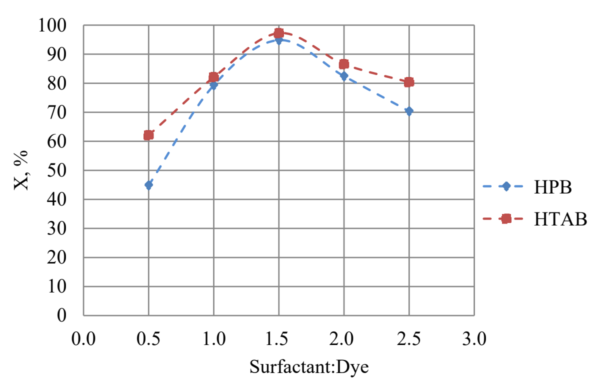

Fig. 1. Dependence of the degree of removal of active bright blue on the ratio of Surfactant:Dye

From the above dependence it can be seen that when using both surfactants in the ratio of Dye:Surfactant = 1:1.5, high degrees of pollutant removal are achieved – more than 90 %. However, in all cases, the purification efficiency with HTAB is higher, so this surfactant was chosen as a collector for the removal of bright blue. For a more detailed study of the effectiveness of the use of the selected surfactant, a series of experiments was carried out and the change in the degree of removal of the dye over time was studied for various ratios of the Dye:Surfactant. Studies were conducted for a ratio of 1:0.5; 1:1; 1:1.5; 1:2. An additional experiment was also carried out without adding a collector – a blank experiment. The results are presented in Fig. 2.

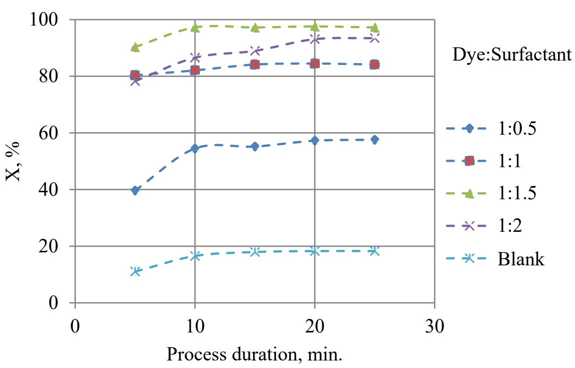

Fig. 2. Change in the degree of removal of active bright blue in time depending on the ratio of Dye:Surfactant

According to the results of the experiments, it was found that the highest degree of removal of active bright blue is achieved at a molar ratio of Dye:Surfactant=1:1.5, that is, 1.5 mol of hexadecyltrimethylammonium bromide must be given per 1 mol of dye. With this ratio, the purification efficiency is already after 10 minutes is 97 %. When using other molar ratios, the efficiency of pollutant removal is lower. In the case of lower molar ratios, this can be explained by the fact that there is an incomplete formation of the ionic associate of the Dye:Surfactant due to the lack of a collector. However, in the case when the excess of surfactant is 2 and 2.5 times greater, the degree of removal is also reduced, since there is a competition of the excess amount of collector with the hydrophobic complex of the Dye:Surfactant for a place on the gas bubble. An excess amount of surfactant also leads to the emulsification of isoamyl alcohol, as a result of which the sublate from the organic phase partially returns back to the aqueous phase, and, as a result, re-contamination occurs [21]. However, theoretically, for solvent sublation of active bright blue, the molar ratio of Dye:Surfactant=1:2 should be used, since the binding of the pollutant to the collector is carried out due to two sodium atoms. In fact, this is not confirmed. Taking this into account, solvent sublation was carried out without the addition of surfactants and it was found that under such conditions more than 16 % of the dye is removed. Perhaps this explains that for this process, 1 mol of dye requires the formation of an ion associate of 1.5 mol of surfactant.

6.2. Extractant selection. The effect of the nature of the organic phase on the efficiency of solvent sublation with the following extractants was studied in the work: polar: octanol, hexanol, butanol, isobutyl alcohol, isoamyl alcohol; non-polar: heptane, isooctane; ether: isoamyl acetate. The results are shown in Fig. 3.

When using polar solvents as an extractant, higher degrees of dye removal are observed compared to heptane, isooctane, and isoamyl acetate; most likely, the ABB-HTAB complex is poorly soluble in nonpolar solvents and ethers. It should also be noted that during the purification process, when using isooctane and heptane, strong foaming occurs above the organic layer, and the solvent itself remains colorless, i. e. the formed ion associate does not enter the organic phase. The purification efficiency with the use of isoamyl acetate is also low: in this case, a thin layer of colored foam forms over the organic phase, and the extractant itself becomes cloudy, which may indicate emulsification. Such processes are undesirable in solvent sublation.In general, there is a tendency that the purification efficiency when using octanol, hexanol, butanol and isobutyl alcohol does not reach its maximum. The best removal of active bright blue is observed after 20 min of solvent sublation – from 84 to 94 %.

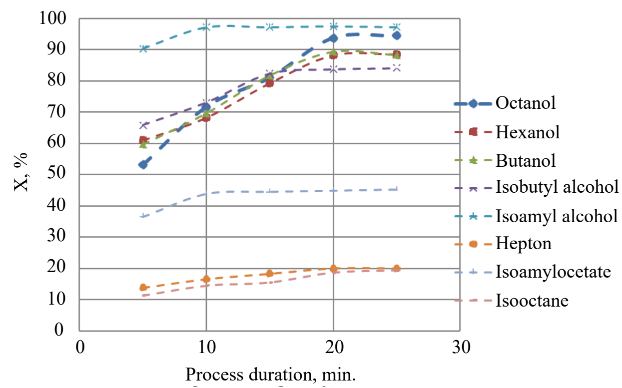

Fig. 3. Changing the degree of removal of active bright blue in time depending on the extractant

Butanol and isobutanol are impractical for extracting the sublate: already after 20 min of carrying out the process, the height of the organic layer decreased by 2.5–3 times. These alcohols dissolve quite well in water ($S_{but.}$=7.9 g/100 cm^3 H_2O; S_{isobut}=8.5 g/100 cm^3 H_2O) due to the rather strong polarization of their molecules due to the OH group. This makes them unsuitable for use as extractants in wastewater treatment by solvent sublation.

Therefore, from the dependences obtained, it can be concluded that isoamyl alcohol is the best extractant for these conditions. It provides over 97 % removal of active bright blue. This can be explained by the fact that the resulting dye-surfactant complex is the most lipophilic to this solvent, so it dissolves better in it.

6.3. Dependence of the degree of dye removal on the process duration. The efficiency of removing the active bright blue dye was studied depending on the process duration. The experiments were carried out in the time interval of 1–25 min. The results are presented in Fig. 4.

It can be seen from the above dependence that 37 % of the dye is removed during the first minute of solvent sublation. In the time interval 1–10 min intensive purification takes place and, accordingly, the degree of removal of active bright blue increases sharply. The rational time for the process is 10 minutes. This provides over 97 % of the pollutant removal. With further continuation of solvent sublation, the efficiency of dye removal increases within 0.5 %.

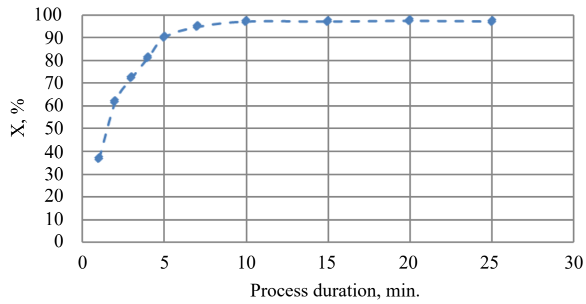

Fig. 4. Change in the degree of removal of active bright blue over time

6.4. Effect of gas bubble size on degree of dye removal. One of the most influential parameters of the solvent sublation process is the bubble size of the gas stream. In a series of experiments, the effect of the pore size of the Schott filter on the efficiency of active bright blue removal over time was investigated. Filters with porosity of 40, 100, and 160 μm were studied. The research results are presented in Fig. 5.

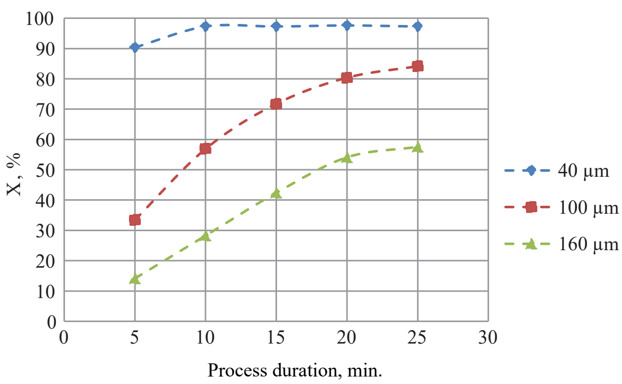

Fig. 5. Effect of gas bubble size on degree of dye removal

The best way to effectively remove active bright blue is to use a Schott filter with a porosity of 40 μm. From the dependences obtained, it is noticeable that when using Schott filters with a porosity of 100 and 160 μm, the purification efficiency is much worse. During the optimal time duration of dye removal (10 min), the process does not reach its maximum. If to analyze the experimental data in the time interval of 15–25 min, the degree of purification is also lower compared to the results when using a Schott filter with a porosity of 40 μm.

According to literature sources [22], a decrease in the size of gas bubbles has a positive effect on the efficiency of solvent sublation, since the area of the interfacial surface increases. It also increases the transit time of the bubbles through the aqueous phase due to the reduction in their rate of rise.

6.5. The effect of medium pH on degree of dye removal. The nature of the effect of the pH of the aqueous medium on the process of solvent sublation purification of active bright blue was studied.

The results are shown in Fig. 6.

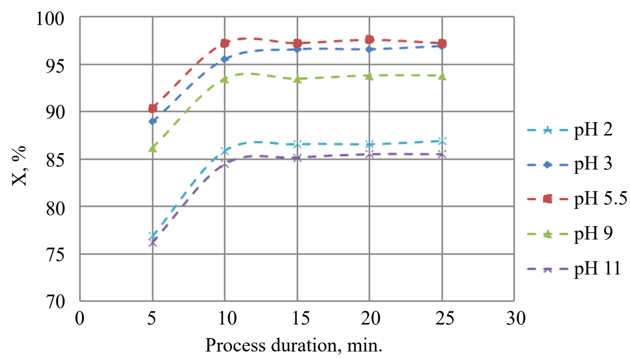

Fig. 6. Effect of medium pH on removal degree

The study was carried out in the pH range of 2–11. The pH of the initial dye solution is 5.5. Fig. 6 shows that after 10 min in a highly acidic environment (pH 2), only 86 % of the dye is extracted. In the pH range of 3–8, the best results are observed, the purification efficiency is 95–97 %. In the area of alkaline pH, solvent sublation purification deteriorates, and at pH 11 it is only 85 %. Fig. 6 shows the dependence of the degree of dye purification on pH over time.

A detailed study of this factor shows that the change in pH partially affects the efficiency of solvent sublation of active bright blue over the entire period of time.

Since the best results were observed at the initial pH of the aqueous solution of the dye, further studies were carried out precisely in this pH range without correction by extraneous solutions.

6.6. Dependence of purification efficiency on the initial dye concentration. The dependence of the degree of dye removal on its initial concentration over time was studied. The results are presented in the Table 1 and Fig. 7.

Table 1

Effect of initial concentration on removal degree

Process duration, min	Initial concentration of active bright blue C_{in}, mg/dm^3									
	5		10		20		25		50	
	C_{in}, mg/dm^3	X, %	C_{res}, mg/dm^3	X, %	C_{res}, mg/dm^3	X, %	C_{res}, mg/dm^3	X, %	C_{res}, mg/dm^3	X, %
5	0.98	80.40	0.89	91.09	2.98	85.10	7.36	70.57	39.21	21.58
10	0.54	89.11	0.39	96.14	2.43	87.87	6.19	75.25	34.66	30.68
15	0.53	89.31	0.40	96.04	1.89	90.54	2.89	88.44	17.71	64.58
20	0.54	89.11	0.40	96.04	1.28	93.61	1.60	93.58	5.43	89.14
25	0.54	89.11	0.39	96.14	0.84	95.79	0.89	96.44	1.44	97.12

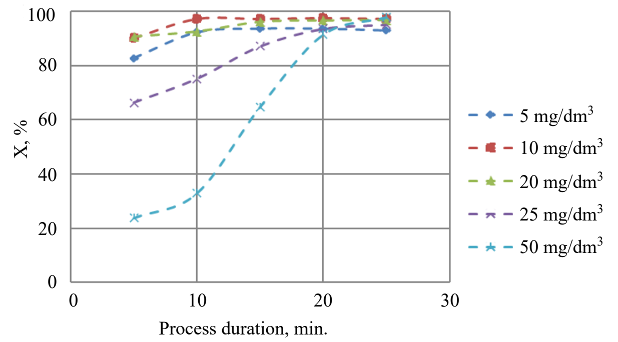

Fig. 7. Effect of initial concentration on the degree of removal

Fig. 7 shows that with a duration of 10 min the removal of active bright blue with a concentration of 5.20–50 mg/dm^3 does not reach its maximum. With a 25-minute purification, a purification degree of about 93 % is achieved in all cases. If to analyze the experimental data over the entire time interval, then the maximum degree of purification is observed when the dye is extracted with a concentration of 50 mg/dm^3 for 25 min. However, in this case, the criterion for evaluating the effectiveness should not be the degree of removal, but the residual concentration of the pollutant. Comparing the data from the Table 1 it can be seen that after 25 min of solvent sublation of a dye solution with a concentration of 10 mg/dm^3, the residual content of the pollutant is 0.28 mg/dm^3, and with a concentration of 50 mg/dm^3 – 1.03 mg/dm^3. It can be concluded that for efficient purification of aqueous solutions contaminated with dyes of higher concentration, the solvent sublation time should be increased.

6.7. Effect of gas flow rate on dye removal efficiency. A study was made of the dependence of the removal efficiency of active bright blue on the gas flow rate in the range of 65–146 cm^3/min. Experimental results are shown in Fig. 8.

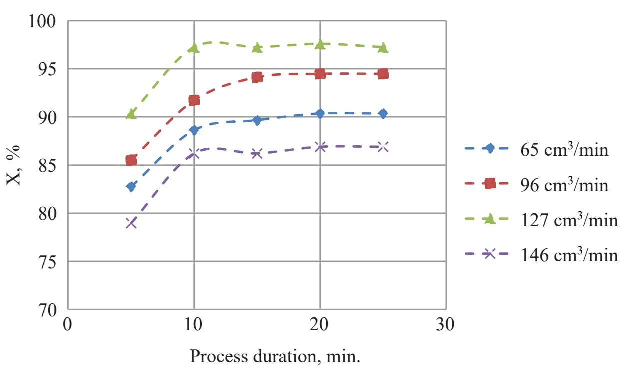

Fig. 8. Effect of gas flow rate on the degree of removal

It was found that the maximum removal of the dye occurs at a gas flow rate of 127 cm^3/min – in 10 min. solvent sublation degree of purification is 97 %. However, a further increase in the intensity of the gas flow to 146 cm^3/min leads to a significant decrease in the purification efficiency, since in this case the integrity of the organic phase and the formed sublate are destroyed. Because of this, only a partial removal of the pollutant and a reverse transition of the sublate into the aqueous phase from the organic is carried out, which leads to re-contamination of the treated water. Therefore, it is rational to carry out solvent sublation at a gas flow rate in the range of 120–130 cm^3/min. This solution makes it possible to achieve high degrees of purification (more than 97 %) without destroying the organic solvent layer. With a decrease in gas flow (up to 65 cm^3/min), the removal of the dye is slightly worse, and within 25 minutes of solvent sublation, the removal of active bright blue reaches 90 %.

7. SWOT analysis of research results

Strengths. The strength of this study is that the method proposed for removing anionic dyes has the following advantages:

1. The formed complex/ion associate, being adsorbed on the bubbles of the gas flow, passes into the organic layer, which is hydrophobic and located on the water surface. During the process, there is no mixing of the aqueous phase and the extractant, so no emulsions are formed during flotation. An exception is considered to be the formation of an aqueous phase emulsion in the organic layer, however, this emulsion is unstable. It should also be noted that in this case, the equilibrium process of substance transfer occurs only on the verge of separation of the water-extractant phases, and not in the entire volume. This suggests that the solvent sublation method, unlike conventional removal, is a non-equilibrium process and is not limited by the equilibrium constant; therefore, it is theoretically possible to completely remove the pollutant.
2. The degree of purification of water bodies practically does not depend on the ratio of the aqueous phase and the extractant, therefore, it allows to work with large volumes of polluted effluents in a ratio of 100:1 to the organic phase.
3. Carrying out solvent sublation purification does not require complex instrumentation and process control is easy. In this case, there is no pressure control, no moving parts, and in general the equipment is quite simple in execution. This greatly simplifies the implementation of this technology.
4. The solvent sublation method requires a small amount of organic solvent, which is cost-effective. In addition, the extract after the process can be regenerated and the extractant can be reused.

Weaknesses. The weaknesses of this study are related to the fact that all data were obtained on model solutions. But real industrial wastewater is a complex multi-component system, often with a high salt content. Therefore, the dependences obtained should be corrected during implementation, taking into account the composition of real wastewater. Also, the cationic surfactant used in research is valuable and quite toxic. Therefore, it would be advisable to use some other, more accessible one. Compared to conventional flotation, a significant disadvantage of this technology is its low productivity. Because the process requires a moderate flow of gas flow to avoid the destruction of the organic layer. To increase productivity and, accordingly, the purification efficiency, it is advisable to reduce the size of the bubbles and the gas flow.

Opportunities. The implementation of the solvent sublation method of purification from anionic dyes will allow not only to purify wastewater to the standards of discharge into the city sewerage system, but also to obtain purified water for production needs using local treatment systems. That is, to solve not only environmental issues, but also to reduce water consumption. In addition, the features of solvent sublation make it possible to regenerate the extractant and surfactant, which can improve the economic performance of production.

Threats. The solutions proposed in this paper are experimental in nature. Practical elaboration and justification are needed before possible implementation decisions. Therefore, the risks are obvious and are associated with possible deviations from the obtained dependencies.

8. Conclusions

1. Cationic surfactant and extractant are experimentally selected, which provide the purification process with maximum efficiency. In the presence of the cationic collector hexadecyltrimethylammonium bromide and the extractant isoamyl alcohol, the degree of solvent sublation removal of the dye is 97 %.

2. The dependence of the degree of dye removal on the surfactant concentration was studied, i. e. from the molar ratio dye: surfactant. The best result was obtained for the molar ratio Dye: HTAB=1:1.5. With this ratio, the purification efficiency is already after 10 minutes is 97 %. When using other molar ratios, the efficiency of pollutant removal is lower.

3. The influence of bubble size and gas flow rate on the degree of dye removal was found out. Maximum dye removal 97 % in 10 min occurs when gas bubbles are generated by a Schott filter with a minimum porosity of 40 μm and at a gas flow rate of 127 cm^3/min.

The dependence of the degree of dye removal on the pH value of the initial solution was studied. The results indicate little effect of pH. When the pH changes from 2 to 11, the degree of dye removal changes from 85 to 97 %. The best result is obtained for solvent sublation at pH 5.5, i. e. without pH adjustment.

4. The change in the degree of dye removal from its initial concentration is established. With a 25-minute purification of low-concentration dye solutions (5–50 mg/dm^3), a degree of purification of about 93 % is achieved. But for solutions with a concentration of 10 mg/dm^3, the residual content of the dye is 0.28 mg/dm^3, and for solutions with a concentration of 50 mg/dm^3 – 1.03 mg/dm^3. For effective purification of aqueous solutions contaminated with dyes of higher concentration, it is necessary to increase the solvent sublation time.

References

1. Hao, O. J., Kim, H., Chiang, P.-C. (2000). Decolorization of wastewater. *Critical Reviews in Environmental Science and Technology, 30 (4),* 449–505. doi: http://doi.org/10.1080/10643380091184237
2. Yaholnyk, S. H. (2008). *Ochyshchennia stichnykh vod vid priamykh barvnykiv aktyvovanym klynoptylolitom*. Lviv: Nats. un-t «Lvivska politekhnika», 19.
3. Hung, Y.-T., Lo, H. H., Yapijakis, C. (2006). *Waste Treatment in the Process Industries*. CRC Press Taylor & Francis Group, LLC, 363–387.
4. Nesterova, L. A., Sarybekov, H. S. (2010). Efficiency of use of turnaround systems of water consumption at the textile enterprises. *Eastern-European Journal of Enterprise Technologies, 4 (8 (46)),* 25–28. Available at: http://journals.uran.ua/eejet/article/view/3022
5. Dafnopatidou, E., Lazaridis, N. (2008). Dyes Removal from Simulated and Industrial Textile Effluents by Dissolved-Air and Dispersed-Air Flotation Techniques. *Industrial & Engineering Chemistry Research, 47 (15),* 5594–5601. doi: http://doi.org/10.1021/ie071235n
6. Roy, D., Wang, G. T., Adrian, D. D. (1993). A simplified solution technique for carbon adsorption model. *Water Research, 27 (6),* 1033–1040. doi: http://doi.org/10.1016/0043-1354(93)90067-r
7. Duggan, O., Allen, S. J. (1997). Study of the physical and chemical characteristics of a range of chemically treated lignite based carbons. *Water Science and Technology, 35 (7),* 21–27. doi: http://doi.org/10.2166/wst.1997.0256
8. Marmier-Dussoubs, D., Mazet, M., Pronost, J. (1991). Removal of dyestuffs by wood charcoal. *Environmental Technology, 12,* 625–634. doi: http://doi.org/10.1080/09593339109385049
9. Low, K. S., Lee, C. K., Wong, A. M. (1996). Carbonized spent bleaching earth as a sorbent for some organic dyes. *Journal of Environmental Science and Health. Part A: Environmental Science and Engineering and Toxicology, 31 (3),* 673–685. doi: http://doi.org/10.1080/10934529609376380
10. Mittal, A. K., Venkobachar, C. (1993). Sorption and desorption of dyes by sulfonated coal. *Journal of Environmental Engineering, 119 (2),* 366–368. doi: http://doi.org/10.1061/(asce)0733-9372(1993)119:2(366)
11. Kuo, W. G. (1992). Decolorizing dye wastewater with Fenton's reagent. *Water Research, 26 (7),* 881–886. doi: http://doi.org/10.1016/0043-1354(92)90192-7
12. Ince, N. H., Gonenc, D. T. (1997). Treatability of a textile azo dye by UV/H_2O_2. *Environmental Technology, 18,* 175–179. doi: http://doi.org/10.1080/09593330.1997.9618484
13. Bandara, J., Nadtochenko, J., Kiwi, J., Pulgarin, C. (1997). Dynamics of oxidant addition as a parameter in the modelling of dye mineralization (Orange II) via advanced oxidation technologies. *Water Science and Technology, 35 (4),* 87–93. doi: http://doi.org/10.2166/wst.1997.0093
14. Stolz, A. (2001). Basic and applied aspects in the microbial degradation of azo dyes. *Applied Microbiology and Biotechnology, l,* 69–80. doi: http://doi.org/10.1007/s002530100686
15. Kanekar, P., Sarnaik, S., Kelkar, A. (1996). Microbial technology for management of phenol bearing dyestuff wastewater. *Water Science and Technology, 33 (8),* 47–51. doi: http://doi.org/10.2166/wst.1996.0151
16. García-Martínez, Y., Bengoa, C., Stüber, F., Fortuny, A., Font, J., Fabregat, A. (2015). Biodegradation of acid orange 7 in an anaerobic-aerobic sequential treatment system. *Chemical Engineering and Processing – Process Intensification, 94,* 99–104. doi: http://doi.org/10.1016/j.cep.2014.12.011
17. Pinheiro, H. M., Touraud, E., Thomas, O. (2004). Aromatic amines from azo dye reduction: Status review with emphasis on direct UV spectrophotometric detection in textile industry wastewaters. *Dyes Pigments, 61,* 121–139. doi: http://doi.org/10.1016/j.dyepig.2003.10.009
18. Gavazza, S., Guzman, J. J. L., Angenent, L. T. (2015). Electrolysis within anaerobic bioreactors stimulates breakdown of toxic products from azo dye treatment. *Biodegradation, 26 (2),* 151–160. doi: http://doi.org/10.1007/s10532-015-9723-8
19. Horng, J. Y., Huang, S. O. (1993). Removal of organic dye (direct blue) from synthetic wastewater by adsorptive bubble separation techniques. *Environmental Science & Technology, 27 (6),* 1169–1175. doi: http://doi.org/10.1021/es00043a017
20. Chung-Shin, L., Chiing-Chang, C. (2013). Ion and Adsorbing Colloid Flotation of Auramine. *Journal of The Chemical Society.* doi: http://doi.org/10.1002/jccs.200300142
21. Lu, Y., Zhu, X. (2001). Solvent sublation: theory and application. *Separation & Purification Reviews, 30 (2),* 157–189. doi: http://doi.org/10.1081/spm-100108158
22. Bi, P., Dong, H., Dong, J. (2010). The recent progress of solvent sublation. *Journal of Chromatography A, 1217 (16),* 2716–2725. doi: http://doi.org/10.1016/j.chroma.2009.11.020
23. Bi, P., Dong, H., Wang, N. (2007). Solvent sublation of dyes. *Chinese Chemical Letters, 18 (10),* 1293–1296. doi: http://doi.org/10.1016/j.cclet.2007.08.009
24. Astrelin, I. M., Obushenko, T. I., Tolstopalova, N. M., Tarhonska, O. O. (2013). Teoretychni zasady ta praktychne zastosuvannia flotoekstraktsyy: ohliad. *Voda i vodoochysni tekhnolohii, 3,* 3–23.
25. Obushenko, T., Sanginova, O., Tolstopalova, N., Reminna, K. (2019). Simulation of solvent sublation process to forecast the amount of removed dyes. Water and water purification technologies. *Scientific and technical news, 1 (24),* 25–33. doi: http://doi.org/10.20535/2218-93002412019172906

ISSN 2664-9969

26. Obushenko, T., Tolstopalova, N., Kulesha, O., Astrelin, I. (2016). Thermodynamic Studies of Bromphenol Blue Removal from Water Using Solvent Sublation. *Chemistry & Chemical Technology, 10 (4),* 515–518. doi: http://doi.org/10.23939/chcht10.04.515

27. Obushenko, T., Tolstopalova, N., Kholmetska, Y. (2017). The removal of indigo carmine from water by solvent sublation. Water and water purification technologies. *Scientific and technical news, 1 (21),* 31–38. doi: http://doi.org/10.20535/2218-93002112017121431

28. Obushenko, T., Tolstopalova, N., Baranuk, N. (2018). The solvent sublation of bromocresol green from waters solutions. *Technology audit and production reserves, 2 (3 (40)),* 48–53. doi: http://doi.org/10.15587/2312-8372.2018.129634

✉***Tetiana Obushenko,*** *Senior Lecturer, Department of Inorganic Substances, Water Purification and General Chemical Technology, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Kyiv, Ukraine, e-mail: tio1963@gmail.com, ORCID: http://orcid.org/0000-0003-0731-0370*

Nataliia Tolstopalova, *PhD, Associate Professor, Department of Inorganic Substances, Water Purification and General Chemical Technology, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Kyiv, Ukraine, ORCID: http://orcid.org/0000-0002-7240-5344*

Olga Sanginova, *PhD, Associate Professor, Department of Inorganic Substances, Water Purification and General Chemical Technology, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Kyiv, Ukraine, ORCID: https://orcid.org/0000-0001-6378-7718*

Yevhenia Yuzupkina, *Department of Inorganic Substances, Water Purification and General Chemical Technology, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Kyiv, Ukraine, ORCID: https://orcid.org/0000-0002-5101-925X*

✉*Corresponding author*