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Sustainable Assessment of Aerosol Pollution Decrease Applying Multiple Attribute Decision-Making Methods

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Abstract: Air pollution with various materials, particularly with aerosols, increases with the advances in technological development. This is a complicated global problem. One of the priorities in achieving sustainable development is the reduction of harmful technological effects on the environment and human health. It is a responsibility of researchers to search for effective methods of reducing pollution. The reliable results can be obtained by combining the approaches used in various fields of science and technology. This paper aims to demonstrate the effectiveness of the multiple attribute decision-making (MADM) methods in investigating and solving the environmental pollution problems. The paper presents the study of the process of the evaporation of a toxic liquid based on using the MADM methods. A schematic view of the test setup is presented. The density, viscosity, and rate of the released vapor flow are measured and the dependence of the variation of the solution concentration on its temperature is determined in the experimental study. The concentration of hydrochloric acid solution (HAS) varies in the range from 28% to 34%, while the liquid is heated from 50 to 80 °C. The variations in the parameters are analyzed using the well-known VIKOR and COPRAS MADM methods. For determining the criteria weights, a new CILOS (Criterion Impact LOSs) method is used. The experimental results are arranged in the priority order, using the MADM methods. Based on the obtained data, the technological parameters of production, ensuring minimum environmental pollution, can be chosen.

Keywords: pollution decrease; MADM; CILOS method; VIKOR method; COPRAS method

1. Introduction

The social, economic, technological, and biological processes taking place in the environment are so closely related today that production can be considered a complex sustainable ecological and economic system, linking the social production with the environment [1].

The intense technological development is accompanied by the increase in air pollution with various materials and, particularly, with aerosols [2,3]. Over the past decades, drastic measures have been taken to reduce air pollution. However, the level of air pollution is still too high, and the air quality problem is still acute. A large part of the world's population lives in urban areas, where pollution, not complying with the air quality standards, poses a threat to human health and the environment [4].

One of the most acute global sustainable development problems is associated with decreasing harmful technological effects on the environment and the human health. Various methods of reducing pollution should be investigated and applied [5].

The best production technologies, ensuring the lowest possible environmental pollution, should be implemented [6,7]. Special attention must be paid to the production processes, where harmful substances, such as electrochemical etching with a hydrochloric acid solution (HAS), are used. These processes occur in baths, where hydrochloric acid vapors are formed.

Usually, vapors of water or many other substances are invisible. Vapor is a mixture of fume and spray, consisting of liquid particles suspended in a gaseous medium [8,9]. The aerosol absorbs gases due to the large total surface area of these particles. It quickly reacts with the fluid, diffuses light effectively, and is a good catalyst.

A rise in the air temperature at the workplace is associated with a higher risk of poisoning because when the air temperature rises, the volatility and evaporation of toxic materials increase, thereby increasing the air humidity, which, in turn, increases the toxicity of hydrochloric acid (hydrogen fluoride).

The work of Murugappa, Huang, Cabaleiro, *et al.* [10–12] is aimed at improving the equipment for gas storage and cleaning, as well as developing the methods for describing the processes related to the movement of gas, and determining the nature of pollution caused by manufacturing processes.

The action of transferring mass from the vaporized fluid into the environment can be associated with the process of diffusion and the forced or natural convection. The dynamics of streams created over the bath with the fluid is very complicated [13–15]. Many mechanical devices, removing the volatile aerosols from the surface of the vaporized fluid are not sufficiently effective. Therefore, absorbers of aerosol pollutants are used now. However, their work efficiency is often not sufficiently high. It depends on the transfer processes taking place on the surface of the vaporized liquid. The complicated process taking place on the surface of the hot liquid in an absorber fixed to the bath wall [16]. The fumes start to rise, while the absorber on the edge of the bath should force the air to move at the speed, at which vapors would change the direction of movement and flow towards the absorber's slot [17].

Rota, Marzal, *et al.* [13,18] have examined the exhaust, suction and the influence of rising vapor flow velocity on the pollutant concentration at the workplace, but have not proposed any methods for reducing the concentrations of pollutants at the place of their occurrence. Article [16] presents the views of the vapours' spread at the rate of 0.3 m/s and vapours' take-off velocity of 0.05 m/s, when the velocity of the pumped air flow is within the range of 1.55 m/s to 4.17 m/s. This proves that the pumping rate determines the elevation angle of pollutants above the emission surface of the liquid, but its value depends on the speed of blowing and the vapors' take-off.

When an absorber does not work or its efficiency is insufficient, the vapors found on the opposite side of the slit absorber are not evacuated. With the increase in the temperature of the hydrochloric acid solution, the take-off velocity increases, which results in the increase in the concentration of vapors and pollutants. By varying the hydrochloric acid solution concentration and heating temperature, the intensity of evaporation can be reduced. The optimal solution concentration and temperature can be determined using the multiple attribute decision-making (MADM) techniques [19–22]. A great number of MADM methods have been developed and applied [23–29]. Currently, hybrid MADM methods are used for solving the evaluation problems [30–32]. A very feasible way to apply hybrid DEMATEL + ANP (DANP) methods [33–36]. MADM methods are based on the decision matrix, R, criterion statistics (experimental criterion values), and the criteria weights' vector, Ω [20,37,38].

For comparison, 16 groups of criteria were used in the analysis based on the application of such MCDM methods as VIKOR (from Serbian Vise Kriterijumska Optimizacija I Kompromisno Resenje) [39–42] and COPRAS (Complex Proportional Assessment) [43–46].

In practice, subjective weights determined by experts are commonly used [47–49]. However, experts usually cannot assess the impact of experimental results on the criteria.

The data structure and the degree of dominance (or the objective weight) of each criterion can be determined. In practice, the objective weights are applied less frequently than the subjective weights [19]. The combined weighting is based on the integration of the subjective and objective weights [50].

In performing the experimental study, an objective method for evaluating the criteria weights, a new CILOS (Criterion Impact LOSs) method [51–53], was applied.

2. The Test Setup

Hydrochloric acid heating processes were investigated, using a test setup, schematically shown in Figure 1.

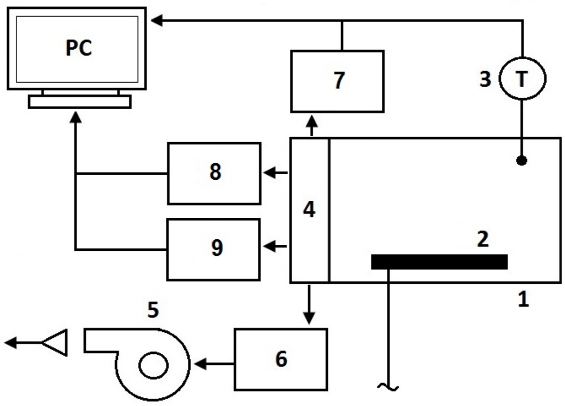

Figure 1. The schematic view of the test setup of the side absorber: 1 an open-surface tank; 2 a heater; 3 a thermometer; 4 a side absorber; 5 a fan; 6 a frequency drive; 7 a device for measuring pressure and flow velocity; 8 a gas density meter; and 9 a viscometer.

The vapor flow is formed above the container with the hydrochloric acid solution (1), which is heated by a heater (2) and whose temperature and humidity changes are detected by a multifunctional humidity and temperature sensor (3). The aerosols formed on the surface of the hydrochloric acid solution are drawn in by the side absorber (4), which is fixed to the container (1) and is connected to the edge of the fan (5). The exhaust airflow can be adjusted with a frequency drive (6). The dynamic steam viscosity is determined by a viscometer (9), while its density is measured by a hygrometer (8), while the velocity is determined by the flow meter (7).

The hydrochloric acid solution was heated in the bath (Figure 2) with the width B of 0.3 m, length L = 0.415 m, and the height from the hydrochloric acid solution surface to the top of the bath, H = 0.08 m, depending on the solution temperature at the ambient temperature of 20 °C. It is recommended that the blowing slot would be at least 5 mm wide (0.011B, where B is the bath width) and the space from which the air has been removed, would be at least 50 mm (0.21B) wide.

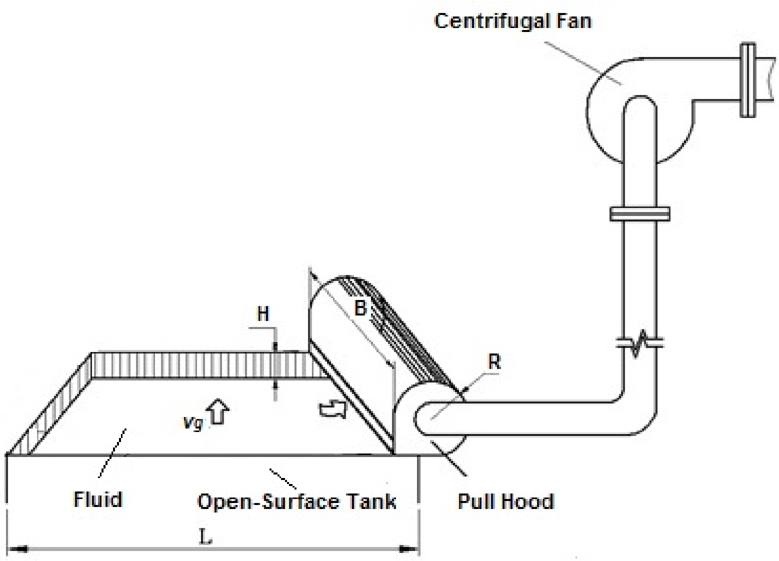

Figure 2. The push system and its geometric parameters.

Two conditions should be satisfied in designing the absorber: the flow generated by the pollution source should be drawn in, while the flow towards the absorber in the critical cross-section should be steady. The flow is considered steady if its speed at the critical cross-section is as follows:

$$u = 7u_{kr}, \text{ when } H \geqslant 0.15 \quad (1)$$

or:

$$u_{kr} = 1.83\sqrt{gB\frac{\Delta t}{t_a}}, \text{ when } H \leqslant 0.15B \quad (2)$$

where u_t is the speed of the disruptive torrent (permissible air speed inside a building is 0.2–0.5 m/s), g is gravity, m/s^2, Δt is the temperature difference between the ambient air and hydrochloric acid solution, °C, and t_a is the ambient temperature (20 °C).

3. Vapor Viscosity, Density, and the Flow Rate

A complicated process takes place during the vapor suction above the bath. The stream rises over the bath and this process is followed by the suction itself and blowing. The hot surface of the hydrochloric acid solution (HAS) is vaporized, and, with the increase in the temperature, the concentration of vapors also increases, which, in turn, activates the movement of the flow and increases environmental pollution.

A rising vapor flow is convective and passes two stages: the formation, when the axial velocity on the surface of the source increases from zero to a maximum value, and the main stage, when the axial velocity decreases or remains constant, when the flow is receding from the source.

The variation of the rate of vapor spreading (m/s) in the main convection stream was calculated for the bath length of one meter by the formula:

$$v_g = 0.053\sqrt[3]{q_{k0}} \quad (3)$$

where q_{k0} is the amount of the convection heat, W.

The speed of the flow along the bath length should not be lower than the critical value (U_{kr} = 1.4 to 3.5 m/s). In this case, about 90% of the pollutants would be removed [54].

The determination of the vapor components' concentration depends on the partial pressure of the component above the hydrochloric acid solution surface, as well as on its molecular weight and temperature. A thin saturated vapor layer is above the surface of the hydrochloric acid solution. Therefore, the partial pressure of the component vapor above the HAS surface is equal to the partial pressure of the saturated vapor at the actual temperature on the solution surface. When the hydrochloric acid solution is stirred, its surface temperature is equal to the temperature at its depth, and the evaporation surface can be several times larger than the surface area of still fluid.

The weighted vapor concentration (mg/m^3) above the surface of the hydrochloric acid solution was calculated by the formula:

$$C_i = 16 p_i M_i \times 1000 / \left[(273 + t_{sk}) \times 133.3 \right] \tag{4}$$

where M_i is the molecular weight of the component; t_{SK} is the hydrochloric acid solution temperature, °C.

The vapor density was calculated according to the formula [55], mg/m^3:

$$p_g = \sum_{i=1}^{n} C_i \tag{5}$$

When a gaseous matrix above the liquid surface is covered with a number of substances (components), *i.e.*, air, fluid (solution) vapor, then, theoretically, its dynamic viscosity can be calculated by the formula [55]:

$$\mu_g = \frac{M_g}{\sum_{i=1}^{n} i_i M_i / \mu_i} \tag{6}$$

where M_g is the relative molecular mass above the hydrochloric acid solution surface: $M_g = \sum_{i=1}^{n} i_i C_i$, $i_i = p_i / p$ is the volume part of the medium component above the hydrochloric acid solution, i is the component; p_i is the component's partial pressure above the hydrochloric acid solution surface at the temperature t_k, Pa; p is the ambient pressure, Pa; μ_i is the dynamic viscosity component over the hydrochloric acid solution surface at the hydrochloric acid solution temperature t_k: $\mu_i = \mu_0 \frac{273 + Sat}{T_{sk} + Sat} \left(\frac{T_{sk}}{273} \right)^{1.5}$, μ_0 is dynamic viscosity of the component above the hydrochloric acid solution surface, when t_k = 0 °C, Pa· s; *Sat* is Sutherland's constant, T_k is the temperature of the hydrochloric acid solution, *K*.

The experimental studies of the flow spread were performed to determine the temperature of the liquid (hydrochloric acid solution) and the concentration of the substance at ambient temperature of 20 °C.

During the investigation, the hydrochloric acid solution was poured into the bath, which was heated to the temperature from 50 to 80 °C. Dry ice pellets were used for visualization of evaporation, which is shown in Figure 3.

Figure 3. Visualization of evaporation.

With the increase in the hydrochloric acid solution surface temperature, the upward movement of vapors also increases. Under the action of the rising forces, the aerosol moves upwards, and the concentration of aerosols and pollution increase.

The take-off velocity v_g largely depends on the amount of heat. When the temperature of the hydrochloric acid solution rises from 50 to 80 °C, the vapor's take-off velocity increases from 0.21 to 0.32 m/s.

When the temperature of the hydrochloric acid solution rises from 50 to 80 °C, while the concentration is in the range of 28%–34%, its vapor density varies between 0.9883 and 1.24448 kg/m^3. The largest value of the dynamic vapor viscosity, making 1.873×10^{-5} Pa· s, was obtained at 50 °C and 28% hydrochloric acid solution concentration, while the smallest 1.680×10^{-5} Pa· s was obtained at 70 °C and 34% hydrochloric acid solution concentration. In order to get optimal combinations of the obtained results, the MADM methods should be applied to the analysis of the data.

4. Experimental Results

Spreading of aerosol vapors depends on the concentration and temperature of the hydrochloric acid solution. The concentration of the hydrochloric acid solution varied during the experiment from 28% to 34%, and the temperature changed from 50 to 80 °C. The measured parameters included vapor density, dynamic viscosity, and the velocity of the vapor flow.

Smaller pollution values were obtained when the density of the vapor mixture and its dynamic viscosity were higher, but the velocity of vapor flow was lower.

Sixteen groups of the experimental data are presented in Table 1. However, the data do not show what experimental results are optimal; therefore, the effective MADM methods were applied to the obtained data analysis.

Table 1. Experimental data on the evaporation of hydrochloric acid.

Experiment	(HAS) Concentration, %	(HAS) Temperature, T, °C	Vapor Density, ρ_g kg/m^3 X_1	Dynamic Viscosity of Vapor, μ_g, 10^5 Pa· s X_2	Velocity of Vapor Flow, v_g, m/s X_3
1	28	50	1.0839	1.868	0.224
2	30	50	1.0995	1.855	0.223
3	32	50	1.1278	1.825	0.242
4	34	50	1.1789	1.775	0.250
5	28	60	1.0488	1.873	0.259
6	30	60	1.0742	1.845	0.265
7	32	60	1.119	1.810	0.272
8	34	60	1.1986	1.740	0.278
9	28	70	1.0155	1.835	0.284
10	30	70	1.055	1.815	0.291
11	32	70	1.1243	1.765	0.297
12	34	70	1.2448	1.680	0.304
13	28	80	0.9883	1.820	0.302
14	30	80	1.0118	1.975	0.309
15	32	80	1.1194	1.735	0.314
16	34	80	1.2370	1.655	0.323

5. MADM Methods

In the present work, the MADM methods, including VIKOR and COPRAS, were applied. The new CILOS method was also used.

5.1. The VIKOR Method

The VIKOR method (abbreviated from Serbian [36] Vise Kriterijumska Optimizacija I Kompromisno Resenje) uses the following normalization:

$$\bar{r}_{kj} = \left(r_j^* - r_{kj}\right) / \left(r_j^* - r_j^-\right) \tag{7}$$

where $r_j^* = \max_k r_{kj}$, $r_j^- = \min_k r_{kj}$, if the jth criterion describes the benefit and $r_j^* = \min_k r_{kj}$, $r_j^- = \max_k r_{kj}$, if the jth criterion describes cost $0 \leqslant \bar{r}_{kj} \leqslant 1$.

The method uses three evaluation criteria, S_k, R_k, Q_k ($k = 1, \ldots, m$).

The criteria S_k and R_k were calculated according to the formulas:

$$S_k = \sum_{j=1}^{n} \omega_j \bar{r}_{kj} \tag{8}$$

$$R_k = \max_j \left(\omega_j \bar{r}_{kj}\right) \tag{9}$$

where ω_j is the weight of the j-th criterion and $\bar{r}_{kj}$ is the normalized value (ratios of common units) of the j-th criterion for the k-th alternative.

The aggregate criterion Q_k of VIKOR is based on the criteria S_k and maximal gap/regret R_k in alternative k and may be calculated by the formula:

$$Q_k = v\left(S_k - \min_k S_k\right) / \left(\max_k S_k - \min_k S_k\right) + (1 - v)\left(R_k - \min_k R_k\right) / \left(\max_k R_k - \min_k R_k\right) \tag{10}$$

where ν is the strategic weight, the majority criterion (in further calculations ν = 0.5).

5.2. The COPRAS Method

The criterion of the COPRAS (Complex Proportional Assessment) method [43] Z_k was calculated as follows:

$$Z_k = S_{+k} + \frac{\sum_{k=1}^{m} S_{-k}}{S_{-k} \sum_{k=1}^{m} \frac{1}{S_{-k}}} \tag{11}$$

$S_{+k} = \sum_{j=1}^{n} \omega_j \bar{r}_{+kj}$ is the sum of the weighted values of the maximized criteria $\tilde{r}_{+ij}$,

$S_{-k} = \sum_{j=1}^{n} \omega_j \bar{r}_{-kj}$ is same for the minimized criteria,

where ω_j is the weight of the j-th criterion and $\bar{r}_{kj}$ is the normalized value of the j-th criterion for the k-th alternative:

$$\bar{r}_{kj} = \frac{r_{kj}}{\sum_{k=1}^{m} r_{kj}} \tag{12}$$

5.3. The CILOS (Criterion Impact LOSs) Method of Criteria Weight Determination

This is another promising method based on the criteria impact loss and determination of the objective weights [51–53]. The method evaluates the impact (significance) loss of each criterion until one of the remaining criteria reaches the optimum, the maximum or the minimum, value. The method's algorithm, formalization, description, and application are presented in [53]. The logic of the method of the criteria impact (significance) loss, as well as the basic ideas, stages, and the calculation algorithm are described below.

The criteria that are minimized were converted into the maximized criteria, according to the following equation:

$$\bar{r}_{kj} = \frac{\min_k r_{kj}}{r_{kj}} \quad (13)$$

A new matrix was denoted as $X = ||x_{kj}||$. The maximum values of each column (*i.e.*, every criterion) were calculated as follows: $x_j = max_k x_{kj} = x_{t_j j}$ where $t_j j$ denotes the lines of the column with the largest number of the element.

The square matrix $A = ||a_{ij}||$ was formed from the values of t_j = s rows of the matrix X; x_{ij} correspond to the j-th maximum criterion: $a_{jj} = x_j$ (i, j = 1,2, ..., n; n is the number of criteria), which means that the maximum values of all the criteria will appear in the main diagonal of the matrix.

The matrix $P = ||p_{ij}||$ of the relative losses is given below:

$$p_{ij} = \frac{x_j + a_{ij}}{x_j}, p_{ii} = 0;\ i, j \in \{1, 2, \ldots, n\} \quad (14)$$

The elements p_{ij} of the matrix P show, what the relative loss of the j-th criterion will be, if the i-th criterion is selected to be the best.

The weights $q = (q_1, q_2, \ldots, q_n)$ can be found from the system:

$$Fq = 0 \quad (15)$$

where the matrix F is as follows:

$$F = \begin{pmatrix} -\sum_{i=1}^{n} p_{i1} & p_{12} & \cdots & p_{1n} \\ p_{21} & -\sum_{i=1}^{n} p_{i2} & & p_{2n} \\ \cdots & & & \\ p_{n1} & p_{n2} & \cdots & -\sum_{i=1}^{n} p_{in} \end{pmatrix} \quad (16)$$

The method based on the criterion impact (significance) loss offsets the drawbacks of the entropy method. Thus, when the values of a criterion do not considerably differ, the elements p_{ij} of the matrix P of the relative loss of the criterion impact (14) approach zero, while the respective criterion weight increases and has a strong impact on the evaluation. In the case of homogeneity, when the values of one of the criteria are the same in all the alternatives, all relative losses of the criterion, as well as its total loss, are equal to zero. Therefore, the linear system of Equation (15) makes no sense because one column of the elements in the matrix P is equal to zero.

6. The Evaluation Results

The calculated CILOS weights of criteria are presented in Table 1. The values obtained in weighting are given in Table 2.

Table 2. Weights obtained by the CILOS method.

Criterion	X_1	X_2	X_3
Weight	0.3641	0.5019	0.1340
Rank	2	1	3

The priorities determined by using a general theory of weights and various MADM methods are presented in Table 3.

Table 3. The ranking of the alternatives based on using the theory of aggregating weights and various MADM methods.

Weights Yielded by CILOS Method									
Method Alternatives (Variants)	VIKOR						COPRAS		The Total Rank *
	S_j	Rank	R_j	Rank	Q_j	Rank	Z_i	Rank	
1	0.3976	2	0.2284	2	0.0423	2	0.0650	2	2
2	0.3945	1	0.2063	1	0	1	0.0651	1	1
3	0.4268	3	0.2353	3	0.0998	3	0.0644	3	3
4	0.4434	4	0.3137	8	0.2585	5	0.0642	4	4
5	0.4864	6	0.2782	7	0.2661	7	0.0630	6	6
6	0.5023	8	0.2422	4	0.2300	4	0.0628	8	5
7	0.5030	9	0.2588	5	0.2592	6	0.0629	7	7
8	0.5079	10	0.3686	13	0.4525	10	0.0631	5	9
9	0.6268	14	0.3255	9	0.5663	12	0.0608	14	12–13
10	0.6115	13	0.2694	6	0.4474	9	0.0611	13	10
11	0.5996	12	0.3294	10	0.5301	11	0.0615	11	11
12	0.5712	11	0.4627	15	0.7111	13	0.0623	10	12–13
13	0.7131	16	0.3641	12	0.7670	15	0.0549	16	16
14	0.4460	5	0.3307	11	0.2914	8	0.0625	9	8
15	0.6764	15	0.3764	14	0.7402	14	0.0605	15	15
16	0.5019	7	0.5019	16	0.8963	16	0.0613	12	14

* The total rank presents the result obtained based on the sum of the ranks of all considered criteria and is given in the last column in Table 3.

MADM analysis, based on using the VIKOR and COPRAS methods, shows that the best results were obtained in the second experiment, when the HAS concentration reached 30% and the temperature was 50 °C. The worst results were obtained in test 13, when the hydrochloric acid solution density was 28% and the temperature reached 80 °C. This means that the dispersion of pollutants depends not only on the density of the hydrochloric acid solution but also on its temperature.

The evaluation of the weights of criteria allows us to state that the dynamic viscosity criterion (X_2) has the largest weight according to the entropy method. It was confirmed by the criterion weight calculation results obtained by summarizing the weights yielded by the CILOS method.

Over the past decades, drastic measures have been taken to reduce the air pollution. However, the level of air pollution is still too high, and the air quality problem is still acute. A large part of the world's population lives in urban areas, where pollution, not complying with the air quality standards, poses a threat to human health and the environment.

Based on the obtained data, the technological parameters of production, ensuring minimum environmental pollution, can be chosen. The best manufacturing technology to ensure the lowest possible environmental pollution should be implemented using these research results.

7. Conclusions

Summarizing the results of the analysis, the authors came to the conclusion that the dispersion of pollutants depends not only on the concentration of the hydrochloric acid solution (HAS), but also on its temperature. The optimal variant was found, when the concentration reached 30% and the temperature was about 50 °C. The evaluation of the results yielded by two MADM methods allowed the authors to conclude that the second variant (alternative) was optimal (the best). It was followed by alternative 1 and alternative 3.

The obtained results confirmed the possibility of optimizing pollution characteristics using MADM methods. In the experimental study, the method of the criteria impact loss (CILOS), suggested by the authors of the present paper, was used for determining the objective weights of the considered criteria. This method compensates for the drawbacks of the entropy method used for the same purpose.

The correlation coefficient for the values of the evaluation criterion Q_k of the VIKOR method and the criterion Z_k of the COPRAS method is r = 0.75. This shows a relatively high consistency of the obtained results.

One of the global sustainable development priorities is the reduction of harmful technological effects on the environment and the human health. The MADM methods can be effectively used for solving various environmental problems. In the future it is planned to carry out environmental pollution researches, depending on the size of aerosol particles.

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