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Development of a cognitive model for the analysis of relationships in the airport environmental management system

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Abstract. Aviation enterprises (airports) are massive facilities with a variety of effects on the environment, yet, those influences are significantly understudied and lack structuring, leaving the airports at low levels of sustainability and with impaired management. Thus, the aim of this research was to compile the mind map to describe a system of environmental impacts and problems associated with the airports. The model (map) was created by conducting complex multi-stage expert surveys with scoping of elements of airport management system, which identified 68 factors belonging to 8 groups. The factors are related to atmospheric air, soil and water, flora and fauna, physical impacts, organisational, environmental, administrative, logistical and spatial issues, construction and technical solutions as well as social, economic and human factors. With the help of ranking based on experts' judgements, 13 most relevant (key) factors of the impact on the environment were distinguished. To build an oriented graph of the airport management system and

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analyse it, the approach of drawing arcs (arrows) of impact was used. It is found that the most influential factors tend to be dynamic, related to the planning stages of airports and instead of purely environmental ones are interdisciplinary. The annual passenger traffic at the airport, compliance with the standards of sanitary protection zones, airport's capacity and types of aircraft received by the airport demonstrated the highest impact on the airport environmental management system. In combination with studies of the effects of individual factors and the impact of the airport on the environment, the results of the work can be applied practically in the management and decision-making processes regarding the environmental safety of the airport

Keywords: mind map; aviation industry; factors of influence; expert assessment; environmental protection; decision-making

Introduction

In ensuring the sustainable development of the aviation industry, an important role is attributed to the environmental vector and compliance with international standards regarding the impact on the environment of both aircraft and airport infrastructure. The impact of airports on the environment is manifested both locally (pollution of the atmosphere, hydrosphere, soil, acoustic pollution, etc.), and in global changes of landscapes and ecosystems, displacement of populations from their natural habitats. Solving a number of current problems in this area at the global level can significantly improve the general environmental situation in Ukraine and the world. However, the aviation industry as a whole, airports as its principal structural units and even individual aircrafts are extremely complex systems with many elements and influencing factors, threats and relationships. It is essential to identify, consider, and analyse the internal connections within those entities and the effects of altering individual elements within them on all other components and the system overall. Thus, the ranking of environmental issues of the aviation industry and its individual divisions, particularly airports, will allow to properly determine the priorities of their solution.

The study of environmental problems of the aviation industry is not a new topic for the scientific community. However, as R. Qiu *et al.* (2021) noted, this topic always remains relevant. For a long time, the main attention of research was given to environmental problems related to airplanes and the process of air transportation itself, and not to the ground infrastructure of airports. A lot of attention is paid only to certain causes and threats that lead to the negative impact of airport infrastructure on the environment. N. Bahman (2023) provided an environmental impact analysis and a life cycle assessment of auxiliary power plants and ground support equipment at the airport, but did not give recommendations for mitigation or management. In turn, V. Parkhomenko (2020) considered the causes and threats that lead to the appearance of birds and other wildlife at the field, but only brief recommendations were given to minimise such collisions.

A significant amount of research is focused on the problem of adverse impacts of an airport's infrastructure on the quality of atmospheric air on a local and regional scale. The problem of regional air pollution by civil aviation airports is discussed in the recent work by O. Zaporozhets *et al.* (2018). But the given strategy of environmental protection regulation involves the organisation of airport's monitoring system, oriented towards the established priorities in regulating the quality of atmospheric air only. Other factors of negative influence are not considered. In conducting this kind of research, it is quite difficult to investigate direct cause-and-effect relationships in this system and establish, in particular, the place of biota in the general objectives of airport environmental management, or to investigate the consequences of secondary effects arising from other impacts as highlighted by F. Greer *et al.* (2020). As a result, threats to the environment resulting from the activities of airports are studied in isolation from each other, either very specifically, that is, with reference to a separate airport, or more generally, analysing all possible environmental consequences.

As noted by R.C. Alberts *et al.* (2023), determining the extent of impact is one of the preliminary stages of environmental impact assessment in environmental quality management. This is important when summarising and assessing the significance of the potential impacts of a project (or activity such as airport construction or operation) and its alternatives (e.g. airport construction alternatives or operating modes). Furthermore, R.C. Alberts *et al.* (2020) emphasised that it also allows to narrow the range of issues that require further consideration and careful assessment, and guide subsequent decision-making processes. E. Zarghami & D. Fatourehchi (2020) argue that impact scoping is often considered very important (sometimes – of utmost importance) in the general practice of environmental impact assessment, but according to K. Emerson *et al.* (2022) it is still understudied.

The later research indicates insufficient attention to the environmental impact of airport operations. While various aspects have been examined individually, there's a lack of efforts to consolidate these factors into a cohesive framework. Such a system could reveal interconnections between environmental issues, offering insights into their mutual influence. To enhance aviation sustainability, creating such a model is a pertinent scientific endeavour. Therefore, developing a comprehensive model of significant airport-environment impacts and their interactions is crucial for a holistic environmental management system (EMS) at airports. The purpose of the study was to develop a cognitive model of the complex impact of the airport on the environment. To achieve this goal, the following research tasks were defined: to determine the main factors of airport's impact on the environment and evaluate their significance; to develop a cognitive model for the analysis of relationships in the EMS of the airport.

Materials and Methods

The model for the analysis of interrelationships in the EMS of the airport was developed using the method of constructing cognitive maps. This method was proposed by R. Axelrod (1976). This study followed one of the most detailed examples in Axelrod's methodology (Chernyshev *et al.*, 2021). The core of the research was a series of surveys to assess the environmental impact of airports survey by the given methodology, involving experts in the field with special knowledge of certain aspects of the aviation industry. The surveys took place during the first half of 2021 via correspondence (*in absentia*). Overall, 7 experts were questioned. All experts were informed about the anonymity of the survey, the ways of information protection, purpose of the investigation and related risks. They also did not have the opportunity to participate in discussions or meetings regarding their expertise and conducted their evaluations independently. In the course of the surveys, the ethical norms of social work with people were adhered (The ethics of social work…, 1994). Due to the announcement of martial law in early 2022, Ukrainian airports have been closed, making it impossible to conduct the second qualitative expert survey after 2021.

The experts were asked to identify, in accordance with their expertise, the full scope of factors, which influence or form the system of environmental management in airports. Further, with the help of cross-examination, grouping and clustering, the main factors of airport's impact on the environment were determined. 68 influencing factors were identified, which were grouped into 8 categories. The next step was the ranking procedure, during which experts were asked to evaluate the importance of all factors by two independent scales:

- absolute, with values from 1 (the least important variable, the impact of the factor on the state of the environment is insignificant), to 4 (moderately important changes in the environment status and impact), to the highest score – 7 (the change is extremely important, the factor has a significant qualitative and quantitative impact);
- relative, with points from 1 to 100, by the procedure of factor's weight assessment. Given the division of variables into groups, it was recommended in each category to assign 100 points to the most significant impact factor with the greatest weight, and then evaluate other factors in the group relative to this variable.

After ranking, all scores were collected and ordered, rating each factor within a separate group. Based on this, the most significant factors were defined by selecting one to three variables from each category based on the sum of their average absolute and relative scores. In this way, 13 main variables were obtained. The subsequent task was to identify interdependencies between the selected variables and to build the table of interdependencies. For this, once more, experts were asked the following questions: "Is there a connection between these two factors?" and "If dependency exists, what is its nature/quality – is it direct or inverse?" Then, for the processing purposes, all data (answers) were placed in a table with the following symbols: "+" – positive connection, direct impact; "-" – negative connection, reverse effect; "0" – the impact is absent or negligent; "?" – the relationship is uncertain, the nature of the impact is unclear. The following rules were established during this procedure:

- if at least 85% of experts (6 out of 7) believe that an impact (with a certain sign) exists, then there is an impact curve; otherwise, the curve is not drawn;
- the sign of the impact curve is placed only if at least 85% (6 out of 7) of the experts agree on the nature of the influence;
- if there is uncertainty about the nature of an impact, but there is clear certainty (agreement) about its presence among experts – the impact curve is drawn, but marked as unclear ("?");
- if experts' opinions were split (three different opinions or more), the impact curve is not drawn at all.

At the end of the study, a cognitive map was built based on the table of interdependencies, which reflects the system of sources and ways of the airport's impact on the environment from the perspective of their significance.

Results and Discussion

68 factors of environmental impact of airports were initially identified, and were grouped into 8 groups. The 1st group of factors is related to the impact on atmospheric air. It includes the following variables: emissions of NO_x, CO, greenhouse gases, particulate matter, volatile hydrocarbons C_xH_y, other possible pollutants (e.g. SO_2, N_2, O_2, etc.), integral air quality index (AQI) by target pollutants, the nature and scale of interaction of pollutants (persistence, accumulation, magnification, etc.), availability and quality of work of the atmospheric air monitoring service.

The 2nd group of factors is related to the impact on soil and water bodies. It includes the following variables: the area of the territory with a solid cover, pollution of soils and water bodies by heavy metals, petroleum products, anti-icing and de-icing agents, the total quantity and quality of effluents/wastewater, secondary pollution (water pollution via soil or soil pollution via water), the type of affected soils and the class of adjacent water bodies, availability and quality of work of the soil and water monitoring service, the efficiency of the wastewater collection and treatment.

Impact on flora and fauna was the focus of the 3rd group of factors. It includes the following variables: the intersection of wildlife migration routes (especially birds) with airport (or its immediate vicinity), the number of Red

List species in the impact zone, the abundance and density of populations around the airport, the levels of habitat fragmentation and destruction, the types of surrounding ecosystems and ecotopes, the distance to the nearest protected areas (sites), availability of ornithological safety service, availability and quality of functioning of ornithological monitoring service, the overall risk (probability) of introducing invasive or pathogenic organisms into the zone/region due to airport activities.

Factors of the 4th group are related to the physical impacts caused by an airport. They include: levels of noise, light, electromagnetic fields and radiation, heat, vibration, visual pollution, protection from exposure to physical factors outside the airport, effectiveness of protective measures for the control of physical factors.

5th group of factors concentrated on organisational, environmental and administrative decisions. The following variables were included: the amount and composition of waste generated at the airport, the method of disposal of solid waste, the presence of solid waste sorting at the airport, the presence and size of payments for comprehensive impact on the environment, the regularity of inspections of technical equipment and airport facilities, approved environmental policy, the presence and nature of voluntary mitigation measures, the number and complexity of additional services on the territory (aircraft repair and maintenance, accommodation, etc.).

Factors related to logistical and spatial decisions are listed in the 6th group. They include the following variables: climate zone of airport, geological and geographical location of the airport (relief and geological-dynamic situation), social and political situation in the area (political tension in the region, proximity to areas of armed conflicts, etc.), compliance with the standards of the sanitary and protective zone for this type of industrial objects, location of airport relative to the nearest population centres and settlements, types of airport commuting, location of the airport relative to large water bodies (levels of sea/ocean etc.), location relative to important airways/hubs (international and domestic).

Construction and technical solutions made up the 7th group of factors. In this group the following variables are included: environmental friendliness of the airport design (degree of its integration into the environment), number and length of runways on the territory, total size of the airport, types of aircraft served by airport (by take-off weight or passenger capacity), airport capacity (average number of aircrafts received simultaneously, the number of terminals and/or boarding gates), the structure of fuel depot, the type of aircraft refuelling system, depreciation of the airport's ground and air equipment.

Finally, 8th group of factors is related to social, economic and human factors, and includes: average annual passenger traffic at the airport; level of qualification of service personnel; environmental training of the staff; frequency of emergency situations; availability, quantity and quality of environmental advocacy, general level of environmental performance and environmental awareness of the country hosting the airport, the image and popularity of the airport, the level of economic development of the country hosting the airport. The results of ranking, arrangement and selection of the most significant factors in each category are presented in Table 1 and Table 2.

Table 1. Expert assessment of the primary factors of the airport's impact on the environment

Group No.	Factors	Expert assessment													
		Absolute value (from 1 to 7)							Relative value (from 1 to 100)						
		1	2	3	4	5	6	7	1	2	3	4	5	6	7
1	Impact on atmospheric air	6	6	7	7	6	6	6	95	95	100	99	100	83	78
	Availability and quality of air monitoring system	5	7	6	7	5	6	6	85	100	80	100	75	85	76
2	Soil and water pollution by petroleum products	7	7	7	7	6	6	7	100	97	100	98	91	80	98
	Efficiency of wastewater collection and treatment	7	7	6	7	5	7	7	100	98	80	100	59	98	100
3	Intersection of wildlife (especially birds) migration routes with the airport	7	7	7	7	7	7	6	100	98	70	100	100	97	83
	Availability and quality of functioning of the ornithological monitoring service	6	7	6	4	7	7	6	90	100	100	75	99	92	85
4	Airport's noise pollution level	6	7	7	7	7	7	7	90	100	100	100	100	99	93
	Effectiveness of protection from exposure to physical factors	7	7	6	6	6	7	7	100	99	30	94	86	100	100
5	The amount and composition of waste generated at the airport	5	7	6	7	7	7	7	75	100	70	100	98	94	92
	Availability of solid waste disposal methods	7	6	6	6	7	6	7	90	85	60	88	97	76	93

Table 1. Continued

Group No.	Factors	Expert assessment													
		Absolute value (from 1 to 7)							Relative value (from 1 to 100)						
		1	2	3	4	5	6	7	1	2	3	4	5	6	7
6	Compliance with the standards of the sanitary protection zone	7	7	7	7	7	7	6	100	95	100	96	99	100	76
	Location of the airport relative to the nearest settlements	7	6	7	7	7	5	5	100	80	100	92	100	69	73
7	Types of aircraft accepted by the airport	7	7	7	7	7	5	6	100	97	100	95	99	62	76
	Airport capacity	6	6	7	6	7	7	7	90	85	90	87	98	99	95
8	Average annual passenger traffic	6	7	7	7	7	7	7	85	100	100	100	98	100	100
	The general level of environmental performance	7	5	6	6	6	7	6	100	85	70	85	80	96	82

Source: made by the authors

Table 2. The results of the assessment of significance of the primary variable (ordered ranking)

Group No.	Factors	Mean absolute significance according to expert evaluation	Median position (absolute significance)	Mean relative significance according to expert evaluation	Relative significance position (rank)
1	Impact on atmospheric air	6.29	5	92.86	5
	Availability and quality of air monitoring system	6.00	7	85.86	13
2	Soil and water pollution by petroleum products	6.71	2	94.86	4
	Efficiency of wastewater collection and treatment	6.57	3	90.71	9
3	Intersection of wildlife (especially birds) migration routes with the airport	6.86	1	92.57	6
	Availability and quality of functioning of the ornithological monitoring service	6.14	6	91.57	8
4	Airport's noise pollution level	6.86	1	97.43	2
	Effectiveness of protection from exposure to physical factors	6.57	3	87.00	12
5	The amount and composition of waste generated at the airport	6.57	3	89.86	10
	Availability of solid waste disposal methods	6.43	4	84.14	15
6	Compliance with the standards of the sanitary protection zone	6.86	1	95.14	3
	Location of the airport relative to the nearest settlements	6.29	5	87.71	11
7	Types of aircraft accepted by the airport	6.57	3	89.86	10
	Airport capacity	6.57	3	92.00	7
8	Average annual passenger traffic	6.86	1	97.57	1
	The general level of environmental performance	6.14	6	85.43	14

Source: made by the authors

Based on the data obtained in Table 1 and Table 2, the key factors of the impact of airports on the environment were determined – they are 20% (13 out of 68) of all the factors, and are listed in Table 3.

Table 3. Key factors of the airport's impact on the environment

No.	Factors
1	Average annual passenger traffic at the airport
2	Noise pollution level
3	Compliance with the standards of the sanitary protection zone
4	Soil and water pollution by petroleum products
5	Intersection of wildlife (especially birds) migration routes with the airport
6	Availability and quality of air monitoring system
7	Airport capacity (the average number of aircraft received at the same time, the number of terminals and/or departure locations)
8	Availability and quality of the ornithological monitoring service
9	Efficiency of wastewater collection and treatment system
10	The amount and composition of waste generated at the airport
11	Type of aircraft served by the airport (by take-off weight or passenger capacity)
12	Location of the airport relative to the nearest settlements
13	Effectiveness of protection from exposure to physical factors

Source: made by the authors

Having examined the identified interdependencies, a cognitive map (model) was drawn up in accordance with the construction method (Fig. 1). On this model the factors presented in Table 3 are marked with numbers, regular arrows show a positive interaction – a direct dependence, dotted arrows indicate a vague influence which requires additional consideration.

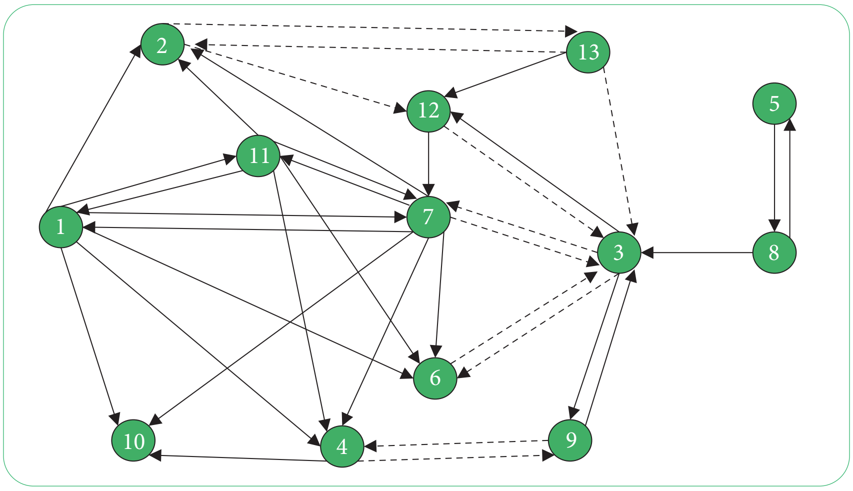

Figure 1. Cognitive model (oriented graph) for the analysis of the environmental situation in the airport impact area
Source: created by the authors

When considering the results of the first stage of expert evaluation (ranking factors by importance), it immediately becomes obvious that most experts consider the factors that are dynamic and/or related to the planning stages of airport facilities to be most important. That is, these are the factors that are not changeable at the existing object, but can be influenced at the stages of planning and construction. Even if the variable is a characteristic of an existing facility, experts also usually prefer those that can be affected in some way during airport operations (e.g. NO_x emissions or noise pollution levels). At the same time, a ratio of 8:5 is observed between purely environmental and interdisciplinary factors. This fact provides important insights into the dependence between the environmental situation in the airport impact area and airport management.

Analysis of relations between individual pairs of factors provides mostly obvious and expected conclusions regarding their interaction. However, for such key factors as 1, 3, 7 and 11 (Table 3) the number of connections and, in particular, the influence on other variables differ significantly. In addition, all these factors are not direct environmental indicators; rather, they are at the edge of environmental components with organisational, technical, logistical, administrative, etc. This means that 4 out of 5 interdisciplinary factors have the highest number of interconnections in the current system. It once again confirms the importance of interdisciplinary factors for the environmental situation in the airport impact area. In turn, most environmental factors are dependent rather than influential, that is, they play certain role in the environmental situation, but their role is passive and/or indicative, so they must be controlled by influencing higher-order or wider-ranging components. As a result, it is possible to formulate the following conclusions, which are important for analysis, planning and decision-making regarding the management and control of the environmental situation in the airport impact area.

Factor number one is the average annual passenger traffic at the airport. It is related to many environmental factors (such as noise level, water and soil pollution around the airport, NO_x emissions, waste generation, etc.). It also has some direct interactions with other complex factors, such as airport's capacity or the types of aircrafts served. Thus, this variable has significant impact on the environmental situation and contributes to the overall instability of the system (since all the identified relationships of this variable are positive), as well as the complexity of its tangential management (especially the reduction of the value). This means that it needs to be controlled directly, for example by setting limits on its value, in order to achieve the desired environmental status at the airport area. This factor is also the least manageable, as airport traffic is of primary importance to the administration.

Third factor – the compliance with the standards of sanitary protection zones for these objects – has the opposite situation, since most experts recognize its importance for the environmental situation of the airport territory and the overall stability of the system. But this variable has a high level of uncertainty about the nature and quality of its interactions, which, on the one hand, indicates their complexity and dependence on other sub-factors, and on the other hand, provides potential opportunity for their regulation.

The situation is quite similar with factors that took the seventh and the eleventh positions according to relative importance – namely, airport capacity (average number of aircraft received at the same time, number of terminals and/or departure points) and types of aircraft received by the airport (by take-off mass or passenger capacity), which also occupy a prominent place in the overall system, but unlike the factor that took the third position, these factors also have strong destabilising effect on a number of other important environmental indicators, but they could be managed easier by controlling variables that affect them, which to some extent puts them in a somewhat intermediate position.

Significant number of works are dedicated to sustainable aviation and aircraft. However, the consideration of airport infrastructure has begun gaining momentum only recently. As suggested by A. Graham (2023), scientists working in this field are in agreement that such developments call for reconsideration of airport's EMS. Some instances of knowledge generalisation on airport's sustainability and its components were made by I. Karagiannis *et al.* (2019), F. Greer *et al.* (2020) and S. Sreenath *et al.* (2021). All those works provide valuable insights in the structure of environmental management of airports, however they still miss some important points on the environmental part, while concentrating on economic, social and technical-operational ones. Their studies identify and evaluate sustainable practices and dimensions in airport operations giving a thorough overview of environmental, social and economic elements and assessing how they are implemented. Yet, those researches also underline that while there are lots of works on aircraft emissions, greenhouse gases, noise, bird strikes – other environmental and especially interdisciplinary factors still remain unexamined and ill-included.

More practical approaches to comprehensive view on elements of the airport's EMS are suggested in works related to airport design and planning. Research by S.K. Kaya & N. Erginel (2020) suggest a way of assessment and integration of sustainability requirements into the airport planning, yet authors note that this is the sole application, meaning the approach is not really practical in terms of management. Investigation by S.L. Boca Santa *et al.* (2020) is the closest to the given research in terms of results, as they were working on indicators – elements of airport's sustainability, relevant for EMS. Still, instead of modelling they incorporated descriptive methods in order to establish the characteristics. Thus, this and previous works lack the understanding of interrelations between separate factors or their groups, and they do not consider how those connections may affect the whole system. Ukrainian examples by V. Isaienko *et al.* (2019) and D. Kalnytska (2020) suggest a more structured and mathematical approach to administration of the airport's technoecosystem, focusing on management and partially addressing the interactions between different components. Yet they consider only generalised environmental and technogenic parts without an in-depth detailed view on the actual multitudes of factors in those groups.

In contrast with all those previous studies, the given work combines comprehensive analysis of environmental management and sustainability factors, as well as both modelling and expert assessment offering a qualitatively new view on the investigated system. Additionally, the proposed model allows a certain degree of flexibility in depth of examination, which can be reached by increasing the number of relevant elements in the system. All those components were identified and presented in the paper, and more complex models may be built by expanding this research and increasing the number of experts involved.

Here, it is worth noting that application of the methodology of expert evaluations has certain limitations. As mentioned by S. Durst & M. Zieba (2019), the most important are their subjective character and human factor. Expert judgments depend on the qualifications of experts, and in case of expert groups, rely on the assumption that if the majority agrees, the results will be true. But in practice this is not always the case. Thus, the higher the qualification is, the higher the probability of reliable results will be. In order to solve this issue, experienced scientists and environmentalists from the aviation industry were involved in this research.

Another significant limitation is the attitude of experts, who can either take the research and its results very seriously or rather lightly. Additional negative point is the discrepancy of repeated assessments, i.e. same experts may give different assessments of the same impact factor over time, in case of repeated assessments. O. Boiko *et al.* (2021) suggest that this problem can be managed by incentivizing experts (e.g. remuneration), which was not the case in this study. In this work, the basis for ensuring objectivity was the strict rules of evaluation, work ethics and the responsible nature of experts. If repeated discrepancies occurred, they were usually resolved by repeated assessments, averaging, or identification of discrepancies and their exclusion. While drawing up this study the usefulness of individual repeated assessments was emphasised, although this was not required.

It should also be noted that cognitive maps themselves have certain limitations in terms of application as stated by G. Felix *et al.* (2019). They are quite complex in their design and interpretation, and their complexity increases proportionally to the complexity of the system under consideration. Additionally, there is an increased likelihood of deviations from the original research topic, resulting in a final sign graph that may not accurately reflect the problem intended for research. Finally, cognitive maps are hardly a stand-alone scientific tool, that is, they should not be relied upon as a single comprehensive answer to all questions. These maps may reveal additional aspects of systems or events, structure well-known ones, assist in decision-making or drawing conclusions, but they are not exclusive in nature and should be used as an additional tool to increase reliability and efficiency.

Nevertheless, the developed model allows for new research and decision-making possibilities. Suggested cognitive map lays the foundation for further research of interdependencies between different groups of factors that create the environmental situation in the airport impact area. It also has a great potential to support administrative and managerial decisions. Thus, despite certain constraints the model still proves to be useful, relevant and applicable both from purely scientific and applied point of view.

Conclusions

The given study has focused on the system analysis of airport's environmental impacts, their management and links to sustainability. It also attempted to generalise elements and interrelations of the studied system and create its comprehensive model (cognitive map) for further use in science, decision-making and administrative work. In accordance with the first objective of the paper, 68 most significant and influential system elements, grouped into 8 categories, were established via expert survey and literature analysis, confirming that the airport's EMS is complex and multi-layered. Using the method of expert evaluation, the main elements and factors of airport's impact on the environment were analysed and evaluated by weight and significance and narrowed down to 13 main factors by means of ranking. On the basis of this analysis, a cognitive model of the relationships between the identified factors within the airport management system was created, pursuing the second objective of the research.

Expert evaluation reveals that factors which tend to be dynamic, related to the planning stages of airports and interdisciplinary (instead of purely environmental) have the highest impact on the overall system (with the ratio of 8:5 between environmental and interdisciplinary factors). Key factors – (1) annual passenger traffic at the airport, (3) compliance with the standards of sanitary protection zones, (7) airport's capacity and (11) types of aircraft received by the airport, – exhibit distinct connections and effects, therefore being central to the system. Most environmental factors are passive, necessitating control through higher-order components. Factor (1) significantly impacts various environmental aspects, demanding direct control and management to improve environmental performance. In contrast, factor (3) holds importance but has uncertain interactions, being both dependent and having potential for tangential regulation.

Further research is possible in directions of errors identification and correction, increase in model detail, consideration of individual factors as separate systems, deepening the understanding of their role in the system of environmental impacts of the airport; finding ways to apply the achievements of this research to regulate the environmental situation in the area of influence of the airport.

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Conflict of Interest

None.

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Розробка когнітивної моделі для аналізу взаємозв'язків у системі екологічного управління аеропортом

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Анотація. Авіаційні підприємства (аеропорти) – це масивні об'єкти з різноманітними впливами на навколишнє середовище, проте, ці впливи досі є недостатньо вивченими, їх розгляду не вистачає структуризації, що спричиняє низьку стійкість аеропортів та погіршує управлінські можливості. Тому метою даного дослідження було скласти когнітивну мапу для опису системи впливів на навколишнє середовище та екологічних проблем, пов'язаних з аеропортами. Модель (мапу) створено шляхом проведення комплексних багатоетапних експертних опитувань зі скоупінгом елементів системи управління аеропортом, у результаті яких було визначено 68 факторів, що належать до 8 умовних груп. Фактори пов'язані з впливами на атмосферне повітря, ґрунти і воду, флору й фауну, фізичними впливами, організаційними, екологічними, адміністративними, логістичними, просторовими, будівельними та технічними рішеннями, а також враховано соціальні, економічні та людські фактори. Експертами виокремлено 13 найбільш релевантних (ключових) факторів впливу на довкілля за допомогою методу ранжування. Для побудови орієнтованого графа системи управління аеропортом та його аналізу використано підхід прокладання дуг (стрілок) впливу. Виявлено, що найбільше на загальну систему впливають фактори, які мають динамічний характер, пов'язані зі стадіями планування аеропортів, а замість суто екологічних є міждисциплінарними. Встановлено, що річний пасажиропотік в аеропорті, дотримання нормативів санітарно-захисних зон, пропускна спроможність аеропорту та типи повітряних суден, які приймає аеропорт, мають найзначніший вплив на систему екологічного менеджменту аеропорту. У поєднанні з дослідженнями впливу окремих факторів та впливів аеропорту на навколишнє середовище, результати роботи можуть застосовуватися практично в процесах управління та прийняття рішень щодо екологічної безпеки аеропорту

Ключові слова: когнітивна мапа; авіаційна промисловість; чинники впливу; експертна оцінка; захист довкілля; прийняття рішень

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Analysis of groundwater recharge in Nadvirna district by the Korkmaz method

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Abstract. The identification of groundwater sources and the prediction of possible water level fluctuations are crucial, as the study of these indicators is important for understanding the renewal of water resources and their efficient use in specific territorial conditions. The purpose of this study was to identify groundwater sources in the area of Mykulychyn village and assess their changes during the period from 2016 to 2022. The study was based on the Korkmaz method and analysis of data on water level in the well and precipitation level in the study area. The structural analysis of groundwater recharge in the Mykulychyn village in Nadvirna district was carried out using the Korkmaz method. It is established that groundwater recharge in Mykulychyn village is due to precipitation. The correlation between the water flow rate from the source and the water level in the well is demonstrated, allowing for projection of the study results to both objects. The average annual rainfall on the territory was 1,055.7 mm. The results of the linear regression analysis showed a connection between the water level and the total precipitation. The analysis of water level fluctuations in the well revealed that the annual water level recharge varies from 782 mm in 2017 to -254 mm in 2022. This indicates that some smaller aquifers may have dried up in 2022. The average annual recharge for the period from 2017 to 2022 is 347 mm, which is about 32.88% of the average annual precipitation. The results of the study can be useful in practice for water management and planning in Mykulychyn village, as well as in similar geographical conditions

Keywords: precipitation; source renewal; level fluctuations; wells; seasonality

Introduction

In 2023, the world is facing numerous challenges in the field of water resources, such as the reduction of the amount of available freshwater, groundwater pollution, and the instability of aquatic ecosystems. These problems are becoming increasingly serious due to the growth of the world's population and the increasing pressure on water resources. The issue of water resources management is becoming particularly relevant due to the increasing burden on natural water sources and the impact of climate change. One of the key components of water resources is groundwater, which

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plays an important role in meeting the needs of the population, the agricultural sector, and industry. The analysis of groundwater recharge and understanding of its cycle is of scientific and practical importance for sustainable development and ensuring access to water resources.

Recent scientific research in the field of hydrology and hydrogeology, such as P. Varnakovida *et al.* (2023), describes the growing interest in the analysis of groundwater recharge and their impact on water resources, noting the consensus on the urgency of this issue. They emphasize that modern hydrology and hydrogeology require a deep understanding of the processes that determine the quantity and quality of groundwater resources to ensure sustainable use and planning of their use. P. Chacuttrikul & S. Thueksathit (2023) focus on the importance of understanding the water balance and sources of groundwater recharge. They consider issues related to the processes that determine the quantity and quality of water that enters underground reservoirs. These studies provide the opportunity to establish which sources of water input to groundwater systems are the most important, as well as which factors affect the level of groundwater.

Other studies, including M.N.H. Mahmud *et al.* (2023), focus on the relationship between precipitation and groundwater level. They study the impact of precipitation on groundwater level fluctuations and develop methods for predicting these changes. The results of these studies provide the opportunity to better understand the relationship between precipitation and groundwater level, which is important for rational water resources management, especially in the context of extreme climate change. Z. Hossain & S.K. Adhikary (2023) proposed an interesting method of groundwater replenishment by applying the definition of potential groundwater recharge zones in the Barind Region of Bangladesh using geospatial techniques. This research method is convenient for faraway regions but it includes subjectivity in assigning hierarchical expert assessments, which can lead to inaccurate results. D.N. Dralle *et al.* (2023) applied a modified method based on the Korkmaz method to study groundwater replenishment in a forested remote region. The researchers also studied a particularly wet cycle in conditions of limited monitoring and taking into account the steepness of the slopes of the hills of the mountainous region. O.A. Bamisaiye (2023) studied the impact of climate change on groundwater replenishment, using historical rainfall data obtained by satellite observation for analysis. By predicting climate change and comparing the obtained data with historical periods, the feasibility and accuracy of using satellite observation data for rainfall have been proven.

Among Ukrainian researchers, V. Khilchevskyi & R.L. Kravchynskyi (2020) are studying groundwater in the region. Based on their monitoring data and local exploration and mapping of sources, a sufficient amount of input data has been obtained for research to determine the level of groundwater replenishment. The importance of replenishment regimes is further traced in the studies of M. Korchemlyuk *et al.* (2019), which note the close links between diffuse pollution and the feeding of water bodies. However, taking into account the regular monitoring component of these authors and access to the necessary input data on changes in water levels in springs and wells, it would be advisable to use a variety of methods for analysing groundwater replenishment.

Although enough attention has been paid to monitoring aspects by scientists, the issue of determining the percentage of groundwater recharge from precipitation has not been resolved and has been considered insufficiently thoroughly for the study region, has not been considered in the context of the use of more accurate satellite data, but used data on precipitation obtained from local meteorological stations. The totality of these aspects served as the reason to carry out this study. The purpose of this study was to analyse the recharge of groundwater in the Mykulychyn village of the Nadvirna district, to identify sources of recharge, and to study possible trends and fluctuations in water level in the period from 2016 to 2022.

Materials and Methods

To analyse the impact of precipitation on groundwater recharge, data from the Earth Observing System (EOS) satellite observation systems were used. These data included historical precipitation observations from local meteorological zones, as well as data from EOS satellites. Data on the amount of rainfall were available from 2016 to 2022 (EOSDA crop monitoring, n.d.).

The study also used data from monitoring of water levels in wells and the discharge of a spring, which allowed to determine the recharge of groundwater by precipitation in the study area of the Mykulychyn village. A well located in the Mykulychyn village, Nadvirna district, Ivano-Frankivsk Region, was selected for the study and analysis of groundwater recharge. It is located at coordinates 48°25′6″ latitude and 24°36′31″ longitude, at an altitude of 650 meters above sea level; it is located in an area with great tourist potential for the study of water resources.

Groundwater recharge in this area is mainly due to atmospheric precipitation, in particular rainfall. These precipitations affect soil moisture and the water level in the well. The well is located 20 meters from the spring. There is a high degree of correlation between the discharge of water from the spring and the water level in the well, which is confirmed by the Pearson correlation coefficient $r^2 = 0.99$. To obtain the correlation relationship, the average daily monitoring data of the water level in the well and the discharge for 2017 were analysed. This means that changes in the water level in the well almost 100% correspond to changes in the water level in the spring, which justifies the choice of these objects for comparative analysis and further research.

To analyse the level of groundwater and its recovery, monitoring of the mentioned well and a nearby spring was established. The monitoring was conducted by the authors in cooperation with the staff of the Carpathian National Nature Park (CNNP) from 2016 to 2022. Data on the fluctuations of the groundwater level were systematically measured several times an hour every day. These data were used to establish seasonal patterns of groundwater level fluctuations, which allowed to obtain more detailed and accurate data on its fluctuations.

In this study, only rainfall is considered among the forms of precipitation. The study was conducted using the method of N. Korkmaz (1990), a detailed description of which is contained in one of his works, where an assessment of groundwater recharge from the hydrography of springs was conducted. To analyse the data on precipitation and groundwater levels, Excel software was used. In this study, Excel and a computerized approach were used for convenience, in contrast to the original Korkmaz method, which was performed manually with paper and graphs. Using Excel, the data were processed and analysed, including the calculation of the average annual precipitation and the construction of graphs of the relationship between precipitation and groundwater level.

Results and Discussion

Recharge of groundwater is a hydrological process where water is directed from surface sources to underground areas. It is the primary mechanism by which water enters an aquifer. Recharge can be defined as the water that is introduced into an aquifer through the unsaturated zone after infiltration and percolation as a result of any intense rainfall. This process occurs through infiltration on the surface of the land (land infiltration) or under a surface water body, such as a pond (pond infiltration). In both cases, some of the water evaporates through evapotranspiration, and the remainder is eventually delivered to the groundwater level as recharge. This process is important for addressing agricultural challenges, forming river flows, and providing local populations with drinking water, and groundwater problems.

The amount of moisture that an area loses through evapotranspiration primarily depends on the amount of precipitation, secondly on climatic factors such as temperature, humidity, etc., and thirdly on the type, method of cultivation, and degree of vegetation cover. In a dry period, when evapotranspiration rates exceed the available moisture from precipitation, groundwater table recharge is negligible, and groundwater levels decline. In the study region, I. Klymchuk *et al.* (2022) conducted sociological surveys among the local population. The results showed that 48.8% of the surveyed residents of the region use water from underground reserves for everyday consumption, and 17.5% have surface waters as a source of water supply. This distribution of water sources necessitates research to determine the recharge of groundwater reserves and to analyse climate change with an emphasis on geographical and topographic factors of the region.

Records of water level fluctuations in wells are important and laborious to collect as they are used as the basis for hydrological interpretations. Therefore, the authors of the study joined monitoring expeditions of the Carpathian National Natural Park, as their monitoring group already had historical data on the parameters of the source discharge and water level in the well in the Mykulychyn village. Monitoring studies of water levels in the region are important for reaching conclusions about the distribution and development of groundwater in specific areas, and many records are still waiting for interpretation. Regular measurements and access to accurate EOS climate data in the study region allowed for a deeper investigation of the dynamics of water level changes in wells and their change according to precipitation. Daily precipitation indicators for the periods of 2016-2022 were selected and the sums of annual precipitation are presented in Table 1.

Table 1. Monthly precipitation by year in the Mykulychyn village, mm

Years	months											
	1	2	3	4	5	6	7	8	9	10	11	12
2016	-	-	-	-	-	-	-	-	-	142	155.2	45.9
2017	32.1	107.8	112.5	170.5	193.6	227.2	119.5	98.5	129.1	149.5	100.8	190.5
2018	30.8	66.7	63.1	26	70.7	195.6	174	78.4	42	38.3	48.2	76
2019	55.1	25.6	32.3	55.1	247	80.1	95	73.1	47.5	36.9	36	72.2
2020	20.3	90.4	56.5	25.8	163.5	204.4	98.2	44	120.4	81.7	26.5	41.8
2021	79.6	184.8	107.4	212.9	213.8	159.1	208.4	76.7	15.2	7.9	16.9	55.8
2022	31.5	26.6	11.2	34.6	34.9	18.1	55.5	32	37.4	-	-	-

Source: created by the authors based on EOSDA crop monitoring data (n.d.)

The Korkmaz method was applied due to the correspondence of the data that this method requires, and the data collected during monitoring and satellite observation analysis. This distinguishes this study from the article by D. Nayak *et al.* (2023). It was not possible to apply the methods mentioned by these scientists to the study region to determine similar goals, since the authors did not have enough input data to apply the method using geographic information systems, which requires a different amount of input data by type and by representation. All of these factors made the well in the Mykulychyn village an ideal object for research using the Korkmaz method to carefully analyse and understand the processes of groundwater recharge in this region. Table 2 contains data on the average monthly water levels in the observation well located in the Mykulychyn village. These data show the average monthly water level in this well during the study period. Data on the water level above the discharge level for the period from January 2016 to January 2022 are given in Table 3.

Table 2. Average monthly water levels in the observation well in the Mykulychyn village

Years	months											
	1	2	3	4	5	6	7	8	9	10	11	12
2016	-	-	-	-	-	-	-	-	-	-	-	-
2017	25.2	31.7	32.2	30.1	37.2	30.6	26.9	25.5	33.8	27.1	26.8	33.1
2018	24	24.6	27.5	26.4	31.9	37	34.8	37.4	26.9	23.3	22.7	21.2
2019	22.8	19	16.4	16.8	30.5	34.5	27.9	27.8	21.4	16.6	16.2	18.3
2020	16	18.9	20.1	20.9	28.4	33.3	28.1	19.8	24.2	29.7	24	18.8
2021	15.8	27	38.6	36.8	39.1	32.7	38.7	34.5	24	22.1	16.8	22.5
2022	18.5	19.9	20.1	18.6	17.5	16.2	17	19.5	20.1	18.8	19.1	17.5

Source: created by the authors

Table 3. Water level from the maximum level in the observation well in the Mykulychyn village

Years	months											
	1	2	3	4	5	6	7	8	9	10	11	12
2016	-	-	-	-	-	-	-	-	-	-	-	-
2017	15.8	9.3	8.8	10.9	3.8	10.4	14.1	15.5	7.2	13.9	14.2	7.9
2018	17	16.4	13.5	14.6	9.1	4	6.2	3.6	14.1	17.7	18.3	19.8
2019	18.2	22	24.6	24.2	10.5	6.5	13.1	13.2	19.6	24.4	24.8	22.7
2020	25	22.1	20.9	20.1	12.9	7.7	12.9	21.2	16.8	11.3	17	22.2
2021	25.2	14	2.4	4.2	1.9	8.3	2.3	6.5	17	18.9	24.2	18.5
2022	22.5	21.1	20.9	22.4	23.5	24.8	24	21.5	20.9	22.2	21.9	23.5

Source: created by the authors

The level of groundwater fluctuates naturally in response to the sequence of climatic events and the limitations imposed by hydrogeological and topographic characteristics. Groundwater recharge is greatest during the late autumn, winter, and spring when plants are dormant and evaporation intensity is low. In the summer, when evaporation intensity exceeds the available moisture from precipitation, groundwater recharge is negligible and the groundwater level decreases. The recovery of the water level (ΔH) and the total amount of precipitation (Pt) during the wet period of the year for 2016-2022 are shown in Figure 1 and Figure 2.

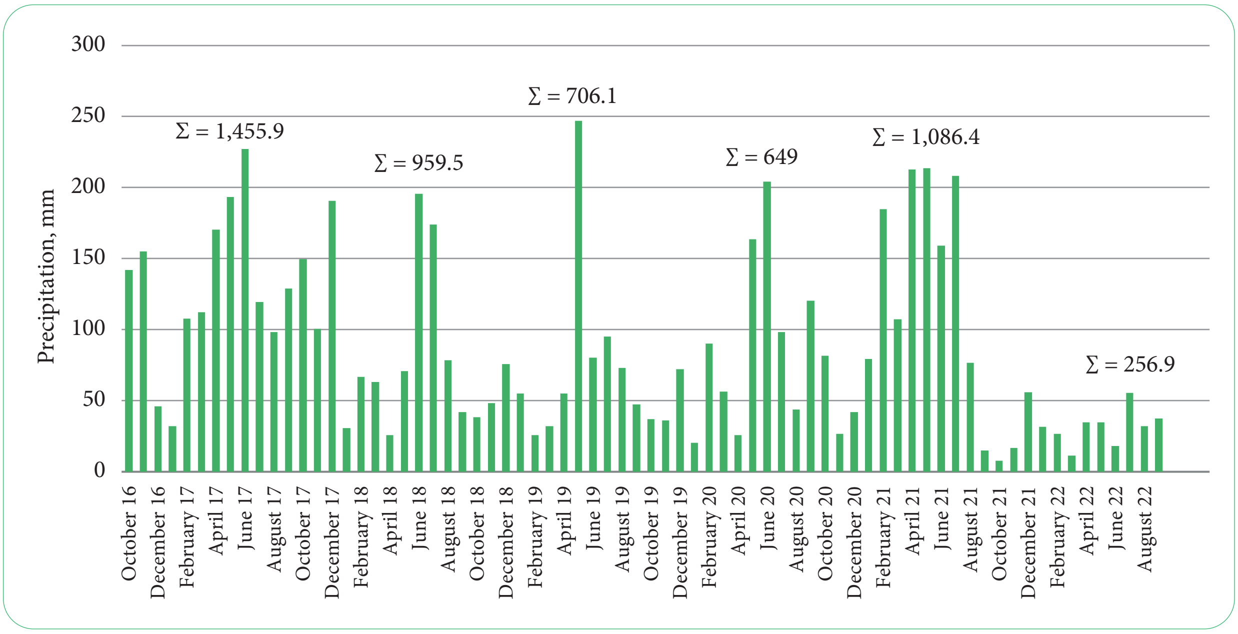

Figure 1. Months with significant average monthly precipitation that affect the increase in water level in the well
Source: created by the authors

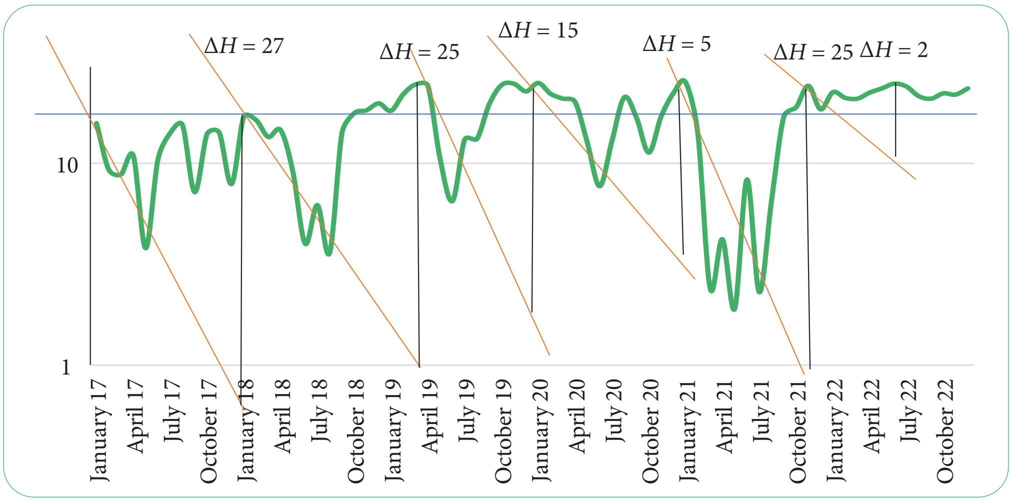

Figure 2. Fluctuations of the water level in the studied well are caused by precipitation that replenishes water reserves
Source: created by the authors

The results of the linear regression analysis are shown in Figure 3. The equation of the linear regression for the selected period is given below. The average level of precipitation (Re) for this aquifer is 170 mm.

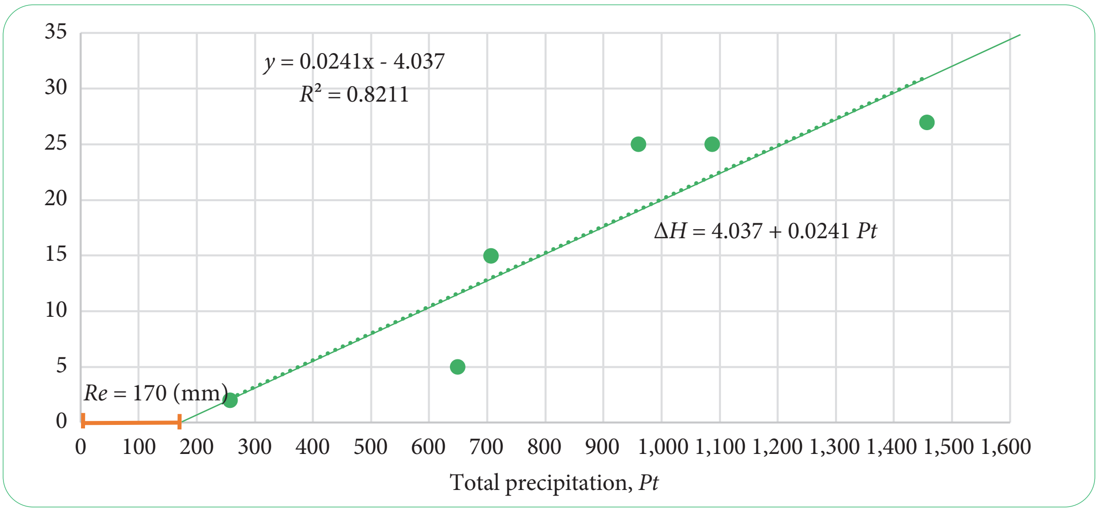

Figure 3. Total precipitation during the wet period – recovery of the groundwater level in the Mykulychyn village and the studied well
Source: created by the authors

Calculated values of total precipitation for the years 2016-2022 are given in Table 4. The results of the calculation of recharge due to atmospheric precipitation of this aquifer for the same period are given in Table 4 and Figure 3.

Table 4. Combined hydrological characteristics of the Mykulychyn village and the studied well

Well: Mykulychyn village, 48°25´6″ 24°36´31″				$(\Delta H\text{-}b)/m$	Precipitation computed – Recharge
Year	Precipitation ΔH	Total Precipitation	ΔH	Precipitation computed	Recharge
2017	1,455.9	1,533.9	27	952.8215768	782.8215768
2018	959.5	1,188.1	25	869.8340249	699.8340249
2019	706.1	873.3	15	454.8962656	284.8962656
2020	649	968.6	5	39.95850622	-130.0414938

Table 4, Continued

Well: Mykulychyn village, 48°25′6″ 24°36′31″				(ΔH-b)/m	Precipitation computed – Recharge	
Year	Precipitation ΔH	Total Precipitation	ΔH	Precipitation computed	Recharge	
2021	1,086.4	1,407.9	25	869.8340249	699.8340249	
2022	256.9	362.4	2	84.52282158	-254.5228216	
Average	**852.3**	**1,055.7**	**16.5**	**517.13693**	**347.1369**	**Recharge 32.88%**

Note: $b = 4.037$; $m = 0.00241$

Source: created by the authors based on rainfall data of EOSDA crop monitoring (n.d.)

Annual recharge in this area during the study period ranged from 782 mm in 2017 to -254 mm in 2022, indicating possible drying up of some smaller aquifers in 2022. A similar pattern of decreasing precipitation and drying up of water sources was found in 2022 in the work of I.Ya. Klymchuk (2022). As a result of monitoring studies during the periods of spring flood and autumn low water in the region, the scientists traced the drying up of some water sources. A similar situation is observed in Iran in the work of R. Noori *et al.* (2023). Iranian scientists note groundwater depletion and the tendency to deplete drinking water reserves. The key role in this process is played by climate change. Similar conclusions were also reached by C. Yang & F.P. Bertetti (2023): on the territory of the United States, there are also such trends towards decreasing precipitation and changes in the renewal of water reserves. The trend toward depletion of groundwater is noted in all the mentioned works, and the authors of this study also join this opinion. It can be assumed that climate change has a global, not regional significance and can pose a threat to the population's access to drinking water not only in the studied region but also in the world as a whole.

The average annual recharge for the period from 2017 to 2022 is 347 mm. This is about 32.88% of the average annual rainfall. The study of groundwater recharge using the Korkmaz method, which was used in this article, proved to be an effective alternative to complex methods, such as the method using geographic information systems, which is presented in the study of D.M. Gururani *et al.* (2023), which requires a large amount of additional data, such as soil and rock composition, density, angles of inclination, drainage characteristics, and other parameters. Due to the high correlation between the water level in the well and the source, the Korkmaz method allowed to achieve significant scientific results and understand the processes of groundwater recharge using a minimum set of input data. This method opens up new opportunities for the study and monitoring of water resources, especially in conditions where other methods become extremely expensive and difficult to implement due to the lack of necessary data.

For the studied region, it is proposed to adopt the experience of Chinese colleagues R.-F. Meng *et al.* (2023), who, based on similar results for the restoration of shallow groundwater depression, developed a plan for optimizing the processes of groundwater recharge. According to the authors, this approach can be applied in Ukraine. The methods of combining several methods have been well established in the work of M.H. Ali *et al.* (2022). These methods of combining methods can have a positive projection on the Nadvirna Region since there is a large amount of other climate data that can be used in combination with several methods to obtain more accurate and comprehensive results of similar studies.

Groundwater management, including artificial recharge proposed by A.S. Jasrotia *et al.* (2019), plays an important role in ensuring the sustainability of water resources on the surface and in-depth. The study was aimed at identifying suitable sites for artificial groundwater recharge in the Himalayas, Jammu division, India, using geospatial techniques and groundwater modelling. It is important to apply the proposed approach in the studied region of Ukraine, anticipating possible climate changes and analysing periods with low precipitation. Artificial recharge could prevent critical loss of groundwater or lack of natural recharge. S.G. Ratna *et al.* (2023), in their conclusion, identified key aspects of the impact of climate change on the hydrogeological systems of Tumakuru, India. The recommendations for optimizing the use of groundwater and increasing groundwater recharge can be applied to the studied region to preserve sustainable groundwater recharge and mitigate the sharp impact of climate change on them.

An important aspect is the monitoring of water quality in aquifers, which is based on measurements at specific points with a limited number of wells, which causes uncertainty in the assessment of the distribution of parameters due to limited data availability. An important problem is to reduce uncertainty to obtain accurate and reliable monitoring results. According to the work of D.W. Gladish *et al.* (2023), who used geostatistical kriging and a differential evolution algorithm to optimize the design of a groundwater monitoring network in the Namoi Region of Australia, the author's study has taken on the challenges of monitoring the Mykulychyn village aquifer. The authors propose the integration of geostatistical methods for parameter interpolation.

Foreign practices for determining groundwater recharge often involve complex methods that require significant resources and, in some cases, participation in state environmental monitoring or supervisory programmes. The

Korkmaz method used in the study of water resources in Mykulychyn village offers a new approach to analysing and understanding groundwater recharge processes in Nadvirna district. This method may help to address the issue of groundwater use.

Conclusions

As a result of the study on the analysis of groundwater recharge in the Mykulychyn village, Nadvirna district, using the Korkmaz method, the following conclusions were drawn, which will contribute to a better understanding of the groundwater regime and its use in this region. The study results show that atmospheric precipitation is the main contributor to groundwater recharge in the Mykulychyn village, accounting for a significant share of the total precipitation in the region. On average, the amount of precipitation was 1,055.7 mm per year, which emphasizes the importance of atmospheric precipitation as a key source of water for groundwater in this area. No less important is the high correlation between the discharge of water from the spring and the water level in the well, which almost reached 0.99. This indicates a close relationship between these two parameters and suggests the possibility of using the results of the study for effective water management and forecasting.

The study revealed the dynamics of changes in the water level and the amount of precipitation over the years. The annual water recharge, which ranged from 782 mm in 2017 to -254 mm in 2022, may indicate the possible drying up of some aquifers in 2022. The average annual recharge during the study period was 347 mm, which is approximately 32.88% of the average annual rainfall. The study also traces the global trend of climate change, as similar conclusions are made by scientists from the United States and China. The results obtained are important for further research and strategic planning of water resources in the Mykulychyn village and similar regions. In connection with climate change and economic development, understanding groundwater recharge is a key factor in ensuring the sustainability of water resources and their efficient use. Future research in this area may include more detailed considerations of hydrogeological conditions and their impact on groundwater recharge in the region, as well as an analysis of the impact of climate change on the groundwater regime. Such studies will help to develop more effective water management strategies and ensure their sustainable use in the future. The study also requires analysis of a large amount of climatic and other hydrological data, which can serve as a continuation of the development of current research.

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None.

Conflict of Interest

None.

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Аналіз живлення підземних вод у Надвірнянському районі методом Коркмаза

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Анотація. Визначення джерел живлення підземних вод і прогноз можливих коливань рівня води є актуальним питанням, адже дослідження даних показників має велике значення для розуміння поновлення водних ресурсів та їх ефективного використання в конкретних територіальних умовах. Метою даного дослідження було встановити джерела живлення підземних вод на території с. Микуличин та оцінити їх зміну протягом періоду з 2016 по 2022 роки. Дослідження базувалося на методі Коркмаза та аналізі даних про рівень води в колодязі та рівень опадів на території дослідження. Проведено структурний аналіз живлення підземних вод на території с. Микуличин у Надвірнянському районі за допомогою методу Коркмаза. Встановлено, що живлення підземних вод у с. Микуличин відбувається за рахунок атмосферних опадів. Також показано кореляційну залежність між дебітом води з джерела та рівнем води в колодязі, що дало можливість проектувати результати дослідження на обидва об'єкти. Середньорічна кількість опадів на території становила 1 055,7 мм. Результати лінійного регресійного аналізу показали зв'язок між рівнем води та сумарною кількістю опадів. В результаті аналізу коливань рівня води в колодязі було виявлено, що щорічне поповнення рівня води варіюється від 782 мм у 2017 році до -254 мм у 2022 році. Це свідчить про можливе пересихання деяких менших за об'ємом водоносних пластів у 2022 році. Середньорічне поповнення за період із 2017 по 2022 роки становить 347 мм, що складає близько 32,88 % від середньорічної кількості опадів. Отримані результати дослідження можуть бути корисні на практиці для керування та планування водних ресурсів на території с. Микуличин, а також у схожих географічних умовах

Ключові слова: опади; поновлення джерела; коливання рівнів; колодязі; сезонність

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Research of gas exchange and air purification processes by plants of the common privet (*Ligustrum vulgare* L.) species

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Abstract. Growing urbanization creates air pollution problems, which is becoming dangerous for human health and unsuitable for indoor ventilation. An effective solution is the combination of green structures with engineering systems, which requires the development of new methods and quantitative laboratory studies of gas and mass exchange processes of plants. The purpose of the study was to quantify the ability of plants of the common privet (*Ligustrum vulgare* L.) to release and absorb oxygen and CO_2, as well as to study the effectiveness of air purification from particulate matter in order to properly take into account the impact of plants in the process of their selection for greening urban landscapes. The research was carried out according to the methodology developed by the authors in a gas exchange chamber, which was upgraded to model external conditions and study plants with small leaf area and developed stems. The results of the experiment showed that *Ligustrum vulgare* L. bushes with a small total photosynthetic leaf surface area are inefficient for carbon dioxide absorption in an urbanized environment, so plants with a significant proportion of photosynthetically active biomass and fast-growing plants should be preferred. It was determined that at maximum illumination, the degree of absorption of PM2.5 and PM10 by *Ligustrum vulgare* L. bushes was $8.84 \cdot 10^{-5}$...$1.5 \cdot 10^{-4}$ μg/s, which confirms the effective absorption of particulate matter with a diameter of up to 2.5 and up to 10 μm from the air by the studied plants. The results obtained indicate an increase in the concentration of total volatile organic compounds in the outlet compartment, which indicates the active release of volatile phyto-organic substances by plants in the amount of 2.442...2.973 μg/s. The results of the study can be used for effective taxonomic selection of woody plants during the design and creation of urban green spaces that are resistant to the conditions of the urban environment

Keywords: green structures; sponge agents; solid particles absorption; PM2.5; PM10; CO_2 absorption

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Introduction

Air pollution has become a serious environmental problem in urban areas of developing countries. The main cause of this problem is urbanization, which has led to an increase in construction sites, vehicles, high energy consumption and industrialization. In this regard, the impact of vegetation on mitigating these negative effects is of considerable interest to scientists and urban planners. For example, urban vegetation is believed to provide a variety of social and environmental benefits to society, collectively referred to as cultural ecosystem services, thereby increasing the resilience of cities. Urban green infrastructure is represented by trees, hedges, and various types of vegetation that can act as a porous barrier to pollutants, changing their dispersion patterns and providing additional surface for deposition.

However, according to the literature review, there is a growing interest in the topic of green structures in the world due to the combination of various effects in one solution. Green structures are biotechnical systems in which the construction of buildings and structures and individual elements are combined with living plants, forming a single system of living and non-living components of biogeocenoses of modern cities in the concept of sustainable development. Green structures include vertical greening systems (green walls, facades); horizontal greening systems (green coatings, green balconies and terraces); kinetic (mobile) greening; greening with the use of algae, as described by such scientists as M. Kravchenko & T. Tkachenko (2023). Green structures provide solutions to a number of important environmental problems, increasing the energy efficiency of indoor climate formation and improving the microclimate of territories through additional thermal insulation of buildings, providing a cooling effect (evapotranspiration) and reflection of solar radiation, and also allow rainwater retention, which leads to a reduction in the load on stormwater drainage systems within the concept of a sponge city (Tkachenko *et al*., 2023).

A separate important environmental function of green structures is their impact on the sanation and improvement of indoor and outdoor air quality due to the phytoncidal properties of plants and the purification of air from various pollutants and dust. The removal of air pollutants by trees and other vegetation, called phytoremediation, is of particular interest because poor air quality in urban areas is one of the main environmental problems that have a direct impact on public health on a global scale. The paper by S. Bandehali *et al.* (2021) provides comprehensive information on plant species that can remove pollutants such as volatile organic compounds (TVOC) and particulate matter (PM), describes the sources of indoor air pollutants, and their impact on human health. In addition, the authors investigated the potential role of green walls and potted plants in improving indoor air quality, proving the effectiveness of this process and suggesting a list of plant species suitable for phytoremediation of indoor air. According to N.J. Paull *et al.* (2020), PM removal and relative frequencies of particle size fractions were found to be statistically different between species, locations, and seasons. It was shown that green wall plants are effective in accumulating PM of different fractions, as all plant species studied had the same efficiency in PM removal with minimal influence of leaf characteristics.

An equally important function of the vegetation of green structures is the absorption of carbon dioxide. M. Lalošević *et al.* (2018) studied green roofs in a densely populated urban area in the centre of Belgrade (Serbia). To analyse the impact of residential urban neighbourhoods on CO_2 concentrations, they developed a baseline model (fully consistent with the actual state and real conditions in the area), as well as modernization models (which include the baseline model with added elements of extensive and intensive green roofs) and conducted numerical simulations of CO_2 concentrations for all presented models. The results of the numerical modelling showed that the use of green roofs instead of classical flat roofs in the Belgrade climate zone can reduce the CO_2 concentration in the atmosphere around the building by up to 11%, on average by 2.3%. It was also found that the greatest impact on reducing CO_2 concentration is felt in the immediate vicinity of plants.

A separate type of green structures intended for engineering and technical structures are rain gardens, which are installed along the road near the roadway and are intended primarily to capture water from both sides. However, no less important benefits for the urban environment from this type of structure as sponge agents are the accompanying effects, namely noise reduction, air purification, CO_2 absorption, O_2 release, increase of the video-ecological aspect and maximum approximation of the urban environment to the natural one. Vegetation of sponge agents can be represented by trees, shrubs, bushes and grasses, occupying a certain part of the land area in cities and improving air quality. According to the analysis of O. Lukash & A. Kushnir (2023), the leader among the taxons used in the construction of hedges within large cities of Ukraine is common privet (*Ligustrum vulgare* L.), which accounts for more than 85% of all plants planted in green areas. In addition, this type of hedges is known for its ability to absorb harmful substances and produce a significant percentage of oxygen in the atmosphere. The purpose of the study was to investigate gas exchange in plants of the *Ligustrum vulgare* L. species, which involves quantifying its ability to release and absorb oxygen and carbon dioxide, as well as to purify the air from harmful substances and release volatile phytobiological substances in order to properly account for the impact of plants on the ecological situation in urbanized cities. In the presented work, it is hypothesized that green structures, as sponge agents representing the urbanized environment, improve air quality compared to areas without them; the degree of removal of pollutants from the air is directly related to the volume and structure of vegetation representing green structures.

Materials and Methods

The material for the research was *Ligustrum vulgare* L., a tall, upright shrub with a dense crown up to 4-5 m in height, which is easy to form and resistant to growing conditions in urban environments. It is widely used in urban greening as plantings for city parks,gardens, squares, residential areas, industrial areas, and motor transport systems. Two mature bushes without pest damage were selected for the study (Fig. 1). The Convention on Biological Diversity (1992) was followed during the study. The study was conducted in 2023.

Figure 1. Specimens of *Ligustrum vulgare* L. bushes that were the objects of the study
Source: created by the authors

The dimensions of bushes I and II of *Ligustrum vulgare* L. were, respectively: height – 67 and 72 cm, width – 85 and 93 cm, depth – 56 and 58 cm. The volumes of the bushes, respectively, were: $V_1 = 0.32$ m^2 and $V_2 = 0.39$ m^2. The plant care regimen before the study was in line with the recommendations for this species and was as close as possible to the operating conditions of green structures. The experiment was carried out in a gas exchange chamber adapted to reproduce the external conditions of the urbanized environment and study plants with a small photosynthetic mass, according to the methodology developed by the authors (Fig. 2).

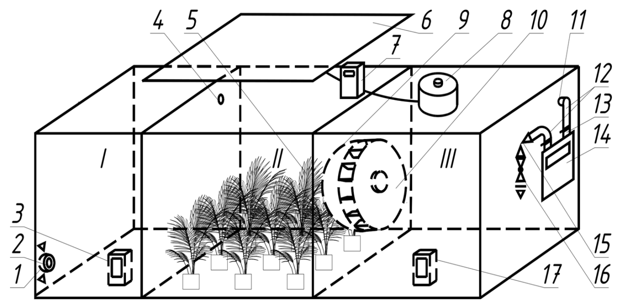

Figure 2. Gas exchange chamber
Notes: I – intake chamber (300×1000×1000(h)); II – gas exchange chamber (1000×1000×1000(h)); III – outlet chamber (1000×1000×1000(h)); 1 – protective grid at the inlet; 2 – inlet (ø 15); 3 – gas analyser; 4 – overflow hole (ø 15); 5 – plants; 6 – lighting panel with full-spectrum LED (light-emitting diode) phytolamps; 7 – voltage relay with a voltmeter; 8 – lighting regulator; 9 – protective grid at the entrance to the fan; 10 – mixing fan; 11 – air outlet; 12 – pipelines; 13 – filter; 14 – gas meter; 15 – control valve; 16 – ball valve (authors' original scheme); 17 – gas analyser
Source: created by the authors

The chamber operates as follows: air enters through the protective grid 1 and the inlet 2 into the intake chamber I with a gas analyser 3. Through the flow hole, it passes to the gas exchange chamber II with experimental plants 5. The chamber is illuminated by a lighting panel with LED phytolamps 6, the actual voltage on which is controlled by a voltage relay with a voltmeter 7, and the brightness of which is set by the regulator 8. After gas exchange, the air is forced through the protective grid 9 by the mixing fan 10 to the outlet chamber III. The mixing fan 10 provides intensive mixing of air in this chamber to avoid the influence of uneven distribution of gases in chamber II. From this chamber, the air exits through an outlet 11 to the pipeline system 12, which contains a filter 13, a gas meter 14, a control 15 and a shut-off 16 valve. The latter is used to prevent dust from entering when the plant is not in operation and can be closed without changing the position of the control valve 15. The gas concentration at the outlet is controlled by a gas analyser 17 in chamber III.

To measure the illumination, a Mustech (China) luxmeter is used, which is introduced after the experiments and slowly moved evenly to cover the entire area of the chamber at the plant level and to average the illumination. The flow orifices are designed to provide a meaningful velocity to avoid back-diffusion of gases. Since the mixing fan 10 performs the mixing function, its speed was not regulated. The lighting regulator 8 should not create electromagnetic interference that could be induced on the gas analysers or the luxmeter. Therefore, in this work, a laboratory autotransformer (LATR) (Megommeter, Ukraine) was used. Voltage relays with a voltmeter were installed to record the current voltage for the possibility of setting the same illumination, as well as to protect the lamp from accidental overvoltage. The air density was calculated using the following formula:

$$\rho = \frac{P_b}{286.9 \cdot T} \cdot \frac{1+d}{1+1.6085744 \cdot d} = \\ = \frac{P_b}{286.9 \cdot (273.15+t)} \cdot \frac{1+d}{1+1.6085744 \cdot d}, \quad (1)$$

where P_b is barometric pressure, Pa; T is air temperature, K; d is air moisture content, g/(kg of dry air); t is air temperature, °C. The saturated vapour pressure was determined by the modified Buck's formula, Pa, after basic simplifications without loss of accuracy:

$$Psat = EF \cdot \begin{cases} 611.15 \cdot e^{\left(23.85455 - \frac{T}{333.7}\right)\cdot\left(1 - \frac{279.82}{T+6.67}\right)} = 611.15 \cdot e^{\left(23.036 - \frac{t}{333.7}\right)\cdot \frac{t}{t+279.82}}, & T < 273.15\text{K}, t < 0°C \\ 611.21 \cdot e^{\left(19.84282 - \frac{T}{234.5}\right)\cdot\left(1 - \frac{257.14}{T-16.01}\right)} = 611.21 \cdot e^{\left(18.678 - \frac{t}{234.5}\right)\cdot \frac{t}{t+257.14}}, & T \geq 273.15\text{K}, t \geq 0°C \end{cases} \quad (2)$$

where EF is the correction for the influence of air molecules (enhancement factor), which is the ratio of the saturated vapour pressure in air to this pressure in a "vapour-liquid-only" system:

$$EF = 1 + 10 - 4 \cdot EF = \begin{cases} 1.00022 + P_b \cdot (6.4 \cdot 10^{-10} \cdot (T - 546.3) \cdot T + 5.1581 \cdot 10^{-5}), & T < 273.15; \\ 1.00072 + P_b \cdot (5.9 \cdot 10^{-10} \cdot (T - 546.3) \cdot T + 4.7220 \cdot 10^{-5}), & T \geq 273.15, \end{cases} = \\ = \begin{cases} 1.00022 + 6.4 \cdot 10^{-10} \cdot P_b \cdot (5{,}984.375 + t^2), & t < 0; \\ 1.00072 + 5.9 \cdot 10^{-10} \cdot P_b \cdot (5{,}423.7288 + t^2), & t \geq 0. \end{cases} \quad (3)$$

The moisture content of the air was determined by temperature and hygrometer readings – relative humidity φ, %, or dew point temperature T_d, K, or T_d, °C, according to equation:

$$d = \frac{0.623 \cdot P_{sat} \cdot \varphi}{P_b - P_{sat} \cdot \varphi} = \frac{0.623 \cdot P_{sat,d}}{P_b - P_{sat,d}}, \quad (4)$$

where P_{sat} is the pressure of saturated vapour at a given air temperature, Pa; φ is the relative humidity (dimensionless); $P_{sat,d}$ is the pressure of saturated vapour at the dew point temperature, Pa. The calculation of the carbon dioxide absorption rate ΔG_{CO_2}, g/s, was carried out according to formula:

$$\Delta G_{CO_2} = 0.0015197 \cdot (Y_{in} - Y_{out}) \cdot G, \quad (5)$$

where Y_{in} is the mole fraction of carbon dioxide in the inlet zone, ppm; Y_{out} is the mole fraction of carbon dioxide in the outlet zone, ppm; G is the mass flow rate of air, kg/s. Oxygen release was estimated according to the gross photosynthesis reaction $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2\uparrow$, g/s, using formula:

$$\Delta G_{CO_2} = 0.72709 \cdot \Delta G_{CO_2}. \quad (6)$$

The absorption of harmful impurities s or particles of a certain size, μg/s, mg/s, was calculated using formula:

$$\Delta Gs = (q_{in}/\rho_{in} - q_{out}/\rho_{out}) \cdot G = (q'_{in} - q''_{in}) \cdot G, \quad (7)$$

where q_{in} is the concentration of an impurity or particles of a certain size, respectively, μg/m³, mg/m³; q_{out} is the concentration of an impurity or particles of a certain size, respectively, μg/m³, mg/m³; q'_{in} is the concentration of an impurity or particles of a certain size, respectively, μg/kg, mg/kg; q''_{in} is the concentration of an impurity or particles of a certain size, respectively, μg/kg, mg/kg; G is the mass flow rate of air, kg/s.

Results

A general view of the gas exchange chamber with *Ligustrum vulgare* L. plants is shown in Figure 3. The studies were conducted at an atmospheric pressure of 1000 hPa and at CO_2 concentrations of 400 ppm and 1025 ppm in the room. The rates of air density, saturated vapour pressure, and air moisture content at the chamber inlet, outlet, and in the meter, respectively, are presented in Table 1.

Figure 3. General view of the gas exchange chamber during the day and at night with plants of *Ligustrum vulgare* L.
Source: created by the authors

Table 1. Calculated rates of air density, saturated vapour pressure and air moisture content at the chamber inlet, outlet and in the meter

Air density ρ, kg/m³			Saturated vapour pressure P_{sat}, hPa			Air moisture content, d		
inlet	outlet	in the meter	inlet	outlet	in the meter	inlet	outlet	in the meter
1.166	1.152	1.120	29.972	35.820	56.216	0.009	0.012	0.017
1.156	1.143	1.107	35.820	40.251	63.095	0.007	0.015	0.024

Source: created by the authors

The rates of air flow and carbon dioxide concentration in plants are presented in Table 2. The readings of the gas analyser in the inlet compartment, in the gas exchange compartment, and in the outlet compartment are presented in Table 3.

Table 2. Air flow rate and carbon dioxide concentration in plants

Air flow rate		Carbon dioxide concentration in plants, g/kg
kg/s	kg/h	
2.668E-05	0.096	0.992
2.513E-05	0.090	1.589

Source: created by the authors

Table 3. Gas analyser readings in the inlet compartment, in the gas exchange compartment and in the outlet compartment

Gas analyser readings	PM2.5, µg/m³	PM10, µg/m³	HCHO, mg/m³	TVOC, mg/m³	CO_2, ppm	Temperature, °C	Relative humidity, %
In the inlet compartment	14	15	0.115	0.4915	400	24	48
	19	21	0.089	0.461	1,025	27	33
In the gas exchange compartment	-	-	-	-	653	28.5	68.4
	-	-	-	-	1,046	37	80
In the outlet compartment	10	11	0.599	0.591	678	27	56
	12	14	0.065	0.591	1,048	29	60

Note: HCHO – formaldehyde
Source: created by the authors

The air parameters at the meter inlet, such as temperature and relative humidity, were 34.9°C and 37.0°C and 47.4% and 60.3%, respectively. The elevated temperature level in the gas exchange compartment can be explained by the presence of LED phytolamps, which release energy in the form of light and heat during operation. This effect is especially important when growing plants in conditions where lighting and temperature conditions are important for their growth and development. Calculations of the degree of carbon dioxide absorption and oxygen release were carried out using formulas (5; 6), the results of which are presented in Table 4.

Table 4. The degree of carbon dioxide absorption and oxygen release by plants of the *Ligustrum vulgare* L. species

Carbon dioxide absorption		Oxygen release	
g/s	g/h	g/s	g/h
-1.127E-05	-0.040	-8.196E-06	-0.029
-8.785E-07	-0.003	-6.388E-07	-0.002

Source: created by the authors

Plants purify the air around the clock. However, during active photosynthesis, the plants saturate the air with oxygen, and during respiration only, they secondary pollute it with carbon dioxide. The photosynthetically active biomass of *Ligustrum vulgare* L. is rather small leaves around the perimeter of the bush. The inner part of the bush consists of a dense stem system that does not photosynthesize. The results of the study allow us to conclude that the process of carbon dioxide emission by *Ligustrum vulgare* L. plants prevails instead of its absorption. With a mole fraction of carbon dioxide in the air near the plants of 653 ppm, a mole fraction of 678 ppm was recorded at the output. The total carbon dioxide emission was 11.27 μg/s. With a mole fraction of carbon dioxide in the plant zone of 1,046 ppm, the outlet was 1,048 ppm, i.e. almost the same mole fraction. Carbon dioxide emission dropped to an unreliable, close to zero rate of 0.8785 μg/s. Calculations of the degree of absorption of PM2.5, fine dust (PM10), HCHO and total TVOC were carried out according to formula (7), the results of which are presented in Table 5.

Table 5. The degree of absorption of impurities and particles of a certain size by plants of the *Ligustrum vulgare* L. species

Absorption of PM2.5		Absorption of PM10		Absorption of HCHO		Absorption of TVOC	
μg/s	μg/h	μg/s	μg/h	g/s	g/h	g/s	g/h
8.868E-05	0.319	8.840E-05	0.318	-1.125E-05	-0.040	-2.442E-06	-0.008
1.5 E-04	0.537	1.4 E-04	0.535	5.057E-07	0.002	-2.973E-06	-0.010

Source: created by the authors

The most harmful PM is PM2.5. They can penetrate deeply into the lungs and cause irritation of the alveolar walls, their damage, and respiratory distress (Li & Liu, 2021). PM2.5 enters the bloodstream through the alveolar-capillary barrier, causing cardiovascular and respiratory diseases, as well as cancer. Moreover, it is now known to cross the blood-retinal barrier, the epithelial barrier in human nasal epithelial cells, and the skin barrier (Xian *et al.*, 2020). PM10 can also penetrate deeply into the lungs and cause health problems, but they are not as harmfuL. The results of the study under maximum illumination showed the degree of absorption of PM2.5 and PM10 by *Ligustrum vulgare* L. bushes to be $8.84 \cdot 10^{-5}$... $1.5 \cdot 10^{-4}$ μg/s, which suggests that the plants under study effectively absorb PM with a diameter of up to 2.5 and up to 10 μm from the air.

Firstly, plants adsorb PM, when in contact with the microstructure of the leaf surface or when immersed in the cuticle layer. Secondly, PM around the leaf surface is absorbed by the plant through stomata in the process of photosynthesis and transpiration. Thirdly, when the air saturated with PM reaches the crown layer of the plant, the flow rate decreases, which leads to a blocking effect. In the case of the study with *Ligustrum vulgare* L. bushes, which have a voluminous stem part but a small leaf area, it is likely that PM absorption occurred around the leaf surface through stomata during photosynthesis and transpiration.

An interesting result is the increase in the concentration of total TVOC in the outlet compartment, which indicates not the degree of absorption, but the active release of volatile phyto-organic substances by plants in the amount of 2.442...2.973 μg/s. No stable absorption of HCHO was detected, the results were unreliable as they had a very small order and the opposite sign. It is important to note that an increase in TVOC concentration is not always a negative phenomenon. The release of TVOC by plants is an important means of communication and self-defense. In nature, the behaviour of plants that emit TVOC is often considered a defence mechanism. It can be interpreted as an induced resistance, i.e., the release of volatile compounds by plants after mechanical damage, stressful situations, or insect feeding (McCormick *et al.*, 2019). Understanding the mechanisms and types of TVOC released by plants, as well as the biological information conveyed by the released TVOC, can help improve the quality of the urban environment and individual biogeocenoses (Kim *et al.*, 2020).

A comprehensive quantitative study of green structures as sponge agents, taking into account the concomitant positive effects on the air environment, is a fundamentally new approach to the effective development of cities affected by military operations, as well as to improving the quality of the urban environment in generaL. There is a need to grow air-purifying plants in all unused areas of urban and rural areas, namely along roads, in adjacent areas, between fields, gardens, etc. Fast-growing ornamental phytoncidal shrubs, such as *Berberis*, *Cotoneaster lucidus*, *Cornus alba*, *Ligustrum vulgare* L., *Physocarpus opulifolius*, *Philadelphus coronaries*, *Spiraea*, various shrub forms of *Cupressáceae*, including *Juníperus*, are usually recommended for greening. In this study, *Ligustrum vulgare* L. was considered in detaiL.

Whenever possible, hedges should be preferred to construction fences. If a hedge is not possible, most fences can be easily vertically landscaped with climbing plants (various species of *Parthenocissus, Hedera, Clematis*, etc.). Similar vertical (on the facades) and vertical-horizontal (covering the walls and roof) greening can also provide passive air conditioning and thermal insulation. And for very intensive land use, where there is not enough soil for planting, green roofs and terraces on buildings should be used, which also provide thermal and solar radiation improvements. The study confirmed the hypothesis that green structures, as sponge agents, can improve air quality compared to areas without them, and the degree of removal of pollutants from the air is directly related to the morphological characteristics of the vegetation that represents green structures.

Discussion

The results of studies presented in the scientific literature allow to draw a number of valuable conclusions about the impact of vegetation on changes in air quality, but often limit the determination of quantitative indicators of the absorption of certain types of pollutants by specific plants. In addition, research is hampered by the lack of rapid methods to determine the uptake process that need to be developed, and most conclusions that suggest that urban vegetation is an effective means of removing air pollutants are based on modelling results in which pollutant removal is a simple function of deposition rate, pollutant concentration, and some parameters describing vegetation structure (such as biomass index and leaf area).

According to a recent study by J. Linden *et al.* (2023), it was determined that the inclusion of detailed vegetation characteristics in urban air quality modelling would significantly improve the ability to quantify the pollution removal potential of different vegetation types. However, these models often use data from a limited number of sites within a city, making them unlikely to capture changes in canopy structure and urban microclimate conditions. In addition, such models are based on data from chamber studies of plants conducted in the field or in greenhouses, where factors affecting plant physiology and physicochemical processes are studied, as well as studies that measure fluxes of air pollutants, often, for example, over tree crowns. There are only a few studies in which pollutant fluxes have been quantified within vegetation or directly in the crowns of tree and shrub species where pollutant absorption occurs, such as the study by M. Steinparzer *et al.* (2023).

According to the analysis of literature sources, the leaves of trees and grasses allow the removal of PM, gaseous pollutants such as NO_2 (Gong *et al.*, 2022) and CO_2 (Wang *et al.*, 2021), O_3 (Grulke & Heath, 2020) by dry deposition. The removal of organic pollutants by plants has been confirmed by Z. Wei *et al.* (2021). In addition, plants are often used as bioindicators to monitor air pollution by heavy metals. However, the ability of plants to accumulate heavy metals can vary significantly depending on the plant species and its morphology. The authors N. Sevik *et al.* (2020) studied the peculiarities of heavy metal accumulation by some landscape plants growing in the city centre of Kastamonu (Turkey), taking into account plant species and traffic density. For this purpose, samples of leaves and branches were collected from various woody plants commonly used in urban landscape design, including the *Ligustrum vulgare* L. species. It was found that the concentration of Pb in branches was higher than in leaves for all species and depended on traffic density.

Another study conducted by D. Bidolakh & O. Kolesnichenko (2023) helped to study certain ecosystem functions of green spaces (reduction of pollutants, carbon absorption and sequestration, amount of oxygen released). As part of this work, the annual ecosystem function was calculated to absorb 770 kg of harmful compounds (ozone, carbon monoxide, nitrogen dioxide, and PM of various sizes), reduce air pollution by 7.43 metric tons of gross carbon sequestration (19 kg per plant), and reduce water runoff by 684.9 cubic meters. In addition, it was concluded that the highest indicators of ecosystem efficiency belong to park plantings, while trees and shrubs in the central part of the city are more efficient at absorbing pollutants.

However, urban vegetation can also have a negative impact on air quality, in particular through allergenic effects (Poncet *et al.*, 2020), as well as through the emission of TVOC that can form ozone over time (Koppmann, 2020). The results of the experiment in this paper show an increase in the concentration of total TVOC in the outlet compartment of the gas exchange chamber, which indicates not the degree of absorption, but the active release of volatile phyto-organic substances by plants, the impact of which on the air needs to be investigated in future experiments.

The study helped to obtain significant results regarding the peculiarities of the photosynthesis process. The predominance of the process of carbon dioxide emission by *Ligustrum vulgare* L. plants, instead of its absorption, indicates an increase in the photosynthetic mechanism with an increase in carbon dioxide content. But even at this mole fraction, the photosynthetic activity of leaves cannot outweigh the respiration of the entire biomass. The complex and interconnected reactions of photosynthesis are often limited to two more fundamental processes, which are the conversion of solar energy into chemical energy or the diffusion of CO_2 from the atmosphere through stomata and, ultimately, into the chloroplast. The authors E.L. Harrison *et al.* (2020) investigated the effect of plant stomatal morphology (shape, size, pattern) and distribution on photosynthesis through changes in gas exchange, concluding that stomata are an integral part of the photosynthetic mechanism that regulates the amount and rate of O_2 release and CO_2 uptake. It would be interesting to evaluate this in further experiments on the plant species under study.

The results obtained allow us to conclude that the bushes of *Ligustrum vulgare* L., which are characterized by a significant density of sprouts with no leaf mass inside the bush and the presence of leaf mass only on the outer sprouts, have a small total area of photosynthetic leaf surface, are inefficient for carbon dioxide absorption in an urbanized environment. Thus, for efficient carbon dioxide sequestration, plants with a significant proportion of photosynthetically active biomass and fast-growing plants should be preferred. This conclusion is in line with the results of a systematic sampling study of the dependence of CO_2 uptake on the productive photosynthetic area of roadside trees in Bilaspur (India), conducted by A. Ragula & K.K. Chandra (2020). The tree species with the highest CO_2 absorption potential in this study were *Delonix regia, Tamarindus indica,* and *Ficus religiosa*. These were the tree species with the largest crowns, which led to an increase in photosynthetic rate and, ultimately, to carbon dioxide absorption and increased biomass.

Similar to the results of this study, the reduction of PM2.5 and PM10 in the air has been confirmed by numerous studies, indicating a negative correlation between total green area and PM concentrations. However, most of them emphasize the role of trees in this phenomenon, although bushes and herbaceous plants significantly support this potentiaL. In a neighbourhood with high pollution levels and 26% vegetation cover, which is typically inhabited by low-income citizens, K. Wróblewska & B.R. Jeong (2021) conducted an experiment that revealed a 1.6% reduction in PM levels due to trees and another 1.1% due to shrubs and bushes. Similar results were obtained by Z. Cimburova & M. Berghauser Pont (2021), whose research showed that the leaves of woody plants provide an effective large contact area for dry deposition of PM particles, while requiring a relatively small area of land, unlike herbaceous plant species. Another study by D.P.M. Junior *et al.* (2022) compared PM2.5 concentrations in two locations (with and without vegetation cover) in Rio de Janeiro to test how green spaces can actually affect air quality. The results show that the PM2.5 concentrations in the areas with existing tree and shrub vegetation is 33% lower than in other areas. This confirms the possibility of reducing PM2.5 levels through urban green spaces, contributing to the important environmental issue of improving air quality.

Despite the large number of scientific papers on the impact of plants on air quality, the issue of gas exchange in the plant layer plays a key role in ensuring effective air purification, and without a proper understanding of this process, it is difficult to draw valid conclusions. The method and experimental setup for laboratory research of gas exchange in plants shown in this paper allow us to determine the exchange of carbon dioxide and other gases. Tests of the installation confirmed the correctness of the method. The research will contribute to the active implementation of green structures in Ukraine and increase the environmental awareness of residents of modern cities, which are key aspects on the way to implementing the concept of sustainable development of the urban environment.

Conclusions

The results of the study allow to confirm the hypotheses put forward in the work and conclude that the frequency and efficiency of photosynthesis and respiration of *Ligustrum vulgare* L. are closely related to the size of the stems and the leaf surface area, which is small in this plant species, which explains the negative rates of carbon dioxide uptake and oxygen release. *Ligustrum vulgare* L. bushes, which are characterized by a significant density of sprouts with no leaf mass inside the bush and the presence of leaf mass only on the outer sprouts, have a small total area of photosynthetic leaf surface, are inefficient for carbon dioxide absorption in an urbanized environment. They can be recommended as green barriers in urban environments for noise insulation.

The ability to effectively capture PM is an important factor in the selection of optimal plant species for use in urban greening, so it was important to investigate the ability to adsorb PM2.5 and PM10 by *Ligustrum vulgare* L. plants to optimize their use in green urban environments. As can be seen from the results, PM2.5 was adsorbed more than PM10 in terms of the amount of PM absorption, but this is more significant, since PM2.5 poses the greatest threat to human health. It should be concluded that even with a small leaf mass of the studied bushes of the *Ligustrum vulgare* L. species, the amount of adsorbed PM2.5 and PM10 particles is significant for air purification, especially in an urbanized environment, where PM can be toxic and destroy leaf cell tissue, as well as contain heavy metal particles.

By removing pollutants from the air with the help of sponge agents as a special type of green structures, it is possible to improve the quality of the urban environment by reducing the impact of various pollutants. Even if the percentage of air quality improvement due to this type of structure is small, it can be increased by expanding urban vegetation. The methods, techniques, and results obtained correspond to the current level of scientific and technical knowledge, have no global analogues, are unique, and allow for the systematic implementation of green structures with maximum positive effects, engineering calculations, and certification of plant layers.

An increase in the concentration of TVOC in the outlet compartment of the gas exchange chamber may indicate a defence mechanism of *Ligustrum vulgare* L. plants due to stressful situations. However, there is still a lack of reliable and relevant data to understand the true mechanisms of pollutant removal and factors in these systems (plant species, microorganism species, pollutant composition, light source, number of plants), which may be the direction of further research and development of appropriate methods.

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None.

Conflict of Interest

None.

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Дослідження процесів газообміну та очищення повітря рослинами виду бирючини звичайної (*Ligustrum vulgare* L.)

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Анотація. Зростаюча урбанізація створює проблеми забруднення повітря, яке стає небезпечним для здоров'я людей та непридатним для вентилювання приміщень. Ефективне рішення – поєднання зелених конструкцій з інженерними системами, що вимагає створення нових методів і виконання кількісних лабораторних досліджень газомасообмінних процесів рослин. Метою дослідження було кількісне визначення здатності рослин виду бирючини звичайної (*Ligustrum vulgare* L.) виділяти та поглинати кисень і CO_2, а також вивчення ефективності очищення повітря від твердих частинок задля правильного врахування впливу рослин у процесі їх добору для озеленення урбанізованих ландшафтів. Дослідження проводилися за розробленою авторами методикою в газообмінній камері, яка була модернізована для моделювання зовнішніх умов та дослідження рослин із малою площею листя й розвиненими стеблами. За результатами експерименту встановлено, що кущі *Ligustrum vulgare* L., які мають малу загальну площу фотосинтетичної поверхні листя, є неефективними для поглинання вуглекислого газу в урбанізованому середовищі, тому слід віддавати перевагу рослинам зі значною часткою фотосинтетично активної біомаси, і таким, що швидко ростуть. Визначено, що при максимальному освітленні ступінь поглинання PM2,5 та PM10 кущами *Ligustrum vulgare* L. склав $8{,}84 \cdot 10^{-5}...1{,}5 \cdot 10^{-4}$ мкг/с, що підтверджує ефективне поглинання досліджуваними рослинами твердих частинок діаметром до 2,5 та до 10 мкм із повітря. Отримано результати, які свідчать про збільшення концентрації загальних летких органічних сполук у вихідному відсіку, що вказує на активне виділення рослинами летких фітоорганічних речовин обсягом 2,442...2,973 мкг/с. Результати дослідження можуть бути використані для ефективного таксономічного підбору деревних рослин під час проектування і створення міських зелених насаджень, стійких до умов урбанізованого середовища

Ключові слова: зелені конструкції; засоби-губки; поглинання твердих частинок; PM2,5; PM10; поглинання CO_2

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Influence of chemical activation on the ability of Transcarpathian clinoptilolite to adsorb direct dyes

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Abstract. Significant quantities of wastewater are generated in dyes synthesis processes and in technologies involving their use, which are toxic to living organisms, making the purification of industrial wastewater from organic colouring substances a pressing issue nowadays. The aim of this study was to investigate the prospects of using natural clinoptilolite from the Sokyrnytske deposit and its activated forms in the purification processes of wastewater from direct dyes. Natural clinoptilolite was activated by treatment with 5% H_2SO_4 and HCl aqueous solutions and heating at 300°C for two hours. The impact of activation conditions on the structural adsorption properties of clinoptilolite has been determined using a comprehensive thermal analysis method. The adsorption of the direct violet dye by natural and activated clinoptilolite has been investigated using spectrophotometric methods at pH 7 and a light wavelength of 550 nm, corresponding to the maximum value of light absorption coefficient. According to the results of thermal analysis, activated clinoptilolite samples exhibited a more developed specific surface area and a higher presence of hydroxyl groups, which can serve as active adsorption sites on the surface. The results of the violet dye adsorption have corresponded to the monomolecular Langmuir theory, indicating the energetic homogeneity of the adsorption centres. By linearizing the Langmuir adsorption isotherm equation, adsorption characteristics of natural and activated clinoptilolite with a 5% HCl aqueous solution relative to the direct violet dye have been determined. Activated clinoptilolite has shown increased sorption capacity (9.53 mmol/kg) compared to natural clinoptilolite (2.28 mmol/kg). The improvement in adsorption characteristics of activated clinoptilolite has been explained by its partial dealumination, resulting in the appearance of meso- and macropores capable of retaining dye molecules. The use of a 30% H_2SO_4 aqueous solution in activation processes and heating above 400°C has caused mineral degradation, confirmed by electron images of its surface. Practical value of the study lies in the recommendation to apply activated clinoptilolite in the purification processes of wastewater from organic pollutants

Keywords: zeolite; sorbent; colourants; thermal analysis; light wavelength; adsorption characteristics

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Introduction

One of today's problems is the reduction of the world's freshwater reserves. Particularly harmful pollutants in the hydrosphere are organic compounds. Among such pollutants, organic dyes, which are widely used in the technological processes of the light, food, pulp and paper industries, occupy a prominent place. In textile production, direct anionic dyes are widely used. These dyes are characterized by affinity for both cellulose fibres and amphoteric fibres (silk, leather, fur). According to M.G. Koval (2022), depending on the type of dye and the method of dyeing the fabric, from 20 to 50% of dyes enter the wastewater at the end of the production cycle. When washing dyed fabrics, the unfixed dye is washed off the surface of the fibre and enters the wastewater in significant quantities, many times exceeding the norms of maximum permissible concentrations. According to a study by J. Pavlović *et al.* (2022) the presence of dyes in water bodies reduces light transmission, negatively affects photosynthesis, disrupts self-purification processes and causes significant damage to aquatic ecosystems.

There are many technologies for wastewater treatment from organic pollutants. Researchers N.M. Tolstopalova *et al.* (2019) include chemical (coagulation, ozonation, photochemical reactions, electrochemical destruction, electrochemical coagulation), physical (adsorption, membrane separation, ion exchange) and biological treatment to traditional methods of removing dyes from the aqueous phase. In particular, N. Öz *et al.* (2021) investigated membrane microfiltration technology in details. According to spectrophotometric studies, the discoloration effects of dye solutions were 91-95%, 94-98% and 96-99% at light wavelengths of 436 nm, 525 nm and 620 nm. M. Madani (2021) described the technology of electrochemical treatment of effluents from direct dyes, investigated the influence of various factors on the efficiency of dye removal – the duration of purification, the pH of the medium, the presence of sodium chloride in the dye solution. Scientists T.V. Solodovnik *et al.* (2019) investigated the influence of the conditions of coagulation and flocculation processes on the degree of purification of dyed model solutions, similar in composition to wastewater of textile enterprises, using a natural flocculant – chitosan in combination with inorganic coagulants.

During the period of hostilities and limited funds for water protection measures, it is important for enterprises to choose the most optimal wastewater treatment technology. One of the important methods of elimination of hydrosphere pollutants is the technology of adsorption treatment of effluents with the use of mineral sorbents. Scientists S. Matiiuk & V. Gribinko (2019) claim that the sorption method allows to remove a trace amounts of contaminants, makes it possible to remove substances of an extremely wide nature from wastewater, regardless of their chemical resistance. Mineral sorbents of natural origin such as zeolites and clay minerals, which are characterized by a sufficiently high sorption capacity, cation exchange properties, availability and low cost, are widely used for wastewater treatment. Natural sorbents are widespread in Ukrainian deposits and are effectively used in various sectors of the national economy. Significant deposits of zeolite rocks are found in Transcarpathia and the mountainous Crimea. The most significant industrial importance among them belongs to the Sokyrnytske zeolite deposit. O.I. Ivanenko *et al.* (2020) note that the reserves of zeolite deposits of the Sokyrnytske deposit amount to 125.6 million tons, of which 39.5 million tons are high-quality zeolites. Clinoptilolite is one of the varieties of zeolites that belongs to the heulandite group and is widely used in practice.

The specific properties of this adsorbent are caused by the structure of the three-dimensional aluminosilicate framework, the presence of a developed system of cavities and channels, which contain a complex of exchangeable cations and water molecules. However, natural zeolites are not able to absorb molecules of organic pollutants, the size of which is larger than the size of the voids of the mineral. To improve the adsorption properties, zeolites are subjected to various types of activation. It is stated in the work of A. Ivanchenko *et al.* (2021) that under the influence of chemical activation, which proceeds as a result of the action of mineral acids, partial dealumination of the mineral occurs, which is accompanied by a change in the structural and adsorption parameters – specific surface area and pore size. Scientists I. Fediv *et al.* (2022) noted that one of the most common methods of improving the sorption properties of zeolites is thermal treatment at elevated temperatures, which causes water desorption and the release of zeolite channels.

However, the results of research on the adsorption properties of zeolites are still not sufficiently complete and systematized. The method of activation of zeolites, which makes it possible to form a system of channels in the mineral capable of retaining molecules of surface-active substances and dyes in the process of adsorption, requires a more detailed study. The efficiency of mineral modification depends on the nature and concentration of the acid, the contact time of the acid with the sample, the ratio of liquid and solid phases, the temperature at which activation is carried out. It is also necessary to take into account the peculiarities of the structure of adsorbate molecules. In particular, the ability of zeolites to adsorb dye molecules is influenced by the property of dyes to dissociate and, under certain conditions, to form associates. Therefore, the aim of the work was to investigate the effect of complex thermal and chemical activation with the participation of solutions of chloride and sulfate acids on the structural and adsorption characteristics of one of the types of zeolite, Transcarpathian clinoptilolite, for use in the process of wastewater treatment from dyes.

Materials and Methods

In this work, the natural zeolite clinoptilolite of the Sokyrnytske deposit of the Zakarpattia Region (Ukraine) was studied. Chemical composition of the mineral (wt. %): SiO_2 – 70.21; Al_2O_3 – 12.27; Fe_2O_3 – 1.2; FeO – 0.55; TiO_2 – 0.14; MnO – 0.073; P_2O_5 – 0.033; K_2O – 3.05; Na_2O – 1.77; SO_3 – 0.10; CaO, MgO – 10.604. The composition of clinoptilolite corresponds to the formula: $0.2Na_2O \cdot 0.26K_2O \cdot 0.43CaO \cdot 0.2MgO \cdot 9.57SiO_2 \cdot Al_2O_3 \cdot 0.09Fe_2O_3$.

Natural clinoptilolite with an average grain size of 0.25 mm (sample 1) was activated by treatment with a 5% solution of H_2SO_4 (sample 2) and a 5% solution of HCl (sample 3) at a ratio of solid and liquid phases of 1:10 during the day. After activation, the solid residue was washed with distilled water until a negative reaction to Cl^-,SO_4^{2-} ions. Samples treated with mineral acids were kept for two hours at a temperature of 300°C.

Thermal analysis of clinoptilolite samples was performed on a Q-1500 derivatograph of the Paulik-Paulik-Erdey system (MOM, Hungary) in the temperature range of 20-1000°C. The samples were analysed in a dynamic mode with a heating rate of 10°C per minute in an air atmosphere. The mass of the sample of natural clinoptilolite was 500 mg, the mass of activated samples was 400 mg. The sensitivity according to the scale of TG (thermogravimetric curves) was equal to 100 mg, according to the scale of DTG (differential thermogravimetric curves) – 500 μV, and sensitivity according to the scale of DTA (differential thermal analysis curves) – 100 μV. Measurement error of mass loss was ± 0.5%. The reference substance was Al_2O_3. Before conducting thermal studies, clinoptilolite samples were saturated with water vapour for two hours at room temperature. The specific surface area of natural and activated zeolite samples was approximately calculated based on the mass loss during their dehydroxylation. To determine SSA, the area ($0.21 \cdot 10^{-18}$ m^2), which accounted for one chemisorbed water molecule was taken into account (Vasilechko *et al.*, 2000). Direct violet (DV) dye was used to study the adsorption capacity of clinoptilolite samples (Fig. 1).

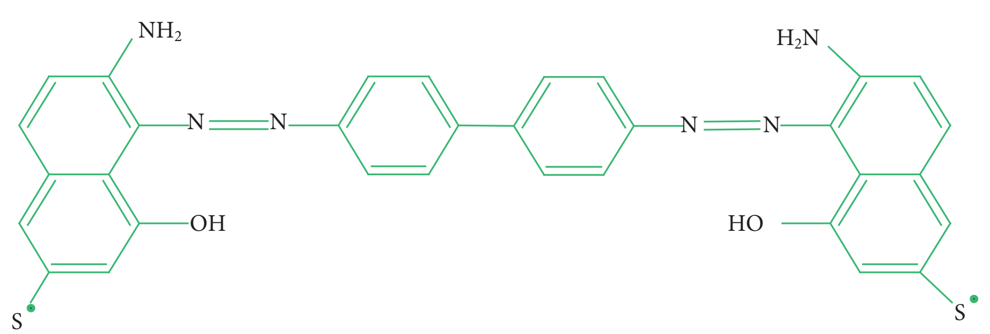


Figure 1. Structural formula of direct violet

Source: created by the authors

The surface tension of aqueous dye solutions and the critical micelle concentration (CMC) were measured by ring tear-off method. To study the adsorption, 0.62 g of clinoptilolite was mixed with 20 ml of DV dye solution of the proper concentration. That suspension was shaken periodically during 12 hours. Next, the suspension was precipitated until the clinoptilolite was completely separated from the dye solution, the liquid phase was filtered out. The adsorption value of the DV dye was determined by the difference in the concentrations of the initial and equilibrium solutions.

Concentrations of dye solutions were found using the Perkin Elmer-402 spectrophotometer (Perten, USA) in the range of light wavelengths of 195-900 nm. The operating range of light wavelengths for adsorption studies was established by determining the dependence of the light absorption coefficient on the light wavelength at different pH values.

To measure pH, an ionometer I-160MI (Tensor, Ukraine) was used, commutated by a system of electrodes ES-10603 and ESr-10103. In the preparation of alkaline solutions (pH 13), 0.5 ml of M NaOH was added to 10 ml of DV dye solution with a concentration of 50 mmol/m^3, and in the preparation of acidic solutions (pH 1-2), 0.2 ml of $1.0 \cdot 10^{-4}$ M HCl and 0.15 ml of $1,0 \cdot 10^{-4}$ M H_2SO_4 were added to 10 ml of dye solution. The adsorption capacity of natural and activated clinoptilolite was evaluated by modelling experimental data with the Langmuir equation (Álvarez-Ayuso & García-Sánchez, 2003):

$$A = \frac{A_\infty Kc}{1 + Kc}, \quad (1)$$

where A – the adsorption value; A_∞ – adsorption capacity of the monolayer or the limit value of monomolecular sorption; K – the constant of adsorption-desorption equilibrium; c – the equilibrium concentration. In order to study the effect on the structure of clinoptilolite at high temperatures and acid solutions of higher concentrations, additional studies were carried out. Clinoptilolite was heated at a temperature of 500°C for two hours, in some studies the mineral was activated with a 30% solution of H_2SO_4. Surface images of natural and activated clinoptilolite samples were obtained using an electron microscope JSM T 220 A Scanning microscope (JEOL, Japan).

Results

Thermal analysis is one of the important methods for studying the properties of a substance. On the basis of thermal analysis data, it is possible to get a visual idea of the nature of water bound by a mineral, and by the nature of its loss when heated, to investigate the influence of various factors on its properties. Figure 2 shows a thermogram of clinoptilolite activated with a 5% H_2SO_4 aqueous solution.

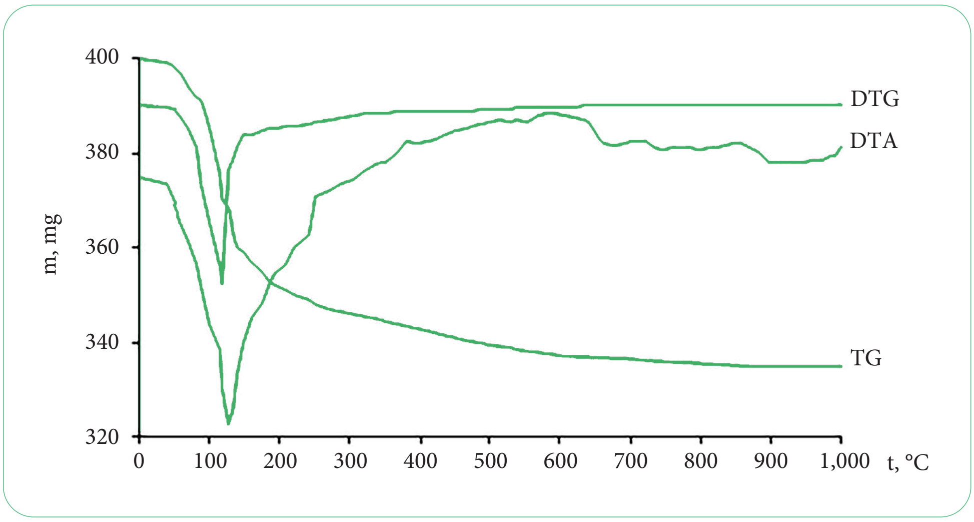


Figure 2. Thermogram of a sample activated with 5% H_2SO_4 aqueous solution (sample 2)
Source: created by the authors

At the first stage of thermolysis of clinoptilolite samples, there was a separation of physically adsorbed, structured water, which is coordinatedly bound to exchangeable cations, and water, which is localized on the surface of the mineral due to hydrogen bonds with surface OH groups (hydroxyl groups). This process was accompanied by a significant loss of sample mass, the appearance of a clear extremum on the DTG curves and a deep endothermic effect on the DTA curves.

At the second stage of thermolysis of the samples, dehydroxylation of the surface occurred, which was accompanied by cleavage of OH groups and gradual loss of sample mass. The process culminated in the destruction of the structure of the mineral. A broad endothermic effect appeared on the DTA curve. The loss of samples' mass at the second stage of thermolysis is proportional to the content of surface OH groups, which are able to serve as adsorption-active centres of the mineral.

Figure 3 shows a comparison of the TG curves of natural and activated clinoptilolite samples. Table 1 presents the results of complex thermal analysis of clinoptilolite samples.

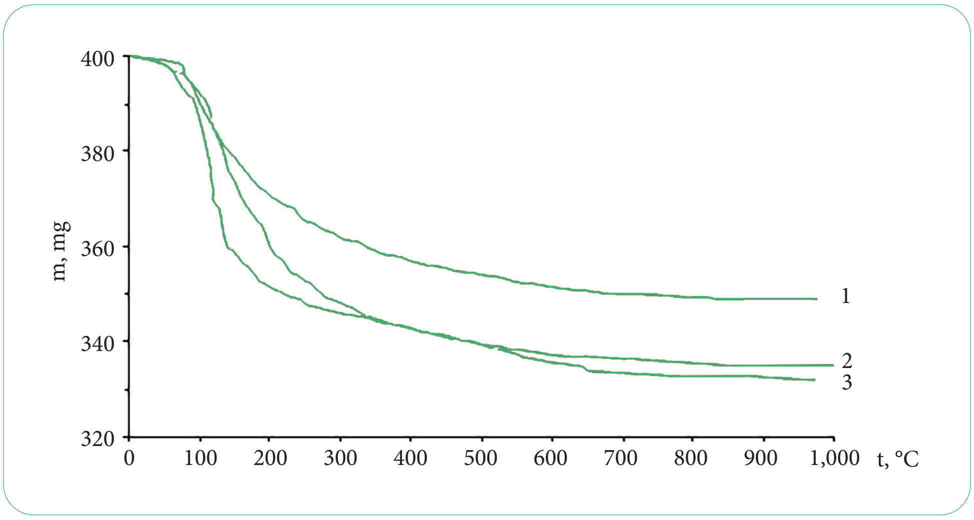


Figure 3. TG curves
Note: 1 – sample 1; 2 – sample 2; 3 – sample 3
Source: created by the authors

Table 1. Results of thermal analysis of natural and activated clinoptilolite samples

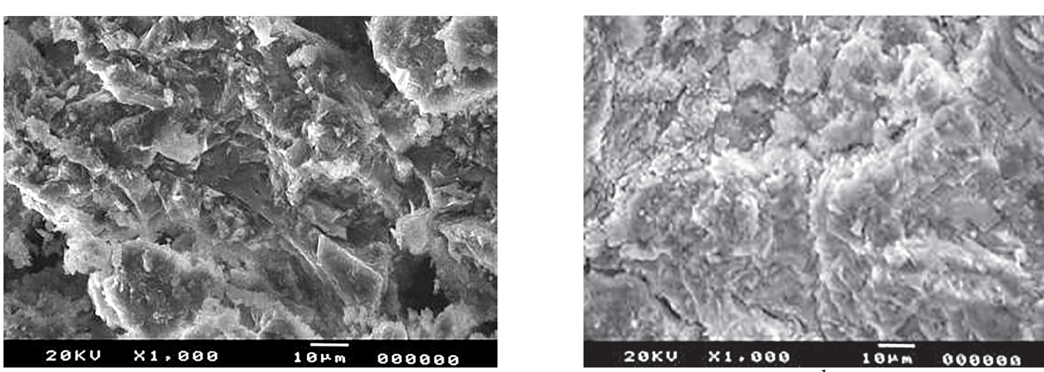
Sample	Stage	Sample weight, mg	Temperature interval, °C	Weight loss, mg	Specific surface area, m^2/g
1	I	500	20-508	48.5	77.26
	II		508-1,000	5.5	
2	I	400	20-525	55.1	96.57
	II		525-1,000	5.5	
3	I	400	20-525	57.5	114.13
	II		525-1,000	6.5	

Source: created by the authors

As can be seen from Table 1, activated clinoptilolite samples were characterized by a higher content of hydroxyl groups and a more developed specific surface area. The increase in SSA under the action of mineral acids can be explained by partial dealuminization of clinoptilolite, which was accompanied by an increase in pore volume, the appearance of secondary porosity and, accordingly, the number of additional adsorption-active centres (Vasilechko *et al*., 2015).

Additional OH groups in the process of chemical activation of clinoptilolite can appear during the interaction of exchangeable H^+ ions with frame oxygen atoms. The action of temperature can also affect the content of the adsorption centres of the mineral. It is known that an increase in temperature causes the diffusion of exchangeable cations into the internal channels of the zeolite structure. Additional OH groups can appear due to the interaction of polarized water molecules, which are coordinately bound to mobile cations (Melnyk *et al*., 2022).

The choice of the optimal temperature for thermal activation of clinoptilolite was established in separate studies. The sample, thermally activated at a temperature of 300°C, had the highest adsorption capacity relative to water vapour. Heating of clinoptilolite to a temperature of 400°C caused deterioration of its structural and adsorption characteristics. The result obtained was explained by the partial destruction and amorphosis of the mineral structure. The beginning of the destruction of the clinoptilolite structure at temperatures above 400°C was confirmed by electron microscope images of its surface (Fig. 4).



a b

Figure 4. Electronic images of the clinoptilolite surface

Note: a – natural; b – heated at 550°C

Source: created by the authors

Clear crystal faces were observed on the surface of the natural clinoptilolite sample, and there was a system of voids and channels. When the clinoptilolite sample was heated to 550°C, defects and disturbances of the crystal lattice appeared, which were accompanied by a decrease in the size of elementary cells. The faces of the mineral became fuzzy and blurred. Under the influence of high temperatures, the surface of the mineral was "sintered" and its structure was destroyed.

The concentration of the acid greatly influences the chemical activation efficiency of zeolite. According to the authors X. Chen & W.V. Srubar (2020) found that H_2SO_4 solutions of low concentration (≤ 5%) are capable of causing decation and slight dealuminization of zeolite, which is accompanied by an increase in its internal crystalline space and an increase in the number of adsorption centres. Sulfate acid solutions of higher concentrations (≥ 25%) can cause significant changes in the structure of clinoptilolite and deterioration of its adsorption characteristics. Figure 5 shows a comparison of surface images of clinoptilolite samples activated with 5% and 30% H_2SO_4 solutions.

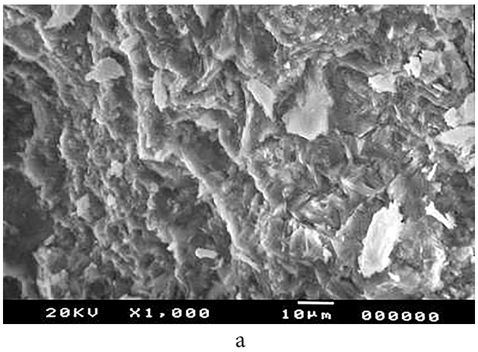


Figure 5. Electronic surface images of activated clinoptilolite
Note: a – activated with 5% H_2SO_4 aqueous solution; b – activated with 30% H_2SO_4 aqueous solution
Source: created by the authors

Treatment with a 30% H_2SO_4 solution caused certain changes in the surface of the sample – the edges of the mineral became less clear, and the appearance of the surface blurred, which indicated the initial destruction of the structure of the mineral. When clinoptilolite was treated with a 5% H_2SO_4 solution, no significant changes were observed in the image of the sample surface. The processes of partial dealuminization of clinoptilolite under the influence of acids of low concentrations (5% H_2SO_4 solution and 5% HCl solution) were confirmed by infrared spectroscopy. Acid solutions caused only a slight dealuminization of clinoptilolite with partial destruction of Si-O-Al bonds, as evidenced by the displacement of the absorption bands of valence intra-tetrahedral oscillations from 1054.00 cm^{-1} (sample 1) to 1074.08 cm^{-1} (sample 2) and 1082.30 cm^{-1} (sample 3). Natural and activated 5% HCl clinoptilolite, which was appropriate to the highest specific surface area, was studied for its ability to adsorb molecules of DV dye. Adsorption of the dye was carried out below the CMC. Dyes are colloidal surfactants that are able to form associates in solution. The dissolution of dyes in water takes place due to the interaction of polar groups with water. At low concentrations, the dye molecules are adsorbed on the surface of the liquid. This process is accompanied by a decrease in the surface tension of the solution. When a critical concentration is reached, a saturated monomolecular layer formed by dye molecules is formed on the surface of the liquid, and dye associations – micelles – begin to form in the solution. Due to the appropriate orientation of the dye molecules in the micelles, the surface tension of solutions at concentrations higher than CMC ceases to change. The CMC of the DV dye was found by breaking in the curve $\sigma = f\,(lnc)$ (Fig. 6).

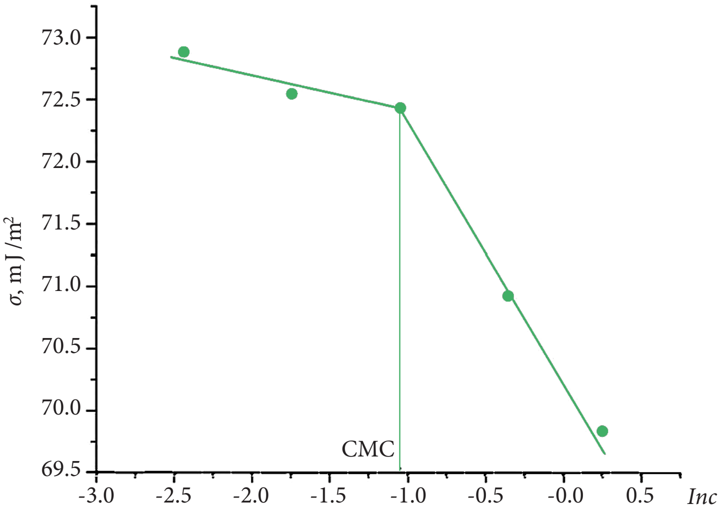


Figure 6. Dependence $\sigma = f\,(lnc)$ for a DV dye aqueous solution
Source: created by the authors

For a DV dye aqueous solution, the CMC was 0.36 mol/m^3. The pH of the medium significantly affects the optical properties of dye solutions. Ionization of the electron-donor amino group of direct dyes occurs with an increase in the acidity of the medium and consists in the attachment of a proton to a nitrogen atom. In this case, the neutral group is converted into a cation (Yahodynets *et al.*, 2019). As a result of the disappearance of the lone pair of electrons, the amino group ceases to be an electron donor substituent and the dye molecule interacts with light as if this substituent does not exist. This can lead to a shift in the maximum light absorption to the long-wavelength region and a decrease in the intensity of light absorption. Figure 7 shows the dependence of light absorption coefficients on the wavelength of light at different pH values.

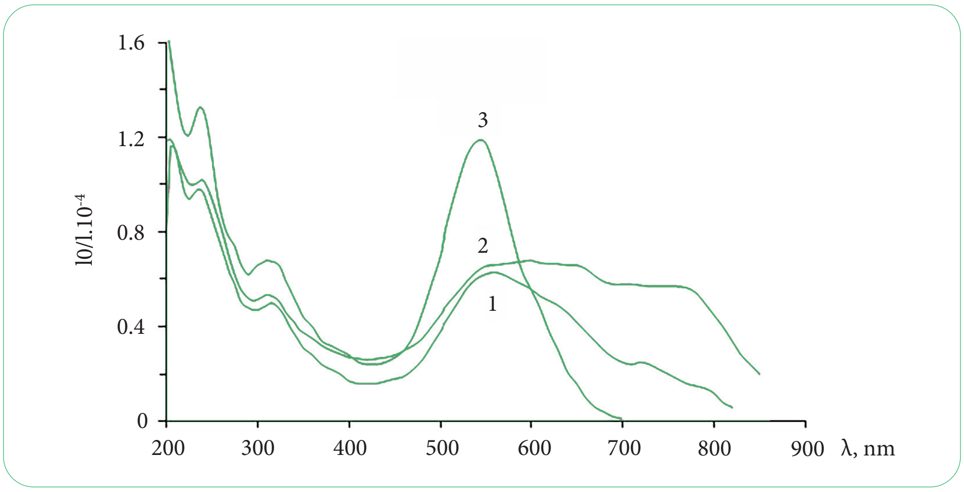


Figure 7. Dependence of light-absorption coefficients of DV solutions on light-wavelength at different pH values
Note: 1 – pH 1-2 when adding $1.0 \cdot 10^{-4}$ M HCl; 2 – pH 1-2 when adding $1.0 \cdot 10^{-4}$ M H_2SO_4; 3 – pH 7
Source: created by the authors

As can be seen from Figure 7, the DV aqueous solution at pH 7 (curve 3) was characterized by a symmetrical band of π-π^* transitions with a maximum light absorption coefficient ($1.18 \cdot 10^4$) at a wavelength of 550 nm. At pH 1-2, when hydrochloric acid dye was added to the solution (curve 1), the absorption band became less intense and asymmetrical, the maximum of the light absorption coefficient ($0.63 \cdot 10^4$) was appropriate to a wavelength of 560 nm. At pH 1-2, when (curve 2) was added to the H_2SO_4 solution, the maximum of the asymmetric band was manifested at a wavelength of 600 nm, it corresponded to the value of the light absorption coefficient of $0.68 \cdot 10^4$.

The influence of the alkaline environment on the value of the light absorption coefficient was insignificant and the appearance of the spectrum (curve 3) of the DV dye solution practically did not change. Therefore, the adsorption of DV dye by natural and activated clinoptilolite was carried out at pH 7 at a light wavelength of 550 nm. Figure 8 shows the isotherms of adsorption of the DV dye by samples 1 and 3. To depict the dependence $A = f(c)$, the equilibrium concentrations of the DV dye in solution were used.

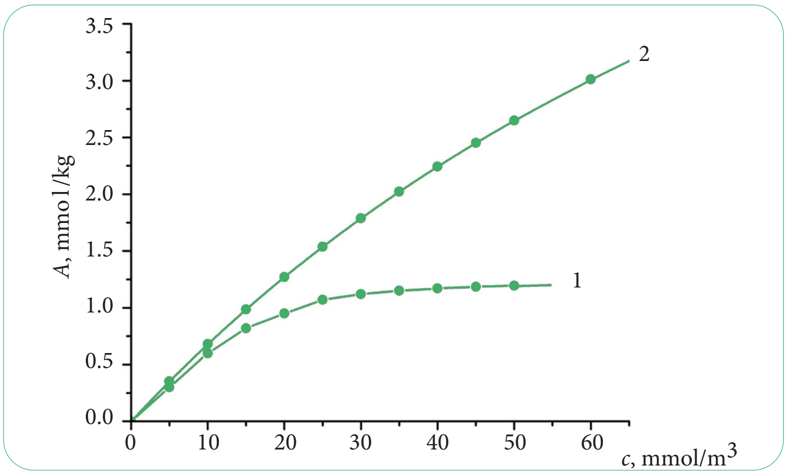


Figure 8. DV dye adsorption isotherms

Note: 1 – sample 1; 2 – sample 3
Source: created by the authors

As can be seen from Figure 8, the adsorption of the DV dye corresponded quite well to the monomolecular adsorption of Langmuir. By linearization of the Langmuir adsorption isotherm equation, its constants were found – the estimated value of the limiting monomolecular adsorbtion A_∞ and the adsorption-desorption equilibrium constant K (Table 2). High values of correlation coefficients (R^2) of experimental and theoretical data evidenced about the possibility of using the Langmuir equation for modelling sorption isotherms.

Table 2. Isotherm parameters of adsorption of DV dye by natural and activated clinoptilolite

Sample	A_∞, mmol/kg	K, m³/mmol	R^2
Sample 1	2.28	0.031	0.98
Sample 2	9.53	0.008	0.99

Source: created by the authors

As can be seen from the above data, activated sample 3 was characterized by a greater adsorption capacity relative to the DV dye. The result can be explained by the fact that in the shallow dealuminization of clinoptilolite, caused by the action of acid, meso- and macropores appear in its structure, which are able to sorb dye molecules. The effect of temperature (300°C) can cause the migration of exchangeable cations to inaccessible areas of the mineral framework, releasing the volume internal crystalline space, which acquires the ability to be filled with adsorbate molecules. Activated clinoptilolite was characterized by a greater adsorption capacity not only in relative to organic dyes, but also to water vapour. This was evidenced by a greater mass loss of activated samples at the first stage of thermolysis in the temperature range of 20-525°C (Table 1).

Adsorption of the dye on the active sites of clinoptilolite can occur not only under the influence of dispersive forces but also as a result of chemical interactions. Donor-acceptor interactions can occur between the OH groups of clinoptilolite (Brønsted acid sites) and NH_2 groups of the DV dye with the participation of protons of the hydroxyl group and an unshared pair of electrons of the nitrogen amino group. Thus, the results of the physical and chemical studies confirm that the activated clinoptilolite of the Sokyrnytske deposit is an effective absorbent for wastewaters.

Discussion

It is also worth to analyse other works on this topic, which consider types of absorbents other than clinoptilolite. Adsorption materials used in wastewater treatment technologies include activated carbon obtained from various natural materials, solid agricultural waste, clays, silica materials, zeolites, etc.

N. Ahmad *et al.* (2023) stated that activated carbon is one of the best adsorbents for the extraction of direct dyes and anionic surfactants from wastewater. Scientists from India N.M. Andal & K. Thangamani (2016) studied the sorption capacity of activated carbon obtained by heat treatment of the bark of the *Prosopis juliflora* shrub. The sorption capacity of carbon relative to the direct black dye was high and amounted to 500 mg/g. Researchers E. Chasova & O. Demchyshyna (2019) conducted a study of the ability of activated carbon obtained from various raw materials to adsorb anionic surfactants. The sorption capacity of stone activated carbon relative to sodium dodecyl sulfonate was 0.42 mol/g, and wood activated carbon was 0.37 mol/g. The data above shows that activated carbon can effectively extract direct dyes as a sorbent. However, its high cost and the need for regeneration have limited its widespread use. Much more accessible and cheaper to extract are sorbents of mineral origin, the most important representatives of which are zeolites, including clinoptilolite, which was studied in this study, and clay materials.

Clays are an important class of mineral adsorbents due to their availability and high sorption capacity. Bentonite clays are especially widely used, the main rock-forming mineral of which is montmorillonite (MMT). As stated by the authors of V. Kochubei *et al.* (2022), montmorillonite is a layered aluminosilicate that has a mobile crystal lattice. In the cavities between the layers there are exchangeable cations that can be easily exchanged for other organic and inorganic cations. Ionogenic organic dyes are colloidal compounds, which are divided into anionic (direct, acidic) and cationic (basic) according to the sign of the ion charge. Bentonite clays are able to actively absorb cationic dyes by the interlayer space, the adsorption of which occurs by the mechanism of ion exchange. Direct diazo dyes, which include DV, in water dissociate into an organic anion, which MMT is able to absorb only by the side faces due to active groups = Al – OH, which dissociate in an aqueous medium by the main mechanism. According to Q. Zhang *et al.* (2019) the adsorption capacity of Shandong Yihe Pharmaceutical's Na-montmorillonite with respect to methyl violet cationic dye was 1.35 mmol/g, and 0.08 mmol/g to anionic methyl orange dye.

The effect of the pH of the medium on the adsorption capacity of nanomontmorillonite by Nanosav Company (Iran) relative to the dye direct red 23 was investigated by the authors S.M. Pormazar & A. Dalvand (2020). The maximum extraction of direct dye from synthetic textile waters was achieved at pH 2. According to the authors, under these conditions, protonation of the active groups of the adsorbent surface occurred, which ensured an increase in the electrostatic attraction of dye anions to the positively charged areas of the MMT. The maximum extraction of direct red

23 dye from a solution with a concentration of 0.05 g/l was 2.5 mg/g. According to the results of the research, the sorption capacity of Transcarpathian zeolite (2.28 mmol/kg) is significantly inferior to the adsorption characteristics of bentonite clays. The lower sorption capacity of zeolites is explained by the peculiarities of their structure – the presence of a rigid crystal lattice, which is not able to expand when absorbing large organic compounds and their associates.

However, the ability of zeolites to take part in adsorption processes is largely determined by the conditions of formation of the host rock, the nature of exchangeable cations, and the structural characteristics of the mineral. The adsorption characteristics of zeolite are significantly influenced by the way it is modified. As confirmed in the studies carried out by the authors of this work, the action of a 5% HCl aqueous solution can cause a threefold increase in the adsorption capacity of Transcarpathian clinoptilolite relative to the DV dye (Table 1). Similar results were obtained by the authors of R. Ebrahimi *et al.* (2018), who investigated the effect of acid activation on the adsorption properties of Iranian clinoptilolite relative to the dye direct red 23. The adsorption of the dye was subject to Langmuir's theory. The action of phosphoric acid caused an increase in the adsorption capacity of zeolite from 0.3 mmol/kg (natural zeolite) to 0.6 mmol/kg. Activation with sulfate acid provided an increase in the adsorption capacity of zeolite to 0.9 mmol/kg. The mean free energy of adsorption was 8.2-8.9 kJ/mol and indicated that the adsorption of the dye was able to proceed by the mechanism of weak chemisorptions.

The authors H. Ünlü & N.J.M. Horing (2022) noted that natural zeolites have a three-dimensional rigid framework that has a negative charge and are characterized by low adsorption capacity relative to direct dyes. To improve the adsorption characteristics of zeolites relative to anionic azo dyes, scientists proposed to modify its surface with a quaternary amine – hexadecyltrimethylammonium bromide (CTAB). As a result of this modification, the surface of the zeolite acquired a positive charge, which led to an increase in sorption capacity relative to anionic dyes. Thus, the modification of Turkish zeolite with CTAB caused an increase in its sorption capacity with respect to active black dye 12.93 mg/g (natural zeolite) to 61 mg/g, relative to active red dye 15.94 mg/g (natural zeolite) to 111 mg/g, relative to active yellow dye from 13.15 mg/g to 89 mg/g. Based on the data, it can be confirmed that surface modification with quaternary amines is more effective than the acid modification in this article. However, it is known that CTAB is a cationic surfactant that can pollute the hydrosphere, which makes the method proposed by the authors of the study safer for the environment.

A. Ivanchenko *et al.* (2021) noted that textile dyes cannot be completely removed from wastewater by traditional methods of water treatment, which leads to the introduction of sorption post-treatment into the complex technological scheme. For the final stage of purification, the authors proposed to use zeolite activated with 7% HCl, H_2SO_4 and H_3PO_4 aqueous solutions. It was noted that zeolite activated by HCl was characterized by the highest efficiency of extraction of anionic dye methylene orange and the best results in the release of elements Al, K, Na, Ca, Mg, Fe, which was accompanied by an increase in the internal crystalline space of the mineral and the number of active sites. Similar results of hydrochloric acid on the structural and adsorption characteristics of Transcarpathian clinoptilolite were confirmed by the thermal analysis data (Table 1) given in this paper.

Like bentonites, zeolites are characterized by a selective ability to adsorb cationic dyes, which is largely determined by the acidity of the medium. M.M. Mahmoudi *et al.* (2019) noted that at pH $\geq$ 8 modified with a 5% H_2SO_4 aqueous solution, Iranian clinoptilolite was characterized by increased sorption capacity against the cationic dye methylene blue. A decrease in pH caused a decrease in the negative charge of the surface, which favoured the adsorption of anionic forms of substances. Adsorption of direct DV dye by Transcarpathian clinoptilolite of the Sokyrnytske deposit was carried out at pH 7. Probably, a decrease in pH can cause an increase in the sorption capacity of clinoptilolite relative to anionic dyes, which may be an interesting object of further research.

Thus, in terms of adsorption characteristics, natural zeolites are inferior to some mineral sorbents. But the surface occurrence, low cost of extraction and large reserves of natural deposits in Ukraine can ensure the widespread use of these minerals in adsorption technologies for wastewater treatment.

Conclusions

According to the results of thermal studies, the chemical activation of the Transcarpathian clinoptilolite of the Sokyrnytske deposit caused an increase in the specific surface area due to the appearance of secondary porosity. According to thermal analysis, the specific surface area of natural clinoptilolite was 77.26 m^2/g. The action of a 5% H_2SO_4 aqueous solution led to an increase in the specific surface area of the mineral to 96.57 m^2/g, and a 5% HCl aqueous solution up to 114.13 m^2/g.

Complex thermal and chemical activation of clinoptilolite caused the appearance of additional adsorption centres, which can serve as hydroxyl groups of the mineral. The appearance of additional OH groups during chemical activation of the mineral with 5% H_2SO_4 and HCl aqueous solutions is due to the interaction of exchangeable H^+ ions with oxygen frame atoms. Additional hydroxyl groups during heat treatment of clinoptilolite arise as a result of the diffusion of exchange ions into the internal channels of the mineral structure and their interaction with polarized water molecules. The use of mineral acids of higher concentration ($\geq$ 25%) in the process of activation and heating to temperatures above 400°C caused the destruction of the clinoptilolite structure.

Adsorption of DV dye with natural and activated clinoptilolite was carried out at pH 7, which corresponded to the maximum value of the light absorption coefficient. In adsorption studies, the initial concentrations of DV dye solutions did not exceed the CMC (0.36 mol/m^3), at which the dye is able to exist in solution in the form of associates. Data of adsorption of DV dye by natural and modified 5% HCl aqueous solution clinoptilolite were consisted with the Langmuir's theory, which testified to the monomolecular mechanism of adsorption and the energy homogeneity of the adsorption centres of the mineral.

Clinoptilolite activated by the action of 5% HCl aqueous solution was characterized by a higher adsorption capacity (9.53 mmol/kg) relative to the DV dye, compared to natural clinoptilolite (2.28 mmol/kg). The use of hydrochloric acid in chemical activation processes caused shallow dealuminization of clinoptilolite and an increase in pore size. Activated clinoptilolite acquired the ability to adsorb dye molecules not only on the outer surface but also on the internal space.

The absorption of direct anionic dyes by zeolites can proceed by the mechanism of weak chemisorption, complicated by electrostatic repulsive forces that occur between the negatively charged surface of zeolite and the anions of direct dyes. The protonation of the zeolite surface, caused by a decrease in the pH of the medium, is greatly able to improve the sorption capacity of zeolite. Therefore, the purpose of further research may be to study the effect of the pH of the medium on the efficiency of extraction of anionic dyes from their aqueous solutions.

Acknowledgements

None.

Conflict of Interest

None.

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Вплив хімічної активації на здатність закарпатського клиноптилоліту адсорбувати прямі барвники

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Анотація. У процесах синтезу барвників і технологіях із їх використанням утворюються значні кількості стічних вод, які є токсичними по відношенню до живих організмів, що робить очищення промислових стоків від органічних забарвлюючих речовин актуальною проблемою сьогодення. Метою роботи було дослідити перспективи використання природного клиноптилоліту Сокирницького родовища та його активованих форм у процесах очищення стоків від прямих барвників. Активація природного клиноптилоліту здійснювалась обробкою 5 % водними розчинами H_2SO_4 і HCl та нагріванням впродовж двох годин за температури 300°C. Вплив умов активації на структурно-адсорбційні характеристики клиноптилоліту встановлювався методом комплексного термічного аналізу. Адсорбція барвника прямого фіолетового природним та активованим клиноптилолітом досліджувалася спектрофотометричним методом за pH 7 за довжини світлової хвилі 550 нм, якій відповідало максимальне значення коефіцієнта світлопоглинання. За результатами термічного аналізу активовані зразки клиноптилоліту відзначалися більш розвиненою питомою поверхнею та наявністю більшої кількості гідроксильних груп, які здатні служити адсорбційно-активними центрами поверхні. Результати адсорбції барвника прямого фіолетового підпорядковувались мономолекулярній теорії Ленгмюра, що свідчило про енергетичну однорідність адсорбційних центрів. Шляхом лінеаризації рівняння ізотерми адсорбції Ленгмюра знаходили адсорбційні характеристики природного й активованого 5 % водним розчином HCl клиноптилоліту відносно барвника прямого фіолетового. Активований клиноптилоліт відзначався підвищеною сорбційною ємністю (9,53 ммоль/кг) у порівнянні з природним клиноптилолітом (2,28 ммоль/кг). Покращення адсорбційних характеристик активованого клиноптилоліту пояснювали його частковим деалюмінуванням, появою в структурі мезо- та макропор, здатних утримувати молекули барвника. Застосування в процесах активації 30 % водного розчину H_2SO_4 та нагрівання до температур вищих 400°C викликало деградацію мінералу, що підтверджувалось електронними зображеннями його поверхні. Практична цінність дослідження полягає в рекомендації застосовувати активований клиноптилоліт у процесах очищення стічних вод від органічних забруднень

Ключові слова: цеоліт; адсорбент; барвники; термічний аналіз; коефіцієнт світлопоглинання; адсорбційні характеристики

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Study of emissions into the atmosphere from the combustion of pellets and solid waste

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Abstract. The problem of waste is becoming increasingly urgent as the volume of waste and its negative impact on the environment grow. Thermal treatment is one of the most effective methods of reducing the volume of waste, but it also results in the release of pollutants into the atmosphere. Therefore, the study of air emissions from the incineration of different types of waste, as well as pellets made from different types of wood, was the aim of this research. During the visit to the solid waste landfill in Rybne village, waste samples were collected for further research. A comparative analysis of the level of emissions into the atmosphere of a mixture of waste corresponding to the morphological composition of the solid waste landfill in Rybne village was carried out. A comparative analysis was also carried out for the level of air emissions and calorific value of each type of waste, pellets and their mixtures. The study showed that the level of pollutant emissions into the atmospheric air depends on the type of waste and the technology of its incineration. The highest pollutant emissions are observed during the incineration of plastic, rubber and bio-waste. Solid fuels such as wood, paper and textiles emit fewer pollutants. A graph comparing the calorific value of different types of waste and pellets with the levels of air emissions has been developed. The graph shows that, as a rule, the higher the calorific value of the fuel, the lower the levels of pollutant emissions. The results of the study are valuable in practice for improving the methods of household waste utilisation for heat production, in particular, for selecting fuel compositions that minimise the levels of the studied pollutants in the air

Keywords: solid household waste; thermal disposal; caloric content; emissions into air; solid particles

Introduction

Solid household waste is one of the biggest problems faced by modern society. Billions of tonnes of municipal solid waste (MSW) are generated worldwide every year and this figure is growing. Solid waste (SW) consists of a wide variety of materials, including plastic, paper, textiles, metal, glass and food waste. MSW continues to grow and poses a significant challenge to local governments, most of which do not keep records of waste generation, sources and characteristics. This lack of information means that decisions on appropriate waste management are based on assumptions

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and guesswork, leading to mismanagement with serious environmental consequences. Examples include contamination of rivers and groundwater by landfill leachate, soil contamination, greenhouse gas emissions and animal mortality. One way to reduce the amount of waste is to convert it into fuel. Solid household waste and solid fuel pellets are a source of energy, but during thermal disposal they also release chemical compounds into the air that can be harmful to human health and the environment.

Studies like A. Kaur *et al.* (2023) show that MSW production will increase from 1.3 billion tons in 2012 to over 2.2 billion tons per year in 2025. This poses serious environmental and sanitary problems due to a lack of disposal sites. The use of MSW as an energy source is gaining popularity due to waste-to-energy technologies. These technologies, including gasification, pyrolysis, and incineration, convert waste into synthetic gas, which is then used to generate electricity. Another paper, by O. Bulyandra *et al.* (2020) focuses on the development of MSW fuel formulations to minimize emissions, demonstrating the potential of this approach. This article complements studies by examining the impact of waste type and wood pellets on emissions and calorific value, offering practical recommendations for improving MSW utilization methods for heat production. Existing research actively explores techniques to minimize the environmental impact of waste disposal. One such study by G. Wong *et al.* (2020) investigated the co-processing of fly ash and bottom slag from MSW incineration through low-temperature melting. This approach aimed to reduce energy consumption and potential leaching toxicity of the resulting slag, demonstrating the potential for innovative solutions in waste management.

In recent years, many countries have shown interest in new environmentally safe and waste-free technologies for the thermal processing of household waste with the formation of combustible gases. These technologies make it possible to obtain energy from solid household waste without releasing pollutants into the atmosphere. In Ukraine, there is a national waste management program, which defines the main directions of the development of the waste management system in Ukraine until 2030 (Resolution of the Cabinet of Ministers of Ukraine No. 117-p, 2019). According to the program, by 2030, the level of solid household waste processing in Ukraine should be at least 50%.

Authors P. Pysarenko *et al.* (2022) studied the impact of landfills on the environment and D. Tokarchuk *et al.* (2023) investigated the possibility of secondary use. The principles laid down in their works formed the basis of presented research. While there are studies on the impact of different Waste-to-Energy technologies on pollutant emissions, there is a lack of information on emissions from different types of waste and fuel pellets. This article focuses on filling this gap. The purpose of the work was to determine the level of emissions of pollutants into the atmospheric air and emissions of solid particles during the burning of waste, according to their different types, as well as solid fuel pellets, to compare the amount of thermal energy with the level of emissions into the atmospheric air.

Materials and Methods

The following methods were used to achieve the aim of the study. Sampling of MSW was carried out in the spring and summer of 2023 on the territory of the "Municipal solid waste landfill" of Rybne village, Ivano-Frankivsk territorial community, Ukraine. Combustible types of waste were selected for the experimental samples, such as: paper, plastic, rubber, textile, wood, bio-waste and unsorted combustible residues, as well as a combined mixture of waste, which corresponds to the morphological composition of the waste of the "Municipal solid waste landfill" of Rybne village. Reference samples of solid fuel wood pellets were selected: oak, pine needles 30%, beech 30%, oak 40%, pine needles 50%, beech 30%, oak 20%, Jerusalem artichoke, pine needles, beech. Their mixture was taken into account in the research.

The method of researching the moisture content in experimental samples of solid household waste and reference solid fuel pellets was used. It is based on drying a weight of fuel in a drying cabinet at a temperature of (140 ± 50°C) and calculating the mass loss. The selection of fuel weights from the analytical sample was carried out in the same way as in the main method of determination, that is, from two or three places of a thoroughly mixed analytical sample. Weight of the fuel gauge (5 ± 0.1 g). The drying cabinet was heated to 140...145°C with the ventilation flaps open. The glasses, with weights, were placed on the cabinet shelf in such a way that part of the shelf openings remained open. The drying time was 20-30 minutes. Determination of moisture content was calculated using the formula:

$$A^a = \frac{m_3 - m_1}{m_2 - m_1} \cdot 100\%, \tag{1}$$

where m_1 is the mass of the crucible; m_2 is the mass with the weight of the fuel sample; m_3 is the mass of the crucible after drying with fuel, g. From the selected and appropriately prepared samples of solid household waste and solid fuel wood pellets, a fuel sample was formed using a press. The mass of the formed sample tablet corresponded to 1 g ± 0.05. The sample was placed in a crucible, which was installed in the holder of the calorimetric cover-bomb, 1 ml of distilled water was introduced into the bomb and placed in the calorimeter to conduct an experiment to determine the heat of combustion.

With the help of a NEUS solid fuel boiler (Noteus LLC, Ukraine), the process of burning test samples was carried out. The process of obtaining data on the levels of harmful substances was carried out according to the method of measuring pollutant emissions from stationary emission sources. Emissions were measured directly in the centre of chimney diameter, not less than a distance of two diameters from the last bend using a measuring probe. The levels of pollutant emissions into the air were measured by the gas analyser OKSI 5M (ECOTEST LTD, Ukraine) and the air quality analyser CEM DT-9881 (CEM Instruments, China). Meteorological characteristics were measured at the level of human breathing (about 2 m). The wind speed was from 0 to 0.2 m/s, the temperature was 18°C. The calorific value needed for this research was determined in previous study (Chupa & Adamenko, 2023). To assess the morphological composition of solid household waste, averaged data for 2020-2021, provided by the Municipal Enterprise "Polygon solid household waste", was used. These data were obtained in accordance with approved by Ministry of Housing and Communal Services methodological recommendations (Order of the Ministry of Housing and Communal Services of Ukraine No. 39, 2010).

Results

The main methods of disposal of solid household waste are the following. Burial is the easiest and cheapest method, but it has a number of negative consequences, such as soil, water and air pollution. Recycling is a process that allows to turn solid household waste into secondary raw materials that can be used for the production of new goods. Thermal processing is a process in which solid household waste is burned to obtain energy in the form of heat or electricity. Thermal processing of solid household waste has a number of advantages: it reduces the volume of solid household waste, which reduces the need for the construction of landfills, receives energy that can be used to provide heat and electricity; reduces greenhouse gas emissions as solid household waste is incinerated instead of landfilled. The increasing volume of waste and its environmental impact highlight the need for effective waste management practices. While thermal treatment offers a valuable means of waste volume reduction, concerns regarding pollutant emissions remain. Thermal treatment of MSW has some disadvantages: causes emissions of air pollutants such as nitrogen oxides, sulphur oxides, carbon dioxide, heavy metals and particulates; leaves behind waste such as ash, sludge, slag, boiler ash, effluent and emissions.

When planning the incineration of solid household waste, the following factors must be taken into account. Disposal technology: it can be incineration to obtain energy, incineration to obtain chemical products or landfill. Morphological composition: waste can consist of paper, plastic, metal, glass, organic substances, etc. Necessity of preliminary preparation of waste: waste may require grinding, sorting, separation of metal, etc. State of waste: waste can be dry, wet, contaminated, etc. Fractional composition: waste can be homogeneous or heterogeneous. Moisture: the moisture content of waste affects its energy value and composition of emissions. Slag and ash: slag and ash are formed during the burning process and require disposal. Emissions into the atmosphere during combustion are one of the most important indicators to consider, as they can have a negative impact on the environment.

According to data provided by the Municipal Enterprise "Polygon solid household waste" approximately 64-68% of solid household waste entering landfills is suitable for energy recovery. About 32% of solid household waste is not suitable for energy production, as it is non-combustible, includes glass and metal, as well as unsorted residue, which is not taken into account during laboratory studies and calculation of the energy potential of solid household waste. A study of the ash content of all types of fuel was conducted, namely 7 samples of solid household waste of different types, 7 samples of solid fuel pellets from different tree species and 2 samples of mixtures: a mixture that corresponds to the morphological composition of MSW landfill with Rybne village; an averaged mixture of wood pellets. 16 samples of 1,500 g were prepared according to the established component composition, which is given in the Table 1, another group of test samples was also prepared.

Table 1. Description of the investigated components of solid household waste and pellets in the samples

No.	Types of pellets	Components of solid household waste
1	Oak	Paper and cardboard
2	Pine 30%, beech 30%, oak 40%	Plastic
3	Pine 50%, beech 30%, oak 20%	Wood
4	Artichoke	Textile
5	Pine (1)	Rubber
6	Pine (2)	Bio-waste
7	Beech	Unsorted combustible residue

Source: made by the authors

Groups of samples of waste and solid fuel pellets were burned in a solid fuel NEUS boiler. After complete combustion of each of the test samples, the working part of the boiler was cleaned of ash and combustion products. A total of 16 fuel samples were prepared, of which 8 samples are solid household waste, and the other 8 samples are solid fuel pellets. All of this is presented in Figure 1.

a b c

Figure 1. Test samples and facility for burning them

Note: a – NEUS boiler; b – solid household waste; c – solid fuel pellets

Source: made by the authors

During the combustion process, a study of the emissions of harmful substances into the atmospheric air was carried out using the gas analyser OKSI 5M, as well as the air quality analyser CEM DT-9881, which measured solid particles. To obtain data on the levels of harmful substances, the technique of measuring pollutant emissions from stationary emission sources was used. Emission measurements were carried out directly in the chimney, in the centre of its diameter, at a distance of at least two diameters from the last bend. Measurements were carried out using a measuring probe (Fig. 2). Meteorological measurements were conducted at head height (2 meters).

Figure 2. Conducting research on atmospheric air pollution levels

Source: made by the authors

From previous studies by V. Chupa & Ya. Adamenko (2023) the calorific value was determined for each of the samples of solid fuel wood pellets and their averaged mixture, and different types of waste, as well as a mixture of solid household waste according to the morphological composition suitable for burning at the Rybne village landfill. In accordance with the standards for the maximum permissible emissions of pollutants from stationary sources, the values of the standards for the maximum permissible emissions of vaporous and gaseous inorganic compounds, as well as suspended solid particles of undifferentiated composition are given in Table 2 (Order of the Ministry of Environmental Protection of Ukraine No. 309, 2006).

Table 2. Norms of maximum permissible emissions of vaporous and gaseous inorganic compounds, as well as suspended solid particles undifferentiated by composition

The name of the substance	The amount of mass loss, g/h	Maximum permissible emissions, mg/m^3
Substances in the form of suspended solids particles undifferentiated in composition	500 <	50
Sulphur dioxide (dioxide and trioxide) in converted to sulphur dioxide	5,000 <	500
Nitrogen oxides (nitrogen oxide and dioxide) in terms of nitrogen dioxide	5,000 <	500
Carbon monoxide	5,000 <	250

Source: created by the authors

All the averaged results obtained during the study are shown in Table 3. The most important indicator from the point of view of the efficiency of obtaining thermal energy is the calorific value of the fuel, and from the point of view of the impact on the environment, it is the level of emissions of pollutants into the atmospheric air. Also, an integral part of this impact are solid volatile particles that negatively affect the human respiratory system.

Table 3. Calorific value and atmospheric emissions of the studied samples

Type of fuel	Calorie content, J/g	Dust 2.5	Dust 10	CO	NO	NO_x	NO_2	SO_x	SO_2	CO_2
Plastic	39,970.00	0.000968	0.277884	54	510	516	108	498	432	1.90%
Rubber	32,373.00	0.001275	0.324795	78	654	558	108	639	540	2.10%
A mixture of waste from the Rybne village landfill	18,487.9	0.000784	0.125671	37	258	282	144	256	72	1.50%
Pine 30%, beech 30%, oak 40%	18,399	0.000571	0.005463	21	24	6	36	24	27	0.10%
Oak	18,313	0.000461	0.003628	19	54	30	144	54	21	0.20%
Average pellet mixture	17,947.16	0.000510714	0.004117286	22	55	22	82	55	42	0.25%
Tree	17,947.00	0.000562	0.001287	34	342	432	72	339	108	0.60%
Pine 50%, beech 30%, oak 20%	17,882	0.000613	0.004273	24	42	17	108	42	10	0.30%
Artichoke	17,728	0.000487	0.003471	23	72	42	108	72	12	0.40%
Pine (2)	17,693	0.000581	0.003962	25	78	18	36	78	19	0.25%
Beech	17,668	0.000389	0.003285	17	54	30	72	54	17	0.15%
Pine needles (1)	17,643	0.000473	0.004739	24	60	24	72	60	42	0.35%
Textile	17,580.00	0.000751	0.124621	53	348	426	108	338	360	1.10%
Bio-waste	13,637	0.000543	0.001675	76	570	582	144	557	468	1.30%

Table 3. Continued

Type of fuel	Calorie content, J/g	Dust 2.5	Dust 10	CO	NO	NO_x	NO_2	SO_x	SO_2	CO_2
Paper, cardboard	13,457.00	0.000457	0.001354	43	426	492	108	418	288	1.50%
Unsorted combustible residue	9,622.00	0.000897	0.018467	45	426	492	72	409	612	1.70%

Source: created by the authors

According to the obtained data in the Table 3, a visualization of the obtained data using a summary graph is visible (Fig. 3). It can be noted that such types of solid household waste as plastic and rubber have a rather low level of moisture within the range of 3-5%, which accordingly has a positive effect on their combustible properties. All types of wood pellets are characterized by a low level of moisture and a sufficiently high level of calories, regardless of their origin (type of wood). Samples such as paper, textiles, wood waste, a mixture of solid household waste from the Rybne village landfill, unsorted combustible residue of solid household waste and bio-waste showed the worst indicators of the ratio of caloric content to moisture. The mass of bio-waste is the least suitable for obtaining thermal energy, without preliminary preparation, the moisture content can be significantly reduced with the help of preliminary drying, but this is an additional cost of thermal energy. For bio-waste, the best disposal solution remains composting.

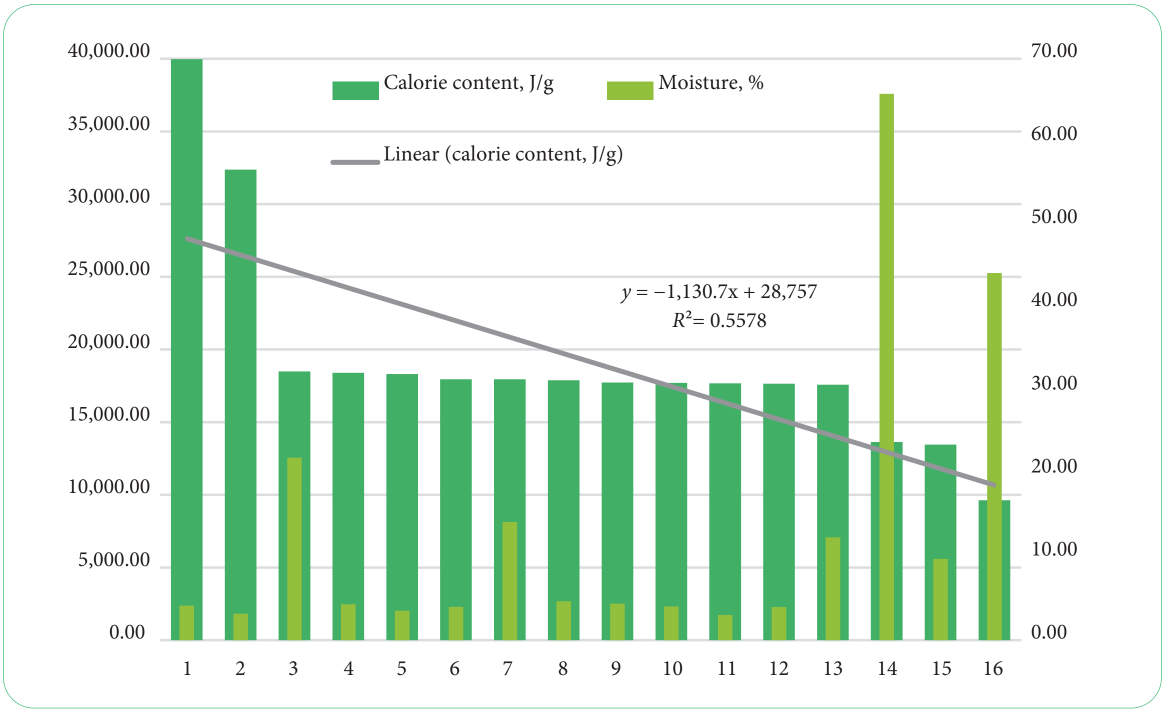

Figure 3. The ratio of caloric content and moisture level of experimental samples

Note: 1 – plastic; 2 – rubber; 3 – a mixture of waste from the Rybne village landfill; 4 – pine 30%, beech 30%, oak 40%; 5 – oak; 6 – average pellet mixture; 7 – tree; 8 – pine 50%, beech 30%, oak 20%; 9 – artichoke; 10 – pine (2); 11 – beech; 12 – pine needles (1); 13 – textile; 14 – bio-waste; 15 – paper, cardboard; 16 – unsorted combustible residue

Source: made by the authors

Figure 4 and Figure 5 illustrate the levels of emissions of harmful substances into the atmospheric air during the burning of solid household waste and solid fuel wood pellets, respectively. The blue line of the graphs indicates the level of thermal energy released during the burning of the test samples, the orange line indicates the norms of the maximum permissible output for such harmful substances as NO_x, SO_x and their derivatives NO, NO_2, SO_2, the grey line shows the normative level of the maximum permissible output CO carbon monoxide.

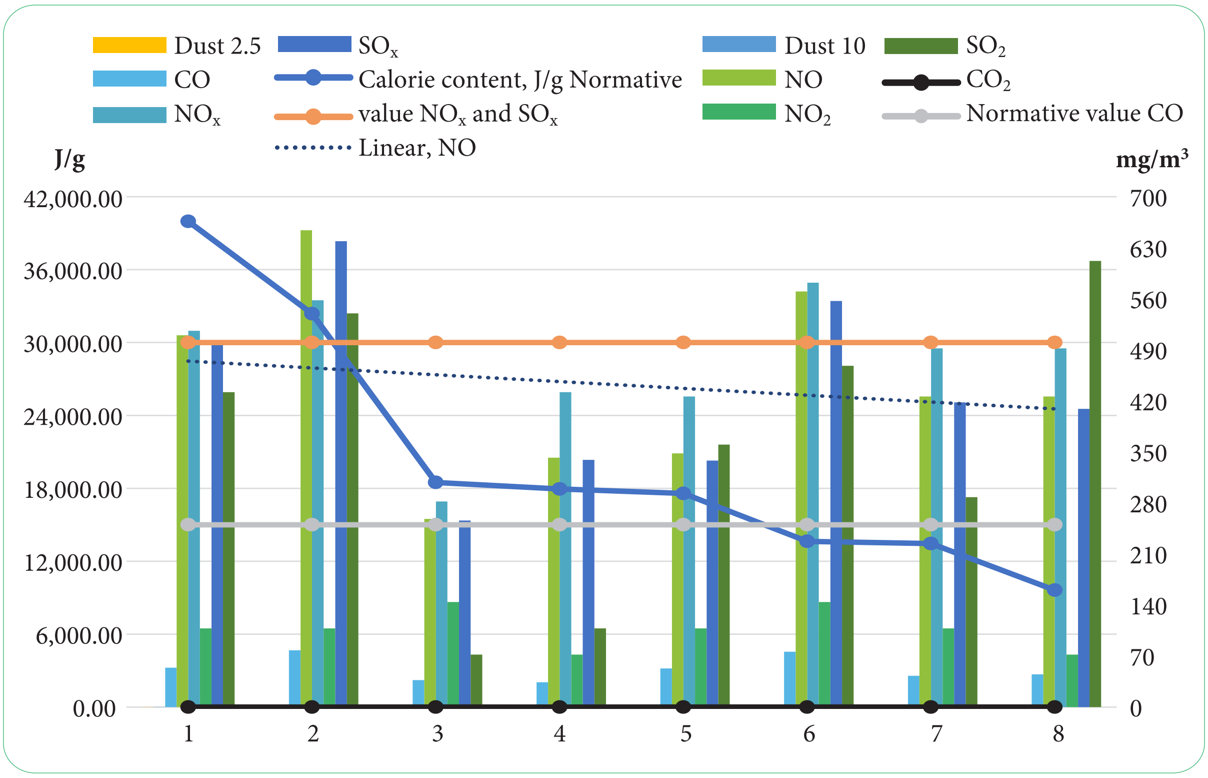

Figure 4. Graph comparing the level of caloric content and emissions into the atmosphere of solid household waste
Note: 1 – plastic; 2 – rubber; 3 – a mixture of waste from the Rybne village landfill; 4 – tree; 5 – textile; 6 – bio-waste; 7 – paper, cardboard; 8 – unsorted combustible residue
Source: made by the authors

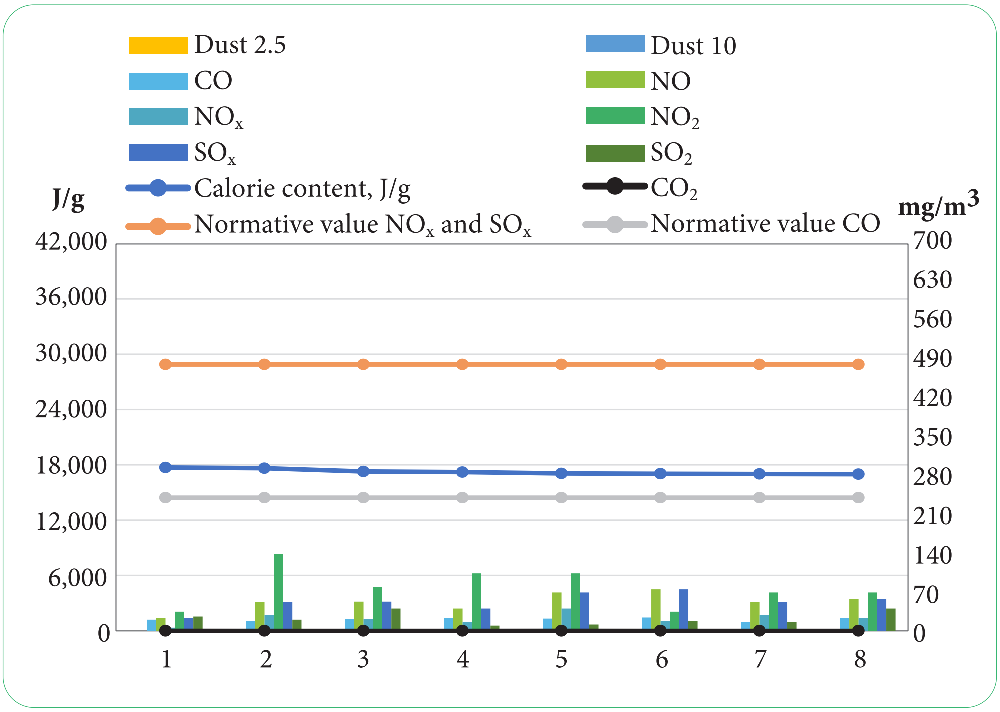

Figure 5. Graph comparing the level of caloric content and emissions into the atmosphere of solid fuel wood pellets
Note: 1 – pine 30%, beech 30%, oak 40%; 2 – oak; 3 – average pellet mixture; 4 – pine 50%, beech 30%, oak 20%; 5 – artichoke; 6 –pine (2); 7 – beech; 8 – pine needles (1)
Source: made by the authors

After analysing the graphs, it can be seen that the highest rate of emission of harmful substances into the atmospheric air is observed in samples of rubber, bio-waste and plastic. At the same time, the best ratio of caloric content (18,399 J/g) to atmospheric emissions is in the samples of the pellet mixture (Pine 30%, beech 30%, oak 40%). Also, the worst ratio of caloric content (9,622 J/g) to atmospheric emissions is observed in samples of unsorted combustible residue. Also, it can be noted that excess emission levels of pollutants such as NO_x and SO_x are observed in rubber, plastic and bio-waste, and excess CO emission levels are not observed, since the level of carbon monoxide characterizes the quality of the combustion process itself and its efficiency solid fuel installation.

Discussion

It's crucial to compare the calorific values of various waste types with studies conducted in different settings. A broader approach ensures comprehensive understanding and enables more accurate assessments of the energy potential inherent in various types of waste. Understanding the environmental impact of burning different waste types is crucial for making informed decisions about waste management practices.

The A.O. Popoola *et al.* (2023) research focuses on evaluating the calorific potential of MSW in Enugu, Nigeria, for electricity generation, providing comparisons across different landfill sites. This variation in waste composition and calorific values underlines the importance of regional studies in understanding waste-to-energy efficiency. Such comparisons validate the relevance of further research in this domain, including the investigation of emissions from waste combustion. Unlike the studies of the M.C. Unegg *et al.* (2023), who focused their research on the comparative analysis of CO_2 emissions with different types of waste management and J. Saleem *et al.* (2023), who considered only the same type of waste, such as plastic, authors of the presented research focused their attention on the study of toxic emissions from various types of waste. Several studies, like the one by M. Abis *et al.* (2020), analyse the state of MSW management in the EU, highlighting the importance of increasing recycling rates and optimizing ash recovery from incineration. This current research builds upon such efforts by investigating air pollutant emissions from various waste types during thermal treatment.

The study of thermal utilization of municipal waste and its impact on air emissions is a topical area. In the paper, the authors analyse pollutant emissions from the combustion of various types of waste and wood pellets. Their results confirm the dependence of emissions on the type of waste and combustion technology, with plastic, rubber, and bio-waste showing the highest levels of pollution. This study complements R. Nandhini *et al.* (2022) work by focusing on a specific waste composition at a landfill in Rybne, Ukraine. Burning technology is also important in thermal disposal of household waste. For example, the paper by C.I. Idumah (2022) examines the impact of different combustion technologies on pollutant emissions. This article complements existing research by studying the pollutant emissions of different types of waste and wood pellets made from different types of wood.

The work of A. Voronych *et al.* (2023) analysed the morphological composition of MSW. The approximate percentage of SW suitable for energy utilization from the total mass of SW entering landfills has been determined. The level of reduction in mass of MSW during incineration was determined. Some characteristic parameters of thermal treatment of SW by experimental method were determined. The location of this study coincides with this research, so the data obtained by the researchers formed the basis of this analysis and comparison of the obtained results. C. Yue *et al.* (2022) directed their research in a slightly different direction of analysis of the process of energy recovery from solid household waste, namely pyrolysis and the effect on this process of different proportions of gases in the reactor of the pyrolysis plant. This research on the contrary describes a less technically complex process of energy recovery from solid household waste, but the principles of using waste as a source of thermal energy are somewhat similar.

The authors of the study analysed the possibility of producing fuel pellets using bio-waste and its ash. The process of creating such fuel pellets is quite complicated, as the authors B.R. De Almeida Moreira *et al.* (2021) emphasize that this fuel is a possible substitute for coal. In authors research, the path of simpler processing of bio-waste than the production of coal from it was chosen. H. Tran *et al.* (2023) examine the emissions of pollutants into the atmosphere accompanying the production of fuel pellets from wood waste. The direction of such research is very interesting, since few people are engaged in researching the negative effects of the production process itself, in particular, this aspect is not taken into account in presented research, but in the following publications authors want to pay attention to it.

In their study, N. Bublienko *et al.* (2020) meticulously analysed emissions from the combustion of plant residues, which contrasts combustion of MSW and pellets in this study. Specifically, the authors considered emissions resulting from the combustion of fallen leaves and explored their cost-effective processing to produce a biostimulant. They investigated the environmental impact of these emissions, which can offer valuable insights into sustainable waste management practices. An interesting study is the work of Y. Zhang *et al.* (2022). The scientists analysed the emissions of pollutants into the atmosphere if co-combustion is carried out in different proportions of excavation waste with municipal waste. The authors concluded that such incineration with less than 40% of MSW mixed with excavation waste and a sufficiently low combustion temperature can not only improve the overall combustion of waste but also reduce emissions.

Pyrolysis technology allows to decompose solid household waste at a temperature of 500-900°C without access to oxygen. Gasification technology allows solid household waste to be decomposed at a temperature of 800-1000°C in the presence of oxygen. At the same time, combustible gases are formed, which can also be used for the production of electricity or heat. These technologies are promising for solving the problem of solid household waste, as they allow obtaining energy from solid household waste without negative impact on the environment (Pan *et al*., 2022; Lopushniak *et al*., 2023). In previous authors studies, the thermal potential of household waste was also analysed, and the possible calorific value of waste mixed with pellets made from wood and energy crops was calculated.

The study in question delved into the ecological efficiency of utilizing various types of solid fuel pellets and solid domestic waste as a substitute energy source. A critical factor considered was the balance between the fuel's calorific value, which signifies its energy potential, and the level of harmful substance emissions that impact the environment. Solid fuel pellets, specifically a blend of pine, beech, and oak in specific ratios, exhibited high efficiency.

Conclusions

High efficiency of solid fuel pellets conditioned primarily due to their combination of high calorific value and low emission levels, making them a favourable option for use in heat-generating systems that aim to minimize adverse effects on the atmosphere. On the contrary, unsorted combustible waste, which can also serve as fuel, presents a lower energy value and a higher level of harmful emissions. This makes it a less preferable choice from an environmental perspective, despite its potential for energy production. To effectively illustrate the findings of the study, a comparative graph was developed. This graph demonstrates the relationship between calorific value and emission levels for different fuel types. By plotting these variables against each other, the graph provides a clear visual representation of the trade-offs between energy potential and environmental impact. This graph can serve as a valuable tool for selecting the most efficient and eco-friendly fuel for specific needs. It allows users to consider their individual requirements for energy efficiency and environmental standards, thereby facilitating informed decisions about fuel choices.

The study underscores the importance of considering both energy efficiency and environmental impact when evaluating potential fuel sources. While some fuels may offer high energy output, their environmental costs may outweigh their benefits. Conversely, fuels with lower energy output but minimal environmental impact may prove to be more sustainable in the long run. In conclusion, the study provides a comprehensive analysis of the ecological efficiency of various fuels, offering valuable insights for those seeking to balance energy needs with environmental responsibility. The comparative graph developed from the study's findings serves as a practical tool for visualizing these trade-offs and making informed fuel choices. An additional direction of future research will be focused on the generalization and analysis of the obtained research results. Having combined the obtained results, it is planned to develop an automated calculation complex that will receive input data: calorific value, ash content and emissions into the atmospheric air during the burning of pellets and household expenses, and at the output will provide percentage values of fuel compositions according to the initial parameters needed.

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Conflict of Interest

None.

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Дослідження викидів від спалювання пелет та твердих відходів в атмосферу

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Анотація. Проблема відходів стає все гострішою, оскільки кількість відходів і їх негативний вплив на довкілля зростає. Термічна обробка є одним із найефективніших методів зменшення об'єму відходів, але вона ж призводить до викидів забруднювачів в атмосферу. Тому вивчення викидів у повітря від спалювання різних типів відходів, а також пелет, виготовлених із різних типів деревини, було метою цього дослідження. Під час екскурсії на полігон твердих побутових відходів у с. Рибне були зібрані зразки відходів для подальших досліджень. Проведено порівняльний аналіз рівня викидів в атмосферне повітря суміші відходів, що відповідає морфологічному складу полігону твердих побутових відходів у с. Рибне. Також порівняльний аналіз проводився для рівня викидів в атмосферне повітря та калорійності кожного типу відходів, пелет та їхніх сумішей. Дослідження показало, що рівень викидів забруднювачів в атмосферне повітря залежить від типу відходів та технології їх спалювання. Найбільше викидів забруднювачів спостерігається під час спалювання пластику, гуми та біовідходів. Тверде паливо, таке як деревина, папір і текстиль, виділяє менше забруднювачів. Розроблено графік порівняння калорійності різних типів відходів та пелет із рівнями викидів в атмосферу. З графіка видно, що, як правило, чим вища калорійність палива, тим нижчі рівні викидів забруднювачів. Результати дослідження є цінними на практиці для покращення методів утилізації побутових відходів для виробництва теплової енергії, зокрема, для вибору паливних композицій, що мінімізують рівні досліджуваних забруднювачів у повітрі

Ключові слова: тверді побутові відходи; термічна утилізація; калорійність; викиди в повітря; тверді частинки

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Dynamics of forest stands changes on the territory of Skole Beskydy National Nature Park

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Abstract. The relevance of the study is determined by the issue of assessing the condition and utilization of forest cover within the territory of the Skole Beskydy National Nature Park, as well as the necessity to develop effective methods for monitoring and conserving forest ecosystems. The purpose of the study was to investigate the dynamics of forest cover changes within the Skole Beskydy National Nature Park, as well as to assess the losses of forest resources in this area and recommend the obtained series of images to enhance the forest management system. The research was conducted using a comprehensive approach combining various methods of studying forest cover changes and their comparison. The basis for applying remote sensing technologies was the use of specific multispectral satellite images combined with attribute information on forest land geospatial data. The most progressive methods of studying changes in forest plantations based on remote sensing data using geographic information systems have been demonstrated. Satellite images were obtained from the Landsat 8 satellite data set through the United States Geological Survey data portal. The normalized burn ratio and normalized difference vegetation index are calculated and compared. An analysis was also carried out using the Global Forest Watch online resource. As a result of the study, changes in forest cover were identified, an assessment of the changes was provided, and a map reflecting forest changes that occurred in the Skole Beskydy National Nature Park from 2000 to 2020 was developed. According to the results of the analysis, a low level of losses of forest plantations due to natural factors, including losses from fires, was established. The main part of forest losses is caused by anthropogenic factors. The practical significance of the results lies in the possibility of using the obtained series of images within public control and improving the forest management system

Keywords: satellite images; satellite; vegetation index; forest loss; forest gain; tree cover

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Introduction

In the modern world, the urgent problem of deforestation and logging of forest areas underscores the importance of systematic monitoring of forest ecosystems for their preservation. The application of satellite imagery significantly enhances the efficiency of landscape monitoring and serves a wide range of practical and scientific purposes. The use of geographic information systems (GIS) for data analysis and processing allows for the effective management and monitoring of forest areas. This approach is particularly crucial for open forest territories, as traditional on-site data collection methods are time-consuming and require significant financial and labour resources. Satellite monitoring of forest areas provides the opportunity to detect, track, and assess the dynamics of changes in forest ecosystem cover over extensive areas.

To enhance the effectiveness of monitoring changes in forest plantations, a comprehensive approach that combines various research methods is crucial. One such method is the utilization of the Global Forest Watch (GFW) map of global forest changes. In their study, O. Yakovenko (2023) examined the distribution characteristics of forest vegetation on forest "islands" in the Chernihiv Polissia Region and the dynamics of their area over the past 20 years using the GFW online resource. The research demonstrated the high effectiveness of the GFW online resource in studying the dynamics of forest resource changes. By incorporating additional research methods into the analysis of forest cover changes, a more comprehensive and coherent result could be achieved, allowing for the comparison of data obtained through different methods.

Among Ukrainian researchers involved in studies of forest cover change using Earth remote sensing data, notable works include those by O.H. Chaskovskyy & H.H. Hrynyk (2020) and O. Barabash *et al.* (2021). In the study by O.H. Chaskovskyy & H.H. Hrynyk (2020), the GFW map and Sentinel-2 satellite data were utilized to assess forest loss in the Ukrainian Carpathians. The results confirmed the validity of employing various research methods for data comparison and detecting changes in forest cover caused by both logging and natural factors. In the research conducted by O. Barabash *et al.* (2021), the calculation of the normalised difference vegetation index (NDVI) using Landsat 5 and 8 satellite data was applied to track vegetation changes in the Chernobyl exclusion zone. An information system for analysing temporal vegetation changes over decades was developed in the article. The results of NDVI determinations based on Landsat 5 and Landsat 8 satellite image series for the summer periods of 2000, 2010, and 2020 in the Chernobyl exclusion zone were analysed. The research demonstrated that these methods are sufficiently effective for analysing the dynamics of vegetation status over time and allow for identifying overall positive-negative trends in vegetation cover change in the studied area.

Effective development of Earth remote sensing methods has also been facilitated by E. Lossou *et al.* (2019), C. Shang *et al.* (2020) and M.J. Faruque *et al.* (2022). In the study by C. Shang *et al.* (2020), effective forest mapping by attributes using remote sensing data was demonstrated. M.J. Faruque *et al.* (2022) assessed the dynamics of land use and land cover changes for the years 1990, 2000, 2010, and 2020. The analysis revealed a decrease in agricultural lands and an increase in aquaculture. Researchers E. Lossou *et al.* (2019) used optical remote sensing and spatial analysis methods to assess the condition of forest estates. The results of the study showed that forest reserves in the region, which were among the richest in terms of species diversity in high-altitude forests, had undergone significant degradation. The scientists concluded that the use of remote sensing and GIS to detect, quantitatively assess and explain changes in land cover types is effective. The high relevance and promising development prospects of earth remote sensing methods in forest studies were demonstrated by researchers E. Abad-Segura *et al.* (2020).

The Skole Beskydy National Nature Park (Skole Beskydy NNP) was established with the aim of preserving, restoring and sustainably using landscapes in the western part of the Ukrainian Carpathians, which contain typical and unique natural complexes of significant ecological, aesthetic, scientific, educational, recreational and health value (Decree of the President of Ukraine No. 157/99, 1999). Therefore, it is important to conduct scientific research on natural complexes and their changes under conditions of recreational use. The purpose of the study was to monitor the changes in the forest plantations within the Skole Beskydy NNP, to assess the forest loss in the area and to recommend the obtained images for the improvement of the forest management system.

Materials and Methods

The study was carried out as follows: obtaining and processing satellite data; performing segmentation and classification of the obtained images; calculating the NDVI and the normalized burn ratio (NBR); conducting an analysis of forest cover change using the online resource GFW; comparing data from different time periods based on NDVI calculations and GFW data; identifying changes in forest cover within the Skole Beskydy NNP during 2017-2022; assessing changes in forest cover within the Skole Beskydy NNP; based on the analysis results, recommending the obtained images for the possibility of responding to changes in forest cover. In order to obtain an up-to-date and dynamic analysis of forest cover changes, the study period from 2017 to 2022 was chosen.

The United States Geological Survey (USGS) website was used to obtain satellite images. The USGS Earth Explorer data portal was used to access a range of geospatial data. The Earth Explorer browser was used to download images from open archives, allowing the selection of images based on criteria such as scanner type, months of the year during the growing season, day or night capture, and maximum allowable cloud cover. This browser allows the selection of images for a specific area in vector format

(Longhenry *et al.*, 2011). The study used satellite imagery from the Landsat 8-9 satellite.

NDVI and NBR measurements were used to monitor disturbed areas. The NDVI is a standardised vegetation index based on satellite imagery that reflects green biomass. Green biomass absorbs electromagnetic waves in the visible red spectrum and reflects them in the near infrared spectrum. Chlorophyll absorbs solar radiation in the red spectrum (0.62-0.75 μm), while the reflection of energy by leaf cell structure occurs in the near infrared (0.75-1.3 μm). High photosynthetic activity results in low reflectance coefficients in the red spectrum and high coefficients in the near infrared. Comparing these values allows vegetation to be distinguished from other natural objects. The index is sensitive to changes in soil and atmospheric background, except in situations with limited vegetation.

The values of the NDVI range from -1.0 to 1.0. Negative values often indicate the presence of clouds, water bodies, or snow, while values close to zero indicate rocky terrain or bare soil. Very low NDVI values (0.1 and below) may indicate the presence of barren rocky areas, sand, or snow. Moderate values (from 0.2 to 0.3) suggest the presence of shrubs and grasslands, while high values (from 0.6 to 0.8) are characteristic of forests in temperate and tropical regions (Reszka & Fuentes, 2015). The formula for calculating the NDVI is as follows:

$$NDVI = \frac{(NIR-Red)}{(NIR+Red)}, \qquad (1)$$

where *NIR(B5)* is 760-900 nm, near-infrared spectral range; *Red(B4)* is 630-690 nm, visible red spectral range. NBR is used to detect areas affected by fire. The NBR formula includes indicators obtained from signals at wavelengths corresponding to both the near-infrared and shortwave infrared spectral ranges. Healthy vegetation is characterized by high reflectance in the near-infrared spectrum, while areas recently burned by fire are well distinguished in the shortwave infrared spectrum. During the calculation of this index, a raster image obtained using channels of the near-infrared and shortwave infrared spectral ranges is used. NBR values range from +1 to -1. Low NBR values (less than -0.66) indicate significant vegetation damage by fires. Values (-0.66 to -0.1) indicate moderate vegetation damage by fires. Values (-0.1 to 0.1) indicate areas with no vegetation. Values (0.1 to 0.3) correspond to areas with vegetation recovery. Values above 0.3 indicate the presence of vegetation (Alcaras *et al.*, 2022). The formula for the NBR index is:

$$NBR = \frac{(NIR-SWIR2)}{(NIR+SWIR2)}, \qquad (2)$$

where *NIR(B5)* is near-infrared spectral range; *SWIR2* is shortwave infrared spectral range, mid-infrared zone. The QGIS GIS platform was used. QGIS is a free cross-platform GIS. One of the most advanced directions in GIS development is the combination of GIS technologies and remote sensing data processing (Manson *et al.*, 2015). To analyse long-term changes in forest cover, the GFW Interactive world forest map (n.d.) was also used. GFW is an open-source web application designed for monitoring forest resources almost in real-time. The project is an initiative of the World Resources Institute in collaboration with the University of Maryland, Vizzuality, Google, Esri, U.S. Agency for International Development, and others. GFW provides the latest data, tools, and technologies for effective forest monitoring worldwide. The data in GFW are already classified and ready to use (Portillo-Quintero *et al.*, 2021). The platform allowed setting necessary criteria for information search and provided a detailed overview of the forest status in the selected area.

The tree cover loss indicator shows the annual loss of tree canopy, defined as the replacement of vegetation at stand level above 5 metres within the selected area. The indicator of tree cover gain is determined as woody vegetation taller than 5 metres, which can take the form of natural forests, woodlands or tree plantations within the canopy density range (Myronyuk & Bilous, 2017).

Results and Discussion

To analyse the overall condition and trends in forest cover dynamics, remote sensing technologies are often applied. Remote sensing data obtained from satellites can be used for monitoring and mapping land use and vegetation cover. Observing changes is most commonly done by using multispectral satellite images acquired at different times, based on which analysis and forecasting are conducted. The use of specific multispectral satellite images, combined with attribute information on the geospatial data of forested areas, forms the basis for remote sensing technology applications. The result of land monitoring is a cartographic image showing changes in land cover. The detected changes, recorded in different time satellite images, allow for an assessment of these changes. The images undergo digital processing and visual analysis. GIS based on remote sensing data allows for calculating areas and comparing changes over a selected period.

The study of forest cover in the Skole Beskydy NNP was carried out using remote sensing. The online platform of the USGS Earth Explorer data portal allows instant visualisation of satellite data from different satellites and data collections. The search function was used to identify the location of the study area, and the polygon tool was used to create a polygon layer around the study area. Based on the search results, one image was selected from each of the years 2017, 2018, 2019, 2021 and 2022 within the July and August. The selected image is from August 4, 2017 (Fig. 1). The selected satellite images were downloaded in the fourth (*B4*), fifth (*B5*), and seventh (*B7*) channels in tag image file format for further analysis. Satellite imagery was obtained from Landsat 8-9 OLi/TIRS Collection Level 1 data. In conducting geospatial analysis, open-source QGIS desktop GIS software was used to process prepared cartographic materials (Chaskovskyy *et al.*, 2021).

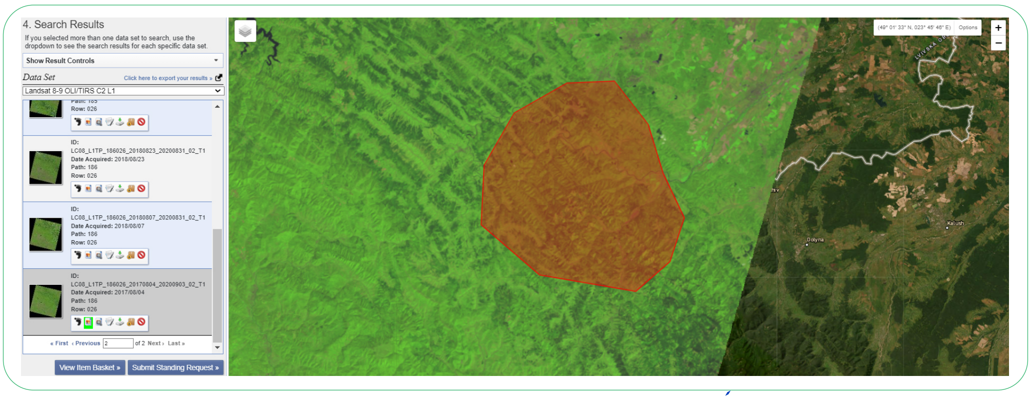

Figure 1. Satellite image dated August 4, 2017

Source: made by the authors

To determine changes in vegetation cover over a specific period, it was necessary to calculate the NDVI values in QGIS. The "Raster Calculator" tool was used to calculate the NDVI (Fig. 2). Subsequently, based on the basic OpenStreetMap Standard map, a vector layer outlining the territory of the Skole Beskydy NPP was created in shapefile format (Fig. 3).

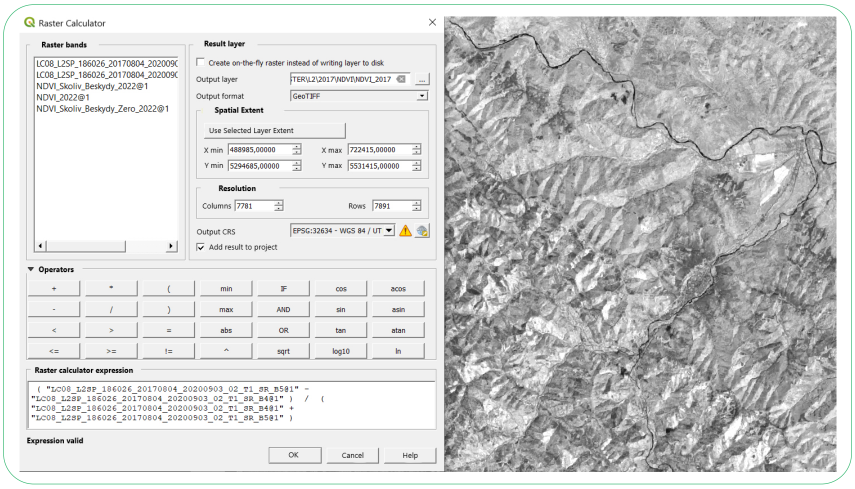

Figure 2. Calculation of the NDVI

Source: made by the authors

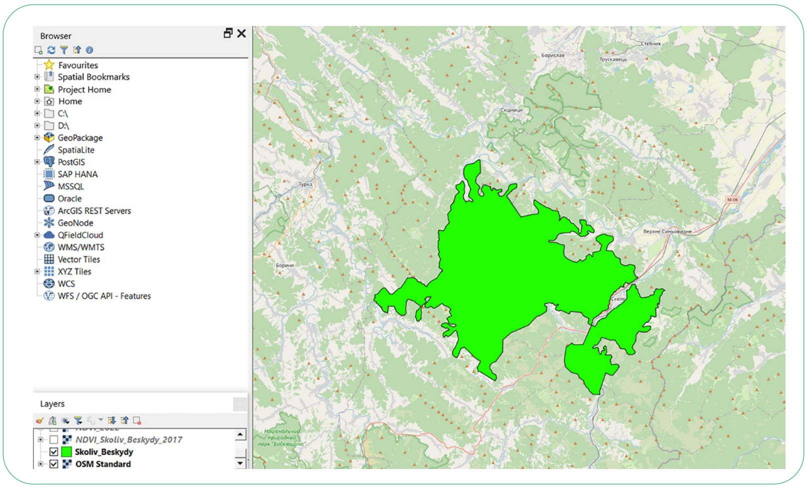

Figure 3. Vector layer of the Skole Beskydy NNP

Source: made by the authors

To conduct the analysis of satellite images within the territory of the Skole Beskydy NNP, a raster image was extracted based on the mask layer. The layer style was set for NDVI values ranging from < 0.2 to 0.9. Upon completing the settings, a ready raster layer within the Skole Beskydy NNP boundaries with the calculated NDVI was obtained (Fig. 4).

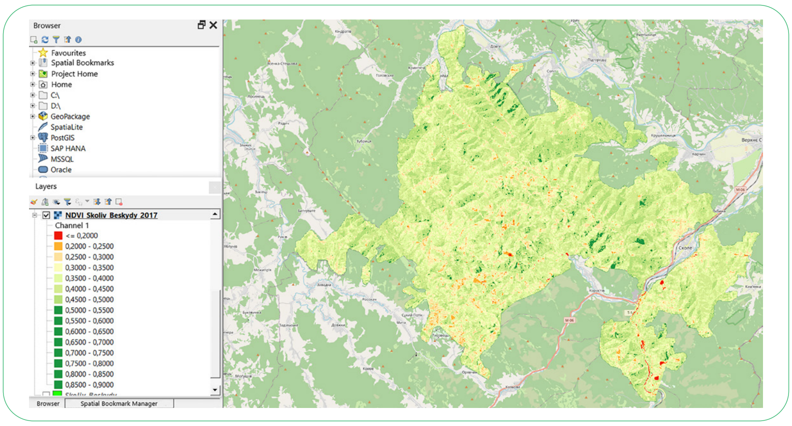

Figure 4. Raster layer of the Skole Beskydy NNP with the NDVI dated August 4, 2017
Source: made by the authors

The same actions were then repeated with the remaining satellite images. Ready raster layers were obtained for the period 2017-2022. On the maps, areas marked in red, corresponding to values < 0.2, indicate places with absent forest cover and areas dominated by shrubs and grasslands (0.2-0.3). The next step involved calculating the NBR index. Recently, the vegetation index NBR has gained special significance due to the increasing frequency of extreme weather events leading to fires and destruction of forest stands. NBR is widely used in forestry to detect fires, analyse fire intensity, and monitor vegetation surviving after a catastrophe. It reflects the spectral brightness curve of the index.

Detecting forest logging presents challenges in cases where logging occupies a small area or is selective. All disturbances to the forest cover (associated with both logging activities and natural factors) generally have similar spectral decoding characteristics. Partial or complete disturbance (removal) of forest cover results in a decrease in the reflection coefficient in the *NIR* zone of the spectrum, due to a decrease in chlorophyll content. At the same time, the reflection coefficient increases in the *SWIR* zone, attributed to the emergence of open soil areas. Additionally, logging sites experience an increase in the reflection coefficient in the visible range (in the red channel), as open soil reflects more solar radiation than tree canopies.

The images obtained from the Earth Explorer resource were downloaded into QGIS, and using the Raster Calculator tool, the NBR index was computed. Subsequently, similar to the process with the NDVI, the calculated raster images for the NBR index were cropped using the mask layer. The resulting layer with the calculated NBR index from August 23, 2018, is presented (Fig. 5). A comparison of the indicators of vegetation absence using the NDVI and NBR is shown in Figure 6.

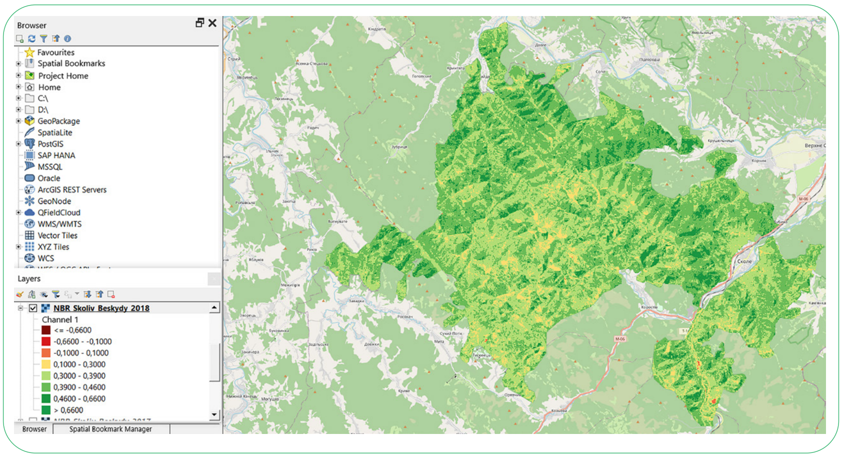

Figure 5. Raster layer of the Skole Beskydy NNP with the NBR index dated August 23, 2018
Source: made by the authors

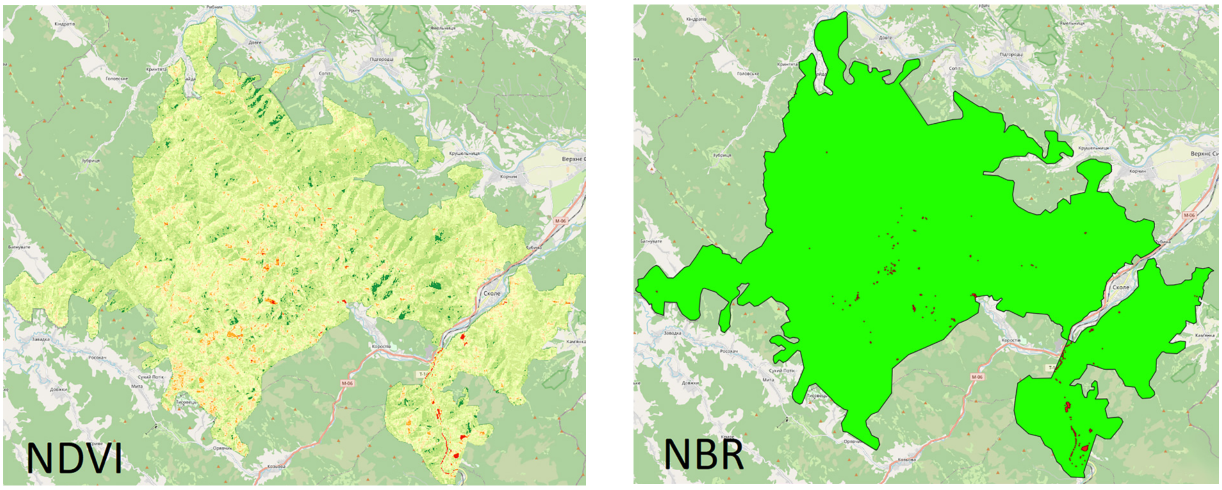

Figure 6. Comparison of vegetation absence using NDVI and NBR indices dated August 4, 2017
Source: made by the authors

Visual analysis of the comparison between the results of analysis using NDVI and NBR indices showed a similarity in the areas with absent forest cover. Figure 7 depicts the result of the statistical report within the period of 2017-2022.

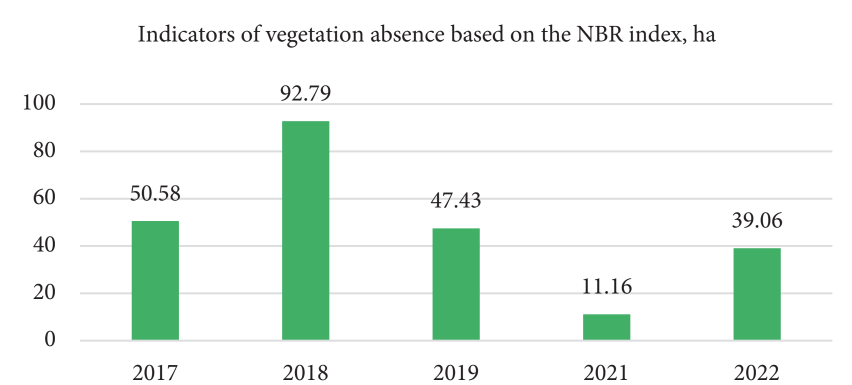

Figure 7. Diagram of areas with absent vegetation cover based on the calculation of the NBR index results
Source: made by the authors

Also, for the analysis of changes in forest cover, GFW was used. The data obtained on the GFW website are widely used in global forest research by leading scientists and represent significant progress in monitoring forest resources. With GFW, the following data can be obtained: the area of forests in the selected area; the area of forest loss, their dynamics over the years, and their spatial representation on the map (for some regions and reasons); the area of new plantations and their representation on the map; tracking of forest fires and their consequences; forest composition by species; the ability to view protected areas with clear boundaries; tree biomass density; key climate indicators (e.g., carbon dioxide emissions from forest loss) and others. This resource contains both forest loss and forest gain maps for the years 2001 to 2022. On the website, users can select or download a file with the area of interest for analysis and map presentation. Users can also specify the years in which these losses or gains occurred. Forest loss includes changes in both natural and planted forests and is not necessarily caused by humans. All these indicators are dynamic and have been tracked since 2000 and updated almost in real-time. A similar analysis has been conducted for the area of Skole Beskydy NNP protected landscape area. Maps displaying forest loss during the observation period from 2017 to 2022 were utilized in the study. Moreover, maps with a canopy cover exceeding 30% were chosen for comparison. Figure 8 displays the occurrence of forest loss during the year 2017 in Skole Beskydy NNP. According to the analysis, the forest loss in 2017 is approximately 55 hectares. Based on the research results, a map of total forest loss for the period 2017-2022 has been created (Fig. 9).

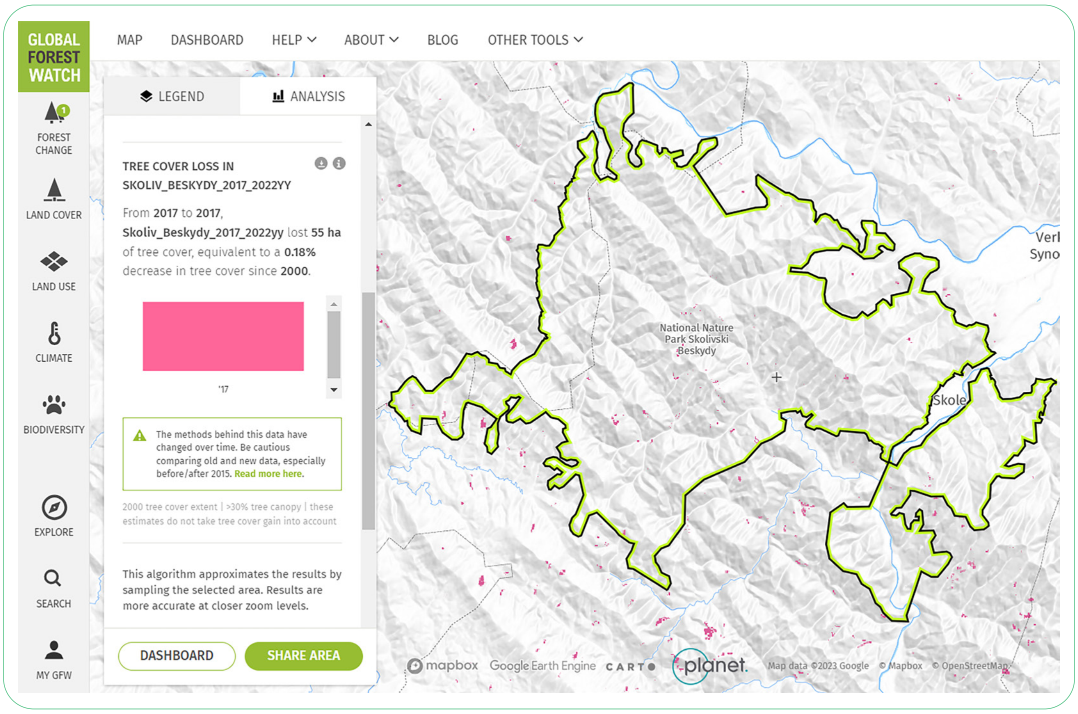

Figure 8. Map of forest loss in the Skole Beskydy NNP in 2017

Source: made by the authors

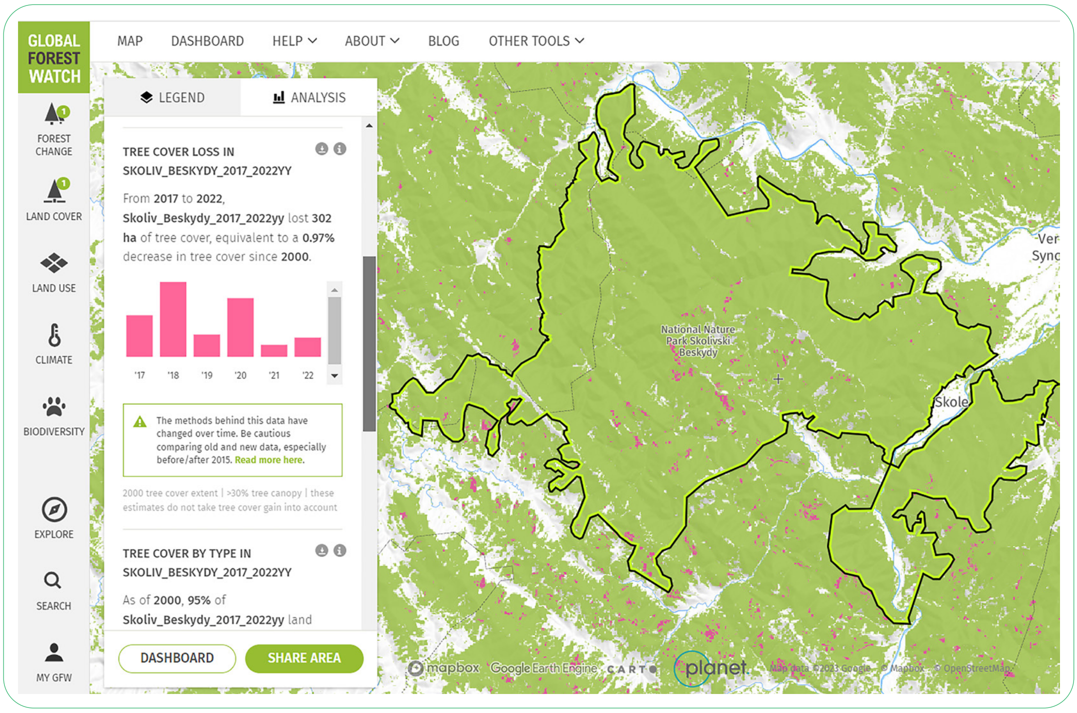

Figure 9. Map of cumulative forest loss in the Skole Beskydy NNP with representation of existing forest cover in the period from 2017 to 2022

Source: made by the authors

From 2017 to 2022, forest losses amounted to approximately 302 ha, which corresponds to a decrease in forest cover of 0.97% since 2000. According to the analytical data downloaded from the GFW website, forest losses in the Skole Beskydy NNP during the period 2017-2022 are shown in Figure 10. Forest cover losses, including those due to fires in the Skole Beskydy NNP, are shown in Figure 11.

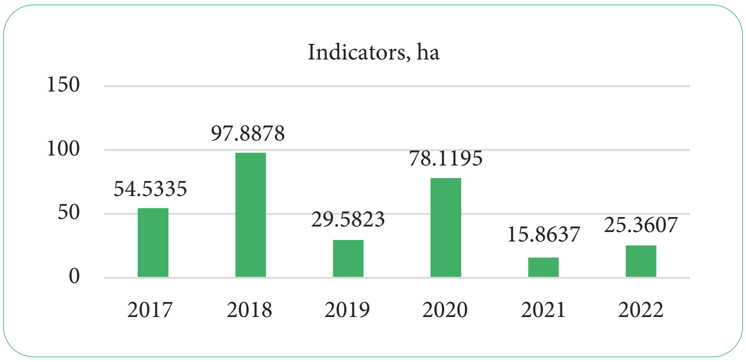

Figure 10. Diagram of forest loss within the Skole Beskydy NNP from 2017 to 2022
Source: made by the authors

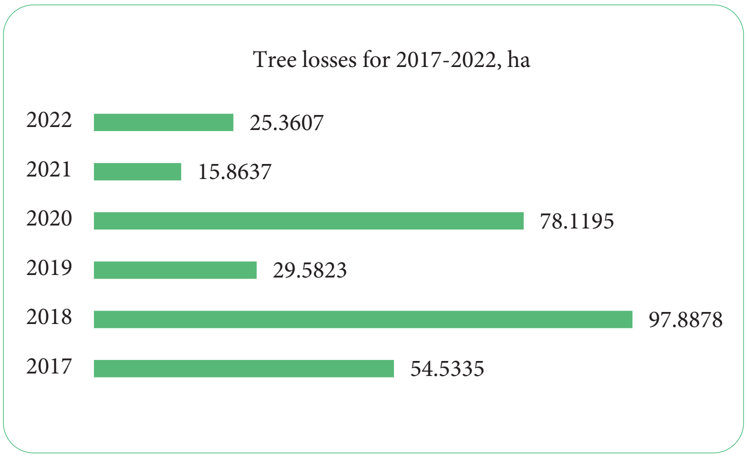

Figure 11. Diagram of forest loss with the indicator of losses from fires from 2017 to 2022
Source: made by the authors

According to the analysis, it is evident that the proportion of forest loss due to fires was highest in 2020 (0.6089 hectares), accounting for 0.77% of the total forest loss in that year. The overall forest loss during the period from 2017 to 2022 amounts to 301.3475 hectares, with 0.8633 hectares attributed to fires, representing 0.0029% of the total share. Due to differences in research methodology, it is not possible to directly compare forest loss estimates from the GFW maps with the results of calculating vegetation absence using the NBR index. However, it is possible to make relative comparisons to understand the overall trend in forest cover changes. The results obtained from the GFW maps represent the loss of tree cover (loss of vegetation at the level of stands of more than 5 metres). On the other hand, the results of the analysis using the NBR index provide an assessment for only one satellite image on a specific date and reflect both absent vegetation and some recovering vegetation. A comparison of vegetation absence according to the NBR index with forest loss results from the GFW website is shown in Figure 12.

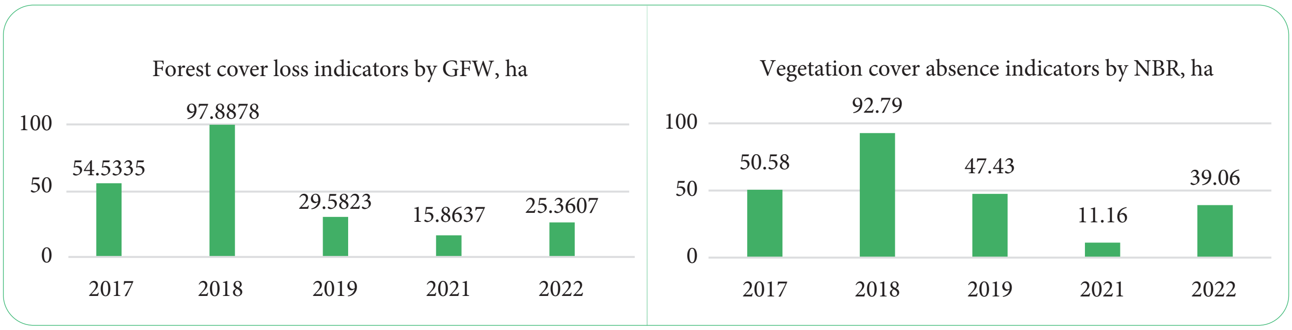

Figure 12. Comparison of diagrams showing the dynamics of forest cover changes based on GFW maps and the NBR index
Source: made by the authors

As shown in Figure 12, the forest loss indicators from GFW for 2017-2022 differ slightly from the calculated NBR index values, but the trend of change dynamics is similar. Determining forest loss using vegetation index analysis becomes challenging when deforestation is small scale or selective. The results obtained from the GFW data can be considered more accurate due to the use of multispectral satellite imagery from the Landsat 5 Thematic Mapper, Landsat 7 Thematic Mapper plus and Landsat 8 Operational Land Imager sensors. The data were processed and analysed on the basis of a large number of satellite images (Shimizu *et al.*, 2020). Observations of the clear land surface in the satellite images were collected and a controlled algorithm was applied to identify tree cover loss at the pixel level. To provide a broader perspective on the dynamics of forest loss and gain within the Skole Beskydy NNP, data for a longer period were analysed. Using data from the GFW resource, which allows for the analysis of forest loss from 2001 to 2022 and tree cover gain from 2000 to 2020, Figure 13 was created.

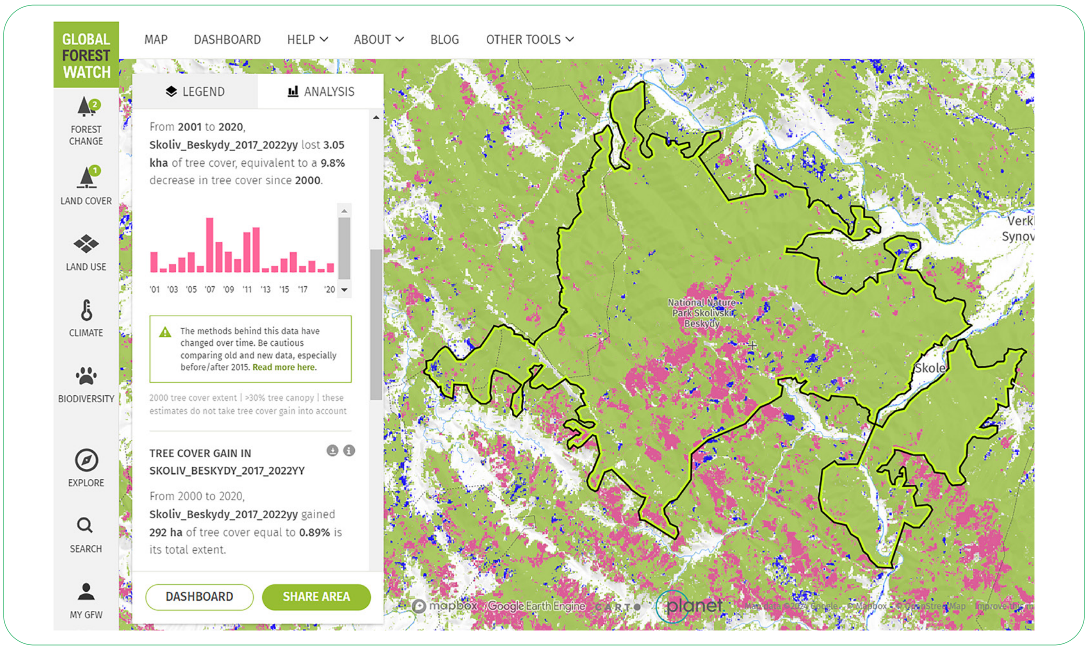

Figure 13. Forest loss and gain from the GFW website

Source: made by the authors

At the time of the study, the resource allowed analysis of forest loss up to and including 2022. However, information on forest cover gain is only available up to 2020. Therefore, to obtain a comprehensive and accurate comparative map of forest loss and gain, data up to 2020 were used. The image shows the changes that have occurred: pink dots represent tree loss from 2001 to 2020, while blue dots represent forest gain from 2000 to 2020. From 2001 to 2020, the Skole Beskydy NNP lost 3.05 thousand hectares of tree cover, which is a decrease of 9.8% since 2000. From 2000 to 2020, the Skole Beskydy NNP will gain 292 hectares of tree cover, which is 0.89% of its total area.

The use of vegetation indices allows for obtaining data on changes in forest cover caused by fires and other factors. This is corroborated by researchers M. Mishkin & J.A. Navarrete Pacheco (2022), who indicate in their study the effectiveness of remote sensing combined with GIS for the management and conservation of natural resources. Studies conducted in reserves have shown that rapid assessments of forest loss, combined with field studies, can lead to more effective interventions in crisis areas. Analysing the dynamics of forest change can provide accurate identification of focal areas for further intervention in forest conservation and management strategies. The analysis conducted using the NDVI has proven useful for characterizing vegetation cover and obtaining cartographic products essential for forest monitoring and detecting changes in forests. Similar conclusions were reached by researchers G.L. Spadoni *et al.* (2020). In their work, scientists created raster forest maps for the territory of Italy using remote sensing methods. Specifically, Sentinel-2 multispectral images were used to obtain NDVI values.

The NBR index also proved effective in determining forest loss within the study area. Visual analysis of images without vegetation cover using both NDVI and NBR indices confirmed the similarity of results in areas without forest cover. In the study by T. Kartika *et al.* (2019), NBR was used to detect forest loss in Riau province. The research results showed that the analysis of forest cover changes using the NBR index provides good results, and the information obtained can be used to detect deforestation, among other purposes. O. Soshenskyi *et al.* (2022) investigated the extent of forest damage caused by forest fires in the Luhansk Region. The scientists used a slightly different methodology, namely different indices – the Composite Burn Index and the Geometrically Structured Composite Burn Index. The authors of the study confirmed the effectiveness of remote sensing data, particularly in cases where it is necessary to map the effects of fires. However, they found that the Composite Burn Index is not always suitable for use, as it can overestimate the level of fire danger.

An important and effective tool for studying the state of forests is the use of the GFW online platform. Inaccurate information about forest resources can hinder forest conservation, restoration efforts, and sustainable management. Remote sensing methods have become key tools for monitoring forest cover. The GFW dataset, as an interactive remote sensing product, is currently used by more than 2 million users, including researchers, conservationists, and local communities, to analyse changes in forest cover. Therefore, understanding the accuracy of the GFW dataset is crucial. Researchers D. Zhang *et al.* (2020) conducted a study on assessing the accuracy of the global forest cover in 2000 in China. The study validated the dataset using a simplified procedure of visual interpretation with the aid of high-resolution optical images in Google Earth to map uncertainties and inaccuracies in the GFW Tree Cover 2000 data in China. They then estimated the forest area in China after considering the data uncertainties and compared these findings with data from China's National Forest Inventory Report to elucidate where and how inventory based on ground data differs from remote sensing data based on presence or absence. The results showed that the overall accuracy of the GFW Tree Cover 2000 data was 94.5%, indicating the high accuracy of the GFW resource data.

Comparative analysis of results from the NBR index and GFW data showed a similar trend in the dynamics of change. A comprehensive approach to analysing changes in forest cover proved to be effective in identifying new areas of absence of vegetation. The production of maps based on GFW data with absent forest cover can be useful for forest protection and improvement of forest management systems. This is supported by research by K. Shea (2022) which measured the impact of forest monitoring. Both qualitative and quantitative analyses provided compelling evidence that the GFW resource contributes to reducing deforestation. The thematic research findings confirmed the evidence from the quantitative assessments and identified specific user groups that were using the tools to directly or indirectly reduce deforestation. There was evidence that the data facilitated increased awareness and decision-making to improve enabling conditions. In Cameroon, for example, the government used the data to inform decisions on forest tenure and management planning. In Uganda, the National Forestry Authority regularly reviewed the data to monitor forest management. Staff of the Uganda Wildlife Authority used GFW data to plan ranger routes for forest patrols, while in Cameroon civil society used it for independent monitoring and reporting of illegal activities.

Thus, the obtained results from GFW data in the form of forest loss maps can be recommended for further study of the state of forest resources within the Skole Beskydy NNP and for monitoring illegal logging activities, as it can be concluded that the main part of the forest loss is attributed to anthropogenic factors. A series of images depicting forest loss over the years is shown in Figure 14.

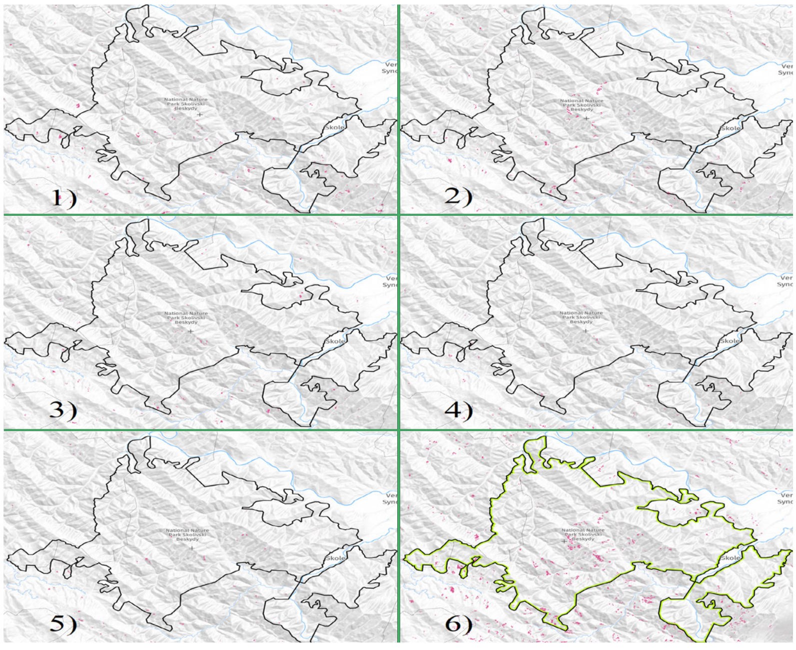

Figure 14. Recommended forest cover loss snapshots based on GFW data

Note: 1 – 2017; 2 – 2018; 3 – 2019; 4 – 2020; 5 – 2021; 6 – 2017-2022

Source: made by the authors

The analysis results from open data sources, acquired series of images, can be utilized in further studies of this area and compared with ground-based data. It is believed that optimal results can be achieved through the integrated use of both satellite and ground research. This implies that ground-acquired data can be used for satellite image analysis, and satellite observation results can serve as a basis for conducting ground-based field studies. Additionally, the data from image series can be employed within the framework of public monitoring and for real-time forest cover change response capabilities.

Conclusions

The application of selected remote sensing methods allowed the assessment of forest cover changes in the Skole Beskydy NNP. Satellite imagery, vegetation index analysis and information from the GFW resource were used to observe changes in forest cover and to identify both natural and anthropogenic influences on these changes. According to the data obtained, the largest forest loss due to fires occurred in 2020 (0.6089 ha), accounting for 0.77% of the total forest loss in that year. The total forest loss from 2017 to 2022 was 301.3475 ha, of which 0.8633 ha was due to fires, representing 0.0029% of the total. In the period from 2001 to 2020, the Skole Beskydy NNP lost 3.05 thousand ha of forest cover, which is a decrease of 9.8% since 2000. In addition, the forest cover increased by 292 ha between 2000 and 2020, which represents 0.89% of the total area of the park. The results of the analysis indicate a low level of forest loss due to natural factors, in particular losses due to fires. The primary cause of deforestation is linked to human activities.

Detecting changes in forest cover can often be a challenging task, especially in large and inaccessible areas. Tools to detect changes in such areas require a comprehensive approach. The use of remote sensing techniques is becoming an effective means of monitoring changes in forest cover, as they allow rapid detection of changes with minimal resource expenditure. The analysis of selected remote sensing methods combined with GIS also confirms their effectiveness in monitoring long-term changes in forests and comparing their dynamics. Research confirms that the relevance and prospects of using these methods to conserve forests and improve their management systems increase over time. Monitoring of forests within national parks is important in the context of their recreational use. Therefore, further research should continue to monitor and analyse changes in forest cover in other Ukrainian National Nature Parks.

Acknowledgements

None.

Conflict of Interest

None.

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Динаміка зміни лісових насаджень на території національного природного парку «Сколівські Бескиди»

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Анотація. Актуальність дослідження обумовлена проблемою оцінки стану та використання лісового покриву на території Національного природного парку «Сколівські Бескиди», необхідністю розробки ефективних методів моніторингу та збереження лісових екосистем. Метою дослідження було вивчення динаміки зміни лісових покривів у межах Національного природного парку «Сколівські Бескиди», а також оцінка втрат лісових ресурсів на цій території та рекомендування отриманої серії знімків для покращення системи управління лісокористуванням. Дослідження проведено з використанням комплексного підходу й комбінації різних методів дослідження змін лісового покриву та їх порівняння. Основою для застосування технологій дистанційного зондування було використання специфічних мультиспектральних супутникових знімків, які комбінувалися з атрибутивною інформацією щодо геопросторових даних про лісові угіддя. Продемонстровано найпрогресивніші методи дослідження змін лісових насаджень на основі даних дистанційного зондування з використанням геоінформаційних систем. Отримання супутникових знімків відбувалося з набору геопросторових даних супутника «Landsat 8» за допомогою порталу даних Геологічної служби США. Виконано розрахунок та порівняння нормалізованого коефіцієнта вигорання та нормалізованого диференційного вегетаційного індексу. Також був проведений аналіз із використанням онлайн ресурсу «Global Forest Watch». У результаті дослідження було виявлено зміни лісового покриву, надано оцінку змінам, розроблено карту відображення змін лісу, які відбулися в Національному природному парку «Сколівські Бескиди» за 2000-2020 роки. За результатами проведеного аналізу встановлено низький рівень втрат лісових насаджень у зв'язку з природними факторами, зокрема втрат від пожеж. Основна частина втрат лісів зумовлена антропогенними факторами. Практичне значення результатів полягає в можливості використання отриманої серії знімків у межах громадського контролю та покращення системи лісокористування

Ключові слова: супутникові знімки; супутник; вегетаційний індекс; втрати лісів; приріст лісів; покрив дерев

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Assessment of the environmental state of tourist resources in the Ivano-Frankivsk Region

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Abstract. In view of the rapid growth of the impact of tourism on the world economy, as well as the environmental problems that it can create, the assessment of the environmental state of the tourism sector is becoming particularly relevant. The purpose of the study was to analyse the ecological state of the Ivano-Frankivsk Region and its impact on the attractiveness of the region for tourists, as well as to develop proposals for the sustainable development of tourism, taking into account environmental aspects. In the framework of the study, various methods were used, in particular, statistical analysis of data on pollutant emissions. The impact of industry and other industries on the environmental condition was analysed and assessed using the analysis method. The dynamics of atmospheric emissions by years and their impact on the ecological state of the region were analysed, with a special emphasis on pollution by sulphur dioxide and other compounds. In addition to atmospheric emissions, the issue of the discharge of pollutants into water bodies and the impact on water quality, which is important for the development of tourism, was considered. It was established that emissions of pollutants significantly affect the quality of atmospheric air, which, in turn, determines the tourist potential of the region, especially in the context of the development of ecological tourism. The need to implement measures to reduce the level of pollution, develop sustainable tourism, and implement environmental standards in the tourism industry is emphasized. Ways to improve the ecology of the region have been established and appropriate proposals have been made, including reducing emissions of pollutants, as well as the use of innovative technologies and approaches in the field of environmental safety and ensuring the sustainable development of tourism in the Ivano-Frankivsk Region. The practical value of the research consists in identifying specific directions for improving the environmental policy of the region, which require practical implementation to improve the environmental condition of Ivano-Frankivsk Region, emphasizing the importance of an integrated approach in solving environmental challengess

Keywords: environmental challenges; industry safety; industrial impact; atmospheric air quality; sustainable use of natural resources

Introduction

In the context of the rapid development of tourism, the environmental aspect is becoming increasingly important and relevant for research. Tourism, being one of the most dynamic sectors of the global economy, has a significant impact on the natural environment. The anthropogenic impact of tourism on the ecological state of the Ivano-Frankivsk Region is particularly noticeable through environmental pollution. Intensification of tourism activities leads to an increase in emissions from vehicles, which is a significant source of air pollution. Such pollution affects not only the quality of the air but also the overall health of the local population and visitors. The intensive use of

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water resources and their pollution by waste from tourism activities jeopardizes the quality of water bodies in the region. Pollution of rivers, lakes, and other water bodies can negatively affect aquatic flora and fauna, and limit opportunities for water tourism and recreation. Another important aspect is soil pollution resulting from tourism activities. For example, emissions from campsites and other tourist facilities, uncontrolled waste disposal, and excessive use of fertilizers in agriculture can lead to soil degradation. Significant use of forest resources for tourism purposes will also contribute to the region's environmental problems. Deforestation to create tourist infrastructure and firewood for campsites reduces forest areas and affects biodiversity.

Considering the range of scientific works on the environmental assessment of tourism resources, the study by N.E. Pankiv (2019) deserves special attention. The researcher focused on the use of tourist and recreational resources in the region, with an emphasis on the development of green and ecological tourism. She conducted an in-depth analysis of ecological routes, including ecological and educational trails in the region's national parks, highlighting their role in tourism development and emphasizing the importance of integrating environmental, cultural, and economic aspects into tourism development strategies. Scientists I. Dubovich *et al.* (2021) focused on analysing the impact of mass forms of tourist and recreational activities on the natural environment of the Ukrainian Carpathians. They found that the intensive development of tourism in this region leads to a significant use of natural resources and a decrease in environmental quality, compared to places where tourism is developing in a controlled or balanced manner. The authors paid attention to the environmental aspects of ecotourism initiatives, emphasizing the need to develop sustainable tourism. They conducted a SWOT (strengths, weaknesses, opportunities, and threats) analysis for national parks and the Carpathian Forest Fund, which includes reducing the negative impact of tourism and recreation activities and encouraging environmentally responsible practices.

The study by M. Gedin (2021) is also a significant contribution to understanding the methodology for assessing Ukraine's tourism potential, with a focus on the factors that affect competitiveness in the tourism industry. The author analyses a wide range of determining factors, including historical and cultural heritage, natural and recreational conditions, infrastructure, finance, investment, governance, social and environmental aspects. The researcher also proposes innovative tools for assessing tourism and recreational potential, including an assessment of the attractiveness of regions and the impact of this sector on the economy. The author emphasizes the importance of an integrated approach to assessment and development of criteria for effective determination of the resource potential of tourist areas. M. Lazutkin *et al.* (2022) conducted a study to assess the ecosystem in the most polluted regions of Ukraine. The authors examine the impact of external factors and risks on production facilities and the environmental situation, which is critical to understanding environmental safety in the region, emphasizing the need for in-depth analysis to ensure environmental sustainability.

In the context of international initiatives and standards, such as the United Nations Environment Programme and ISO 14000, as described by A. Dayankac (2022), as well as in the light of Ukrainian legislation on environmental protection, there is an obvious gap in research related to the development of the environmental aspect in the tourism industry. This situation calls for greater attention to the study and implementation of environmental practices in tourism, which involves the integration of a sustainable approach not only at the level of policy and management but also in the practical implementation of tourism services. Solving this problem requires an integrated approach, including an assessment of the environmental impact of tourism facilities and activities, as well as the development of innovative solutions aimed at minimizing the negative impact on the environment.

In assessing the environmental status of the Ivano-Frankivsk Region's tourism resources, special attention should be paid to analysing the impact of tourism activities on various aspects of the region's ecology. It is important to consider not only direct environmental pollution but also broader environmental impacts, such as changes in biodiversity and landscape alteration. Such a comprehensive approach will help to develop effective mechanisms to minimize the negative impact of tourism on the natural environment, as well as to ensure the sustainable development of the region's tourism sector. Therefore, the purpose of the study was to analyse the environmental state of the Ivano-Frankivsk Region and, on its basis, to further develop directions for sustainable tourism development. Thus, the main objective of the study was to conduct an in-depth analysis of the environmental situation in the Ivano-Frankivsk Region to identify key environmental issues and challenges that affect the development of the region's tourism industry. Based on the data obtained, it was planned to develop strategic directions for sustainable tourism development that would take into account environmental, social and economic aspects in order to achieve a balance between the needs of the tourism industry and the preservation of the natural environment for future generations.

Materials and Methods

The study used a comprehensive approach, including an analysis of data on the environmental situation in Ivano-Frankivsk Region, including the volume of air pollutant emissions and their impact on air quality, as well as an analysis of the region's water resources, land use, and soil resources. The study was based on official statistics from the Main Department of Statistics and the Ivano-Frankivsk Regional State Administration. The statistical data used included information on pollutant emissions, wastewater discharges, and other aspects that directly affect the environmental situation in the region. The use of official data ensured the high reliability and relevance of the information, which is critical for an objective assessment of the environmental situation. A detailed analysis of scientific literature, reports, articles, and other publications related to the research topic was conducted. The analysed sources included the Regional Report on the State of the Environment in Ivano-Frankivsk Region and publications by well-known scientists in the field of tourism and ecology. The application of impact assessment methods, including the calculation of the percentage of emissions by pollution sources and the assessment of the dynamics of changes, made it possible to assess the effectiveness of existing environmental protection measures and identify gaps in the region's environmental policy and to identify the largest pollutants that lead to surface water pollution.

Air pollutant emissions were calculated. The calculation methodology is based on a comparison of annual emissions for the period from 2017 to 2021, with an emphasis on changes in emissions and their structure. This approach allows identifying trends and dynamics of changes in atmospheric emissions, which are critical for assessing the environmental status of the Ivano-Frankivsk Region. For the calculations, 2021 data (Ivano-Frankivsk Regional State Administration, 2022) was used because the lack of information on mobile sources of pollution for 2022 (Ivano-Frankivsk Regional State Administration, 2023) significantly limits the ability to comprehensively understand the anthropogenic impact on the air. Mobile sources, in particular road transport, are significant polluters in many regions, so their contribution must be identified to adequately assess the environmental situation. Also, analysing data for only one year does not allow for the identification of trends and dynamics of environmental change. Whereas, the data for 2021 includes information on both stationary and mobile sources, which provides an opportunity for comparative analysis and determination of the effectiveness of pollution reduction measures. The formula for calculating the percentage share is as follows:

$$\begin{gathered}\text{Percentage share} = \\ = (\text{Emissions from the source} / \text{Total emissions}) \cdot 100 = \\ \text{Percentage share (Total emissions} / \\ / \text{Emissions from the source)} \cdot 100.\end{gathered} \tag{1}$$

An in-depth study of scientific publications, reports, articles, and other information resources related to ecology and tourism played a crucial role in shaping the theoretical framework of the study, which in turn helped not only to collect information on current trends and challenges but also to identify successful practices and recommendations that can be adapted and implemented in Ivano-Frankivsk Region. The comparison method allowed accessing the environmental state of the Ivano-Frankivsk Region over different periods of time. The comparison method was used to analyse the dynamics of changes in pollution levels, water resources, air quality, land use, and other environmentally significant indicators. The comparison was made based on official data collected from the Main Department of Statistics, Ivano-Frankivsk Regional State Administration, and other reliable sources. Thus, the application of impact assessment, analysis, statistical analysis, and comparison methods was an important step in determining the degree of air, water, and land pollution from economic activities. The analysis of the percentage of emissions by the source of pollution, as well as the assessment of the dynamics of these indicators over time, made it possible to identify the main sources of environmental burden, which helped to identify priority areas for the implementation of measures aimed at reducing environmental impact and creating more favourable conditions for tourism development. The involvement of a wide range of information sources and the use of various methods allowed identifying key issues and develop sound recommendations that can contribute to the sustainable development of the tourism industry in the Ivano-Frankivsk Region.

Results

Ecology and tourism are closely interconnected, especially in regions with significant natural resources, such as the Ivano-Frankivsk Region. Sustainable development of tourism in this region requires taking into account environmental challenges and ensuring a balance between meeting the needs of tourists and preserving the natural environment. The ecological condition of tourism resources affects the quality of the tourist experience and contributes to attracting visitors. Air quality is an important aspect in this context, as it directly affects the health and well-being of tourists, as well as the preservation of natural landscapes and biodiversity in the region. Among the most important factors affecting the environmental state of the Ivano-Frankivsk Region is a significant increase in air pollutant emissions. According to 2021 data, total emissions in the region reached 210.3 thousand tons (kt), of which 172.4 kt are from stationary sources of pollution, and 37.9 kt are from mobile sources, mainly road transport (Ivano-Frankivsk Regional State Administration, 2022).

The analysis of industrial pollution sources confirms that the main share of pollutant emissions in the region is accounted for by energy sector enterprises, in particular, electricity, gas, steam, and air conditioning, which account for 89.1% of the total regional volume. The Burshtyn Thermal Power Plant of DTEK Zakhidenergo (Burshtyn TPP of DTEK Zakhidenergo) has the greatest impact on air pollution, accounting for 84.4% of total regional emissions. Emissions from this enterprise increased by 24.4% in 2021, amounting to 145.6 kt (Ivano-Frankivsk Regional State Administration, 2022). This increase in emissions has important implications for the environmental situation in Ivano-Frankivsk Region, particularly in terms of air quality. This not only reduces the aesthetic and recreational attractiveness of the region but also poses a direct threat to the health of tourists and the local population.

According to the latest official data released by the Main Department of Statistics, there has been a significant increase in pollutant emissions (Ivano-Frankivsk Regional State Administration, 2023). Among them, dioxide and other sulphur compounds stand out, with a total volume of 104,884.9 tons (t). This demonstrates the uneven impact of industrial pollution on different districts of the region, with the highest figures in the Ivano-Frankivsk District – 103,487.9 t, in contrast to the Kosiv District, where no sulphur dioxide emissions were recorded (Table 1).

Table 1. Dynamics of air emissions in Ivano-Frankivsk Region, kt

Years	Air emissions			Emissions density per 1 km², t	Emissions per person, kg
	Total	Including			
		Stationary sources	Mobile sources		
2017	198.3	198.3	-	14.2	143.8
2018	221.4	221.4	-	15.9	161.0
2019	205.02	205.02	-	14.7	149.6
2020	178.1	140.4	37.7		-
2021	210.3	172.4	37.9	-	-
2022	152.3	152.3	-	-	-

Source: made by the author based on Ivano-Frankivsk Regional State Administration (2022; 2023)

Thus, as can be seen from Table 1, in 2017, the volume of emissions was recorded at 198.3 kt, which indicates a significant burden on the ecological system due to the activities of stationary sources of pollution. The emission density indicator was 14.2 t per square kilometre, and the estimated emissions per person were 143.8 kg, demonstrating a high level of anthropogenic impact. In the following year, 2018, there was an increase in total emissions to 221.4 kt, which may be due to an increase in industrial production and insufficient effectiveness of emission control measures. The emission density increased to 15.9 t per square kilometre, and emissions per person reached 161 kg, indicating a further deterioration in the environmental situation.

In 2019, there was a slight decrease in emissions to 205.02 kt, which may be the result of the implementation of certain environmental measures and production optimization. The emission density decreased to 14.7 t per square kilometre, and the level of emissions per person decreased to 149.6 kg. In 2020, a significant decrease in total emissions was recorded to 178.1 kt, which was likely due to a decrease in economic activity as a result of the COVID-19 pandemic. For the first time, emissions from mobile sources amounted to 37.7 kt, emphasizing the importance of controlling emissions from road transport. 2021 is characterized by another increase in emissions to 210.3 kt, of which 172.4 kt are from stationary sources and 37.9 kt from mobile sources. This growth can be interpreted as the restoration of production capacity after a period of restrictions. However, 2022 showed a noticeable decrease in emissions to 152.3 kt, which may indicate the successful implementation of environmental measures and strategies aimed at reducing pollutant emissions, as well as a change in the structure of the region's economy towards more environmentally sustainable development. The dynamics of air emissions is shown in Figure 1.

Thus, fluctuations in pollutant emissions have a direct impact on the environmental status of the region's tourism resources. A significant increase in emissions in 2021 indicates the need to strengthen pollution control measures and develop sustainable tourism. Table 2 shows detailed information on emissions of certain pollutants by stationary sources of pollution by districts.

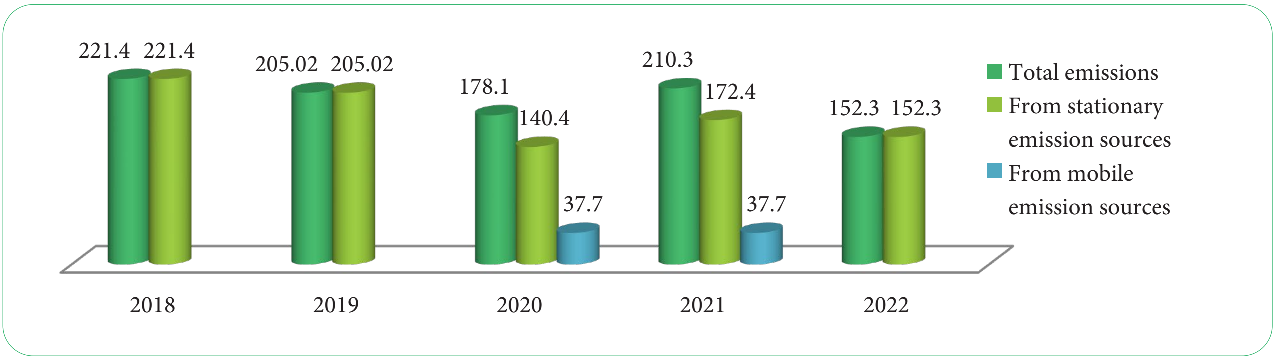

Figure 1. Dynamics of air emissions in Ivano-Frankivsk Region for 2018-2022, kt
Source: compiled by the author based on data from Ivano-Frankivsk Regional State Administration (2023)

Table 2. Emissions of certain pollutants into the atmosphere by stationary sources of pollution by regions, 2022

	Pollutant emissions in total	Including						
		Dioxide and other sulphur compounds	Nitrogen compounds	Methane	Carbon oxide	Substances in the form of suspended solids	Non-methane volatile organic compounds	Additionally, carbon dioxide emissions, kt
Region	152,259.2	104,884.9	12,817.8	6,381.5	2,880.8	20,537.3	4,626.2	10,044.8
Verkhovyna	6.1	2.1	0.9	-	3.1	0.0	-	-
Ivano-Frankivsk	139,244.4	103,487.9	11,151.0	2,220.9	1,413.5	19,429.3	1,477.1	9,559.7
Kalush	8,688.0	1,360.2	1,099.0	2,028.1	1,062.9	962.4	2,112.0	410.0
Kolomyia	322.3	5.4	66.9	32.6	134.0	67.4	15.3	11.8
Kosiv	214.8	0.0	34.4	136.6	22.4	0.0	21.4	5.1
Nadvirna	3,783.6	29.3	465.6	1,963.3	244.9	78.2	1,000.4	58.2

Source: made by the author based on Ivano-Frankivsk Regional State Administration (2023)

Analysing the statistical data for 2022 on emissions of certain pollutants into the air by stationary sources of pollution in the districts of the Ivano-Frankivsk Region, it can be stated that the total amount of emissions amounted to 152,259.2 t. Among this volume, the dominant pollutants are sulphur dioxide and other sulphur compounds with a value of 104,884.9 t, which emphasizes their significant role in shaping the environmental load on the region's atmosphere. Nitrogen compounds, with a volume of 12,817.8 t, and methane, with an indicator of 6,381.5 t, also have a significant impact on air quality. Emissions of carbon monoxide and suspended particulate matter amounted to 2,880.8 and 20,537.3 t, respectively, indicating their presence as pollution factors. Non-methane volatile organic compounds and carbon dioxide, with volumes of 4,626.2 and 10,044.8 t, respectively, complement the picture of anthropogenic impact on the region's atmosphere. There is a significant territorial heterogeneity in the distribution of emissions. Ivano-Frankivsk District makes the largest contribution to total emissions with 139,244.4 t. Kalush District with 8,688.0 t of emissions is also a significant source of pollution, in particular through industrial enterprises (Fig. 2).

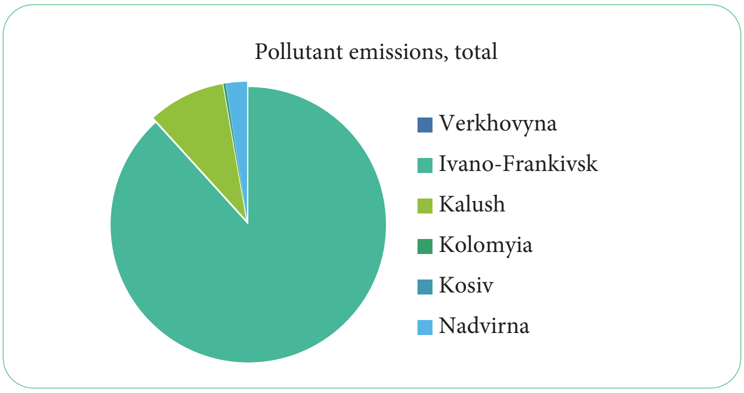

Figure 2. Structure of the ratio of pollutant emissions in Ivano-Frankivsk Region, 2022
Source: made by the authors

The high emissions of pollutants in Ivano-Frankivsk District reflect potential environmental risks that could have a significant impact on the region's tourism sector. On the other hand, areas with lower emission rates, such as Kolomyia District and Kosiv District, where air pollution levels are much lower, have greater potential for tourism development, especially ecotourism. This is due to the fact that higher air quality and better environmental conditions are attractive to tourists looking for places to relax and recuperate in a natural environment. To fully understand the impact of the environmental situation on tourism development in the Ivano-Frankivsk Region, it is important to analyse the main air pollutants based on the types of economic activity, as this will allow identifying specific sources of pollution and understand how different sectors of the economy affect air quality and, consequently, the tourism potential of the region (Table 3).

Table 3. Air pollutant emissions by type of economic activity in 2022

No.	Type of economic activity	Emission volumes by region	
		kt	percentage of the total
1	All types of economic activity, including:	152.3	100
1.1	Agriculture, forestry and fisheries	2.126	1.4
1.2	Mining and quarrying	5.460	3.5
1.3	Processing industry	4.725	3.1
1.4	Supply of electricity, gas, steam and air conditioning	136.4	89.5
1.5	Transport, warehouse management, postal and courier services	3.201	2.1
1.6	Other types of economic activity	0.388	0.4

Source: made by the author based on Ivano-Frankivsk Regional State Administration (2023)

The analysis of data on air pollutant emissions by type of economic activity in 2022 allows drawing important conclusions about the structure and scale of anthropogenic impact on the environment in a particular region. The total volume of pollutant emissions in the region amounted to 152.3 kt, with the main share being emissions from the supply of electricity, gas, steam and conditioned air, which accounted for 89.5% of total emissions. The significant contribution of the electricity, gas, steam, and air conditioning sectors to total pollutant emissions (136.4 kt) emphasizes the critical role of this sector in the anthropogenic load on the region's atmosphere. This distribution of emissions points to the need to focus on reducing emissions in the energy sector to improve the environmental situation in the Ivano-Frankivsk Region. According to the authors, reducing emissions from the supply of electricity, gas, steam, and air conditioning should be a key priority in environmental policy. This approach will not only improve the state of the atmosphere but will also help create favourable conditions for tourism development. A clean environment is a fundamental factor in attracting tourists, especially in the context of the growing demand for environmentally friendly and sustainable tourist destinations.

As part of the study of the interaction between the main sectors of the economy that affect the level of pollutant emissions and the dynamics of tourism development in the Ivano-Frankivsk Region, it is important to analyse the contribution of these sectors to the formation of the tourist attractiveness of this region. The electricity, gas, steam, and air conditioning sector, as a major polluter, has a significant impact on environmental quality, which in turn is a determinant of a region's attractiveness to tourists. Increased levels of pollution associated with this sector can deter potential visitors, especially those looking for vacation destinations with clean air and a natural environment. Thus, modernization of the energy infrastructure and transition to more environmentally friendly energy sources can help preserve natural tourist resources and improve the overall attractiveness of the region. Other sectors, such as agriculture, forestry and fisheries, mining and processing, and transportation, although they have lower emissions, still have an impact on the region's environmental status. For example, pollution caused by the extractive industry can negatively affect water and soil quality, which is important for the ecosystem and landscape that attracts tourists. On the other hand, effective management of emissions and pollution from agriculture can contribute to the preservation of natural landscapes and biodiversity, which is key to ecotourism.

Therefore, ensuring sustainable development in all these areas is of strategic importance for the development of tourism in the Ivano-Frankivsk Region. This involves not only taking measures to reduce pollution but also developing environmentally sustainable infrastructure that can attract more tourists and help maintain the natural and cultural heritage of the region. In addition, the importance and quality of the region's water resources should be investigated. Water resources are a key element in ensuring sustainable tourism, given their importance for natural ecosystems, recreational areas, and overall ecosystem health. The quality of water in rivers, lakes, and other bodies of water directly affects the quality of the environment and the health of local communities and tourists. Water pollution can come from a variety of sources, including industrial discharges, agricultural runoff, and urban wastewater, which points to the need for an integrated approach to water management. Water resources play an important role in the development of various types of tourism, such as fishing, water sports and nature observation. The latest data released by the Ivano-Frankivsk Regional State Administration for 2022 reflects changes in wastewater discharges to surface water bodies in the region. The total volume of wastewater discharged decreased from 60.552 mln m^3 in 2021 to 55.048 mln m^3 in 2022, which demonstrates a positive trend in reducing discharge volumes (Ivano-Frankivsk Regional State Administration, 2023). Table 4 shows the main indicators of pollutant discharges into water bodies and wastewater treatment.

Table 4. Discharge of pollutants into water bodies and wastewater treatment in 2022

Region	Waste water discharged into surface water bodies, mln m³									
	Total		Including							
			without treatment		insufficiently treated		normatively clean (without treatment)		normatively cleaned at treatment facilities	
Ivano-Frankivsk	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
	60.552	55.048	0.027	-	1.279	0.198	6.760	7.806	52.485	47.044

Source: created by the authors based on Ivano-Frankivsk Regional State Administration (2023)

An analysis of the list of water users that discharged polluted wastewater into surface water bodies in 2022 in Ivano-Frankivsk Region indicates a critical need to monitor and control the activities of enterprises in various sectors of the economy in the context of their impact on water resources. Of particular interest is the activity of the processing industry and the water supply, sewerage, and waste management sectors as the main sources of insufficiently treated wastewater. Specifically, Uniplyt, a limited liability company specializing in the production of plywood, wood boards and veneer panels, discharged 0.093 mln m³ of insufficiently treated wastewater, which is a significant share of the total amount of pollution in this area of activity. This demonstrates the need to improve the treatment processes at production facilities and increase the efficiency of treatment facilities.

In the context of water supply and sewerage, there are such enterprises as Tlumachcomunservis and Verkhovyna Water Supply and Sewerage Enterprise, with insufficiently treated wastewater volumes of 0.059 mln m³ and 0.020 mln m³, respectively. The article highlights the need to strengthen control over the quality of wastewater treatment discharged into water bodies and modernize treatment technologies. The activity of medical institutions, in particular the municipal non-profit enterprise Dolyna Multidisciplinary Hospital, with a volume of insufficiently treated wastewater of 0.004 mln m³, requires additional measures to improve treatment systems to minimize the potential risk to human health and the ecosystem. The Syniohora National Nature Park, which is represented in the botanical gardens, zoos, and nature reserves segment, also has insignificant discharges of insufficiently treated water, which indicates the importance of ensuring adequate treatment by institutions that use natural resources for their activities. Thus, to ensure the sustainable development of tourism in the Ivano-Frankivsk Region, it is necessary to focus on reducing the level of pollution of water bodies, which requires a comprehensive approach, including the modernization of existing wastewater treatment systems, the introduction of new technologies and methods of treatment, as well as the development and implementation of water management strategies that meet modern environmental standards. Given the importance of these factors, it becomes apparent that effective measures to improve the quality of water resources in the Ivano-Frankivsk Region are needed.

Analysing the main factors of anthropogenic impact on land resources and soils in the Ivano-Frankivsk Region with updated data for 2022, it becomes clear that these factors continue to be crucial for the sustainable development of tourism in the region. The current state and ratio of land indicate significant challenges, especially in the foothill and lowland areas, where the level of agricultural development continues to be high, varying from 54 to 77%. The overall plowing of these territories indicates that the limits of ecological balance are exceeded, which emphasizes the existing threats to environmental sustainability. It is observed that the high plowing of land, in particular in Kolomyia District and Ivano-Frankivsk District, where it is 63.5-67.3% and 51-57.3%, respectively, indicates the intensive use of land resources for agricultural purposes. Such intensive use can lead to soil degradation and reduced fertility, which negatively affects the environmental stability and biodiversity of the region. This situation poses a significant threat not only to the environmental safety of the region but also to its tourist attractiveness. Healthy ecosystems and preserved natural landscapes play a key role in tourism development, as they are the foundation for various types of tourist activities and recreation.

In the context of sustainable tourism development, it is important to pay attention to the need for rational and balanced use of land resources, the introduction of organic farming methods and the preservation of natural landscapes. Efforts should be aimed at minimizing anthropogenic impact, which will preserve the ecological stability of the region, its biodiversity, and, as a result, its tourist attraction (Ivano-Frankivsk Regional State Administration, 2023). Territorial differences in land use in the Carpathians and adjacent areas, which are caused by the zonation of natural conditions and population settlement patterns, affect the cultivation of crops. The current trend toward intensive land exploitation to maximize production often negates efforts to preserve soil and restore its fertility. Given these factors, it is important to implement measures aimed at the sustainable development of agricultural and other land uses, which would include soil conservation practices, reducing soil degradation and maintaining biodiversity. This will not only increase the environmental sustainability and resilience of the region but will also promote tourism development, ensuring the preservation of natural landscapes and a favourable environment for recreation and leisure.

It is advisable to conduct a detailed analysis and calculations of air pollutant emissions in the Ivano-Frankivsk Region, given their significant impact on the environmental situation and the development of the region's tourism industry. For this purpose, data published by the Main Department of Statistics was used, which reflects the volume of pollutant emissions over the past few years. Data for 2021 is used for the calculations (Ivano-Frankivsk Regional State Administration, 2022). The availability of comprehensive information from previous years contributes to the development of more informed and targeted environmental management strategies. Without a complete picture of the anthropogenic impact, including all possible sources of pollution, it is difficult to prioritize actions to reduce the negative impact on the environment. In addition, an adequate assessment of the environmental situation requires data from various sources and sectors of the economy. The lack of data on certain categories of pollutants can lead to an incomplete or distorted view of the environmental challenges faced by the region and, accordingly, to the development of ineffective solutions. According to the data, total emissions amounted to 210.3 kt. The calculation for stationary sources of pollution is as follows:

$$(172.4\text{ kt}/210.3\text{ kt})\cdot 100 = 81.98\%(210.3\text{ kt}/ / 172.4\text{ kt})\cdot 100 = 81.98\%.$$

This means that stationary sources of pollution, such as factories, power plants, and other industrial facilities, account for approximately 82% of total air emissions in the region. Similarly, for mobile sources of pollution (road transport and other vehicles), the calculation looks like this:

$$(37.9\text{ kt}/210.3\text{ kt})\cdot 100 = 18.02\%(210.3\text{ kt}/ / 37.9\text{ kt})\cdot 100 = 18.02\%.$$

This shows that mobile sources contribute about 18% to the total amount of pollutant emissions. Based on these data, it is important to conduct an in-depth analysis of the impact of anthropogenic activities on the air in the Ivano-Frankivsk Region, as well as to assess the potential consequences for the development of the tourism industry. In 2021, air pollutant emissions amounted to 210.3 kt, which is 15.3% more than in the previous year. Of these emissions, 172.4 kt, or approximately 82%, came from stationary sources, and the remaining 18% (37.9 kt) from mobile sources, mainly road transport. These figures indicate a significant impact of economic activity on air quality in the region. For example, a large share of emissions from stationary sources comes from electricity, gas, steam, and air conditioning companies, which is evidence of the dependence of the region's environmental condition on the energy sector. Burshtyn TPP of DTEK Zakhidenergo remains the largest polluter, accounting for 84.4% of emissions in the region.

Air pollution in the Ivano-Frankivsk Region affects the quality of life of the population and tourists, reducing the region's attractiveness for recreation and tourist visits. Air purity is a key aspect of building tourism potential, especially in an environment where the emphasis is on ecological and nature-based tourism. Increased pollutant emissions can have a destructive impact on the region's ecosystems, contributing to their degradation and climate change. Such processes jeopardize the stability of the tourism sector, which depends on natural resources and is defined by the beauty of natural landscapes. Therefore, the need for effective control and management of pollutant emissions is of key importance for maintaining environmental safety and promoting sustainable tourism development in the region. An integrated approach that includes the modernization of industrial enterprises, the use of environmentally friendly technologies, the development of eco-friendly transport, and the active involvement of the public and representatives of the tourism industry in solving environmental problems is an integral part of ensuring the harmonious development of tourism in the Ivano-Frankivsk Region.

According to the data obtained in the course of the study, the dominant role in the formation of emissions in the Ivano-Frankivsk Region is played by energy sector enterprises, in particular, those engaged in the supply of electricity, gas, steam and air conditioning. Thus, it is important to develop and implement strategies aimed at reducing environmental pollution. In the context of ensuring sustainable tourism development in the Ivano-Frankivsk Region, a key aspect is the implementation of a set of measures aimed at improving the region's environment. The primary task is to reduce emissions of pollutants into the air, which is possible through the modernization of industrial processes and the transition to the use of environmentally friendly, alternative energy sources. This step will not only reduce the negative impact on the environment but also improve the quality of life of the local population and tourists. At the same time, the development of ecotourism in the region will ensure the preservation of the unique natural resources of the Ivano-Frankivsk Region. The promotion and development of ecotourism play an important role in fostering a sustainable attitude towards nature, both among the local population and among visitors to the region. Particular attention should be paid to the introduction of environmental standards and certifications for tourism enterprises and organizations. This will not only help improve the environmental image of the region but also create additional incentives for the development of the tourism business on the principles of sustainability and environmental responsibility.

Discussion

In the context of studying sustainable tourism development and its interaction with environmental challenges in the Ivano-Frankivsk Region, it is important to note the contribution of several modern scientific works that consider aspects of environmental sustainability, carbon footprint, and the impact of pollution on tourism. For example, M.S. Mancini *et al.* (2022), in their article, reveal the development and monitoring of the sustainability of ecotourism packages in protected areas of the Mediterranean, demonstrating a practical approach to the implementation of sustainable tourism. A. Rico *et al.* (2019) and P. Osorio *et al.* (2023) analyse the carbon footprint of tourism in Spain. A. Rico *et al.* (2019), in particular, take into account even tourists who stay in the city for no more than one night, which turned out to be significant for assessing the overall environmental impact of tourism. Y.-Y. Sun *et al.* (2020) review methods for assessing the carbon footprint of tourism, providing valuable insights for strategies to reduce the environmental impact of tourism activities. In addition, Y.-Y. Sun & C.-M. Hsu (2019) previously found a direct correlation between the increase in the number of tourists and the increase in the water footprint. Together, these studies form a comprehensive view of the problem of tourism's impact on the environment and emphasize the need to integrate sustainable practices into the tourism industry to ensure its long-term development with minimal negative impact on the environment. Especially in the Ivano-Frankivsk Region, where natural and cultural resources are key to the region's attractiveness, it is important to pay special attention to environmental initiatives and sustainable development strategies. The topic of the carbon footprint of tourism, considered by P. Dorta Antequera *et al.* (2021) through the prism of inbound tourism, in particular emissions from air travel, and J. Koiwanit & V. Filimonau (2021) on hotel tourism in Thailand, respectively, also resonate in this study. However, this article focuses more on emissions from the energy sector and non-aviation transport in the Ivano-Frankivsk Region, expanding the scope of the discussion to a wider range of pollution sources, which emphasizes the unique approach that includes a comprehensive analysis of the impact of different economic sectors on the environmental sustainability of the region, which is important for formulating more effective strategies to reduce carbon impact.

According to the latest statistics from the United Nations World Tourism Organization (UNWTO), international tourism rebounded significantly in 2022, showing double the growth of the previous year, with more than 900 mln international arrivals (UNWTO 2022: A year in review, 2022). This growth indicates that the industry has recovered to 63% of the pre-pandemic level of 2019, reflecting significant adaptation and recovery from the global crisis caused by the COVID-19 pandemic. However, along with its economic benefits, tourism can also cause several environmental problems. In their study, O. Dovgal & L. Bezuhla (2020) focus on the analysis of potential risks that may affect the development of rural tourism in the region. The study highlights the importance of rural tourism as a component of the region's economy. The author proposes strategic directions for creating an ecotourism model of the region's state to ensure sustainable development of rural tourism. The author pays special attention to the need for an integrated approach to solving environmental problems, which includes both state regulation and attraction of investments in environmentally friendly technologies. Ecotourism in the Mediterranean was also studied by M.S. Mancini *et al.* (2018). The authors created a methodology for measuring environmental sustainability for ecotourism products. The authors provide an example of surveys that can be used to determine the ecological footprint of the tourism sector through further analysis.

The conclusions drawn by L.-C. Lee *et al.* (2021) regarding the impact of tourism on water resources in China are particularly interesting. The researchers found that the largest indirect impact on the water footprint is the supply of food, which, accordingly, occurs by various modes of transportation. Scientists E. Skrimizea & C. Parra (2019), in turn, emphasize the lack of research on the tourist impact on the waters of the popular Greek islands, which is caused, in particular, by the geographical remoteness of the islands from the mainland. In a sense, this is similar to the problem of the narrowly focused analysis of the Ivano-Frankivsk Region in this study. S. Villa *et al.* (2020) note that seasonal tourism at ski resorts in the Alps has a significant impact on the quality of drinking water in the region. The distinguishing aspect is that S. Villa *et al.* (2020) focus on the pollution of alpine waters caused by tourists themselves, pharmaceutical products, and personal care products, while this article examines the discharge of pollutants into water bodies in Ivano-Frankivsk Region by local enterprises, which has a direct negative impact on both the ecological state and the tourist attractiveness of the region.

The research conducted by I. Klymchuk *et al.* (2022) and K. Matiyiv *et al.* (2022) significantly contributes to the understanding of the necessity of preserving natural resources. Through an analysis of the quality of soil and surface water in a mountain tourist region, they highlight the importance of maintaining the cleanliness of water resources for ecological sustainability and the sustainable development of tourism. The studies emphasize the need to implement a comprehensive approach to environmental protection in areas of tourist activity, which should include water monitoring, the development of water treatment technologies, and educational programmes to engage local communities and tourists in water conservation.

As can be seen, the environmental impact of tourism is of considerable interest in the global scientific community, as reflected in the study by U. Phumalee *et al.* (2018), which highlights the impacts of tourism activity on Mu Ko Surin National Park. Similarly, this study focuses on analysing the impact of tourism on air pollution in the Ivano-Frankivsk Region, exploring both direct and indirect effects that may have far-reaching implications for the region's sustainable development. Both studies open up a discussion on the need to integrate environmental sustainability into tourism development strategies, which is critical to ensuring the harmonious coexistence of humans and the natural environment. The aspect of sustainability assessment and monitoring, which is central to the research of Y. Shi *et al.* (2020), and M.S. Mancini *et al.* (2022), reflects the focus of this article on the need to systematically assess the environmental impact of tourism. Thus, comparing the study with other work in the field emphasizes the importance of continuing research to better understand the interaction between tourism and the environment. Given the similarities in the focus on environmental impact and carbon footprint, as well as the need to assess sustainability, the study complements existing research by offering a unique perspective on these important issues in the context of the Ivano-Frankivsk Region.

The differences between the study and other scientific works in the field of sustainable tourism development and its interaction with environmental challenges emphasize the unique contribution of the work to understanding the specifics of the problem at the regional level, in particular in the context of the Ivano-Frankivsk Region. One of the differences is the regional focus of the study. By focusing on the Ivano-Frankivsk Region, the study provides a detailed understanding of the impact of tourism on the environmental condition of a specific region, which differs from the more general approaches of other studies. This regional focus allows for a deeper analysis of the local ecosystems, economic features, and social aspects that affect sustainable tourism development, providing valuable insights that can be used to develop more targeted sustainability strategies. Another significant difference lies in the analysis of the impact that the energy sector and mobile sources of pollution have on the environmental state of the region. In contrast to the part of the research that focuses mainly on direct emissions from tourism activities, this study broadens the scope to include the impact of a wider range of pollution sources, allowing for a more comprehensive understanding of the environmental challenges facing the region and formulating appropriate recommendations to reduce the negative impact of not only tourism but also other key sectors of the economy.

In addition, the difference lies in the integration with other sectors of the economy in the study of the impact of tourism on the environment. Through the interconnection with sectors such as energy and transportation, the study goes beyond the traditional analysis of tourism, emphasizing the importance of cross-sectoral cooperation to achieve sustainable development, which in turn reinforces the idea that sustainable tourism development cannot be achieved without taking into account the impact and capabilities of other sectors of the economy, which will make an important contribution to the development of comprehensive strategies to reduce the environmental burden on the region.

Conclusions

Ivano-Frankivsk Region has significant tourism potential based on the diversity and uniqueness of its natural resources. However, the environmental situation in the region poses a serious challenge to this development. A significant increase in air pollutant emissions, especially in large and industrialized areas such as Ivano-Frankivsk, is taking its toll on air quality and the overall environment. This not only reduces the aesthetic value of natural landscapes but also poses real threats to the health of tourists and the local population. The analysis of data on air pollutant emissions, wastewater discharges, and the impact of these factors on the region's land resources has highlighted the critical role that environmental safety plays in ensuring sustainable tourism development.

The significant increase in emissions of pollutants, including sulphur dioxide and other harmful compounds, by 15.3% in 2021 compared to the previous year indicates a rise in the environmental burden on the atmosphere. Of particular concern is the high share of emissions from stationary sources, such as energy sector enterprises, which accounts for about 82% of total emissions. On the other hand, a significant decrease in emissions in 2022 to 152.3 kt indicates the successful implementation of environmental measures and strategies aimed at reducing pollutant emissions and changing the structure of the region's economy towards more environmentally sustainable development. The analysis of wastewater discharges showed that the volume of wastewater discharged into surface water bodies decreased from 60.552 mln m^3 in 2021 to 55.048 mln m^3 in 2022, which demonstrates a positive trend in reducing discharges. A significant portion of these discharges do not meet environmental standards, which emphasizes the need to improve wastewater treatment systems and strengthen water quality control.

In terms of land resources, intensive agricultural use of land, especially in the foothills and plains, leads to soil degradation and reduced fertility. This threatens not only the environmental sustainability of the region but also its tourism potential. Thus, it is important to implement sustainable land use practices and preserve natural landscapes. As part of future research, the priority is to conduct a comprehensive analysis of the dynamics of pollutant emissions into the air by territorial distribution within the Ivano-Frankivsk Region, which will allow the identification of areas with increased concentrations of pollutants and the development of targeted programmes for their remediation. Particular attention should be paid to analysing the impact of atmospheric pollution on public health and tourist flow, as this plays a critical role in shaping the region's image as a safe and attractive vacation destination.

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Conflict of Interest

None.

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Оцінка екологічного стану туристичних ресурсів Івано-Франківської області

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Анотація. З огляду на стрімке зростання впливу туризму на світову економіку, а також екологічні проблеми, які це може створювати, оцінка екологічного стану туристичного сектору набуває особливої актуальності. Мета дослідження полягала в аналізі екологічного стану Івано-Франківської області та його впливу на привабливість регіону для туристів, а також у розробці пропозицій зі сталого розвитку туризму з огляду на екологічні аспекти. Застосовувалися різноманітні методи, зокрема статистичний аналіз даних щодо викидів забруднювальних речовин. Проаналізовано та надано оцінку впливу промисловості та інших галузей на екологічний стан за допомогою методу аналізу. Проаналізовано динаміку викидів в атмосферне повітря за роками та їх вплив на екологічний стан регіону, з акцентом на забруднення діоксидом сірки та іншими сполуками. Окрім атмосферних викидів, розглянуто проблематику скидання забруднюючих речовин у водні об'єкти та вплив на якість води, що має значення для розвитку туризму. Встановлено, що викиди забруднюючих речовин значно впливають на якість атмосферного повітря, що визначає туристичний потенціал області, особливо в контексті розвитку екологічного туризму. Підкреслено необхідність реалізації заходів для зниження рівня забруднення, розвитку сталого туризму та впровадження екологічних стандартів у туристичній індустрії. Встановлено шляхи покращення екології регіону та надано відповідні пропозиції, що включають зменшення викидів забруднюючих речовин, а також застосування інноваційних технологій та підходів у галузі екологічної безпеки та забезпечення сталого розвитку туризму в Івано-Франківській області. Практична цінність дослідження полягає у виявленні конкретних напрямків вдосконалення екологічної політики регіону, які вимагають практичного впровадження для поліпшення екологічного стану Івано-Франківської області, що підкреслює важливість інтегрованого підходу у вирішенні екологічних викликів

Ключові слова: екологічні виклики; безпека галузі; вплив промисловості; якість атмосферного повітря; стале використання природних ресурсів

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The industrialisation of green building: Prospects for introducing a cluster approach in the People's Republic of China

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Abstract. Green building is a way for the resource-intensive construction industry to transition to sustainability in the context of declining non-renewable resources, climate change and a growing global population. For China, which has a large construction market, the transformation of the construction industry according to modern trends that encompass environmental impact, economic and social development is particularly relevant. The purpose of this study was to provide an overview of the features of green building and to demonstrate the specific features of its development in China. The research used empirical and theoretical research methods such as abstraction, induction and deduction, analysis and synthesis, which made it possible to characterise green building technologies in China and the environmental impact of different types of building materials on improving human welfare and the environment condition. The description of empirical information regarding green building and its primary analysis (from theoretical understanding of the issue to the presentation of green building as a coherent object of study) in the context of global development trends is based on the material that included scientific research, scientific and bibliographic reviews of the literature, documents and reports of international organisations highlighting key elements of green building development. It has been identified that over the past decade, sustainable development and green building have been in the focus of attention of the Chinese state, helping to accelerate its development, but at the same time establishing specific barriers due to the high level of centralised decision-making. The results of the study provide a comprehensive overview of the development of the green building, its place in global development trends, and the inherent features that use the cluster approach in this innovative segment of China's development. In practice, the study outcomes can assist other countries in making decisions on green building matters by adopting China's innovative practices

Keywords: green architecture; environmental impact; eco-friendly building materials; ecological standards; sustainable development

Introduction

Countries worldwide are working towards implementing Agenda 21 to achieve sustainable development. This involves maintaining a state of balance between society, the environment, and other areas to ensure the preservation and reproduction of all components in a healthy state for future generations. Agenda 21 includes a dedicated section on sustainable development of human settlements. It highlights the need to improve the planning and management of the settlement network, as well as the development of environmental infrastructure within them. The document also acknowledges the construction industry's commitment to sustainable development, which is achieved through the

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implementation of green building practices (United Nations, 1992). Green building aims to conserve energy and resources, minimize emissions throughout the life cycle of buildings, and promote a healthy coexistence with nature to safeguard human health.

In 2015, the UN updated and extended the list of Sustainable development goals (2015) to 2030. Other international organisations are implementing the sustainable development agenda. For example, the World Trade Report contains a large theoretical section on the evolution of economic models, technology patterns and governance policies (World Trade Organisation, 2020). For example, the main trends identified in the report for the coming years are a new industrial revolution, the development of innovation, the transition to a digital economy and digital supply chain, and sustainable development, which aims to develop ecosystems using modern innovations. Green building embodies all of these modern trends. These documents, which provide a methodological and theoretical basis for scientific research, offer an opportunity to assess the place and importance of green building in the development of society in general and the economy as its material base. From this point of view, the whole range of instruments used, from management decisions to the technical standards adopted, should be evaluated.

Until recently, research in the field of green building has predominantly concerned itself with energy and resource conservation. X. Zhao *et al.* (2018) delved into this topic by conducting a comprehensive bibliometric review of studies in the domain of green building from 2000 to 2016. Their findings highlight a strong emphasis on economics and ecology, suggesting that these dimensions have been central to the research agenda in this field. Few authors, such as A. Ragheb *et al.* (2016), have explored construction and architecture from the perspective of sustainable development, not only its environmental but also social aspects. In their study, they examined the concept of green architecture in the context of sustainable development, offering insights into how environmentally conscious building practices can also contribute to positive social outcomes.

Scholars such as M.J. Zenglein & A. Holzmann (2019), W. Qiao *et al.* (2022) note that the regulatory instruments for green building in China differ from market-based instruments used in other countries in that they are dominated by explicit government regulation. The first group of researchers conducted a comprehensive analysis of China's industrial policy to achieve global technological leadership, while the second group focused on the government-led synergistic development of the green building market in Tianjin. Together, these studies highlight the significant role of government-led initiatives in shaping the green building landscape in China. It is found that by actively promoting and regulating sustainable building practices, the Chinese government has successfully fostered a robust green building industry with potential implications for global sustainability efforts. A group of Chinese scholars, F. Xue *et al.* (2019), conducted a comprehensive study on green building rating systems in China. They explored the new biophilic trend of green buildings, which together with their natural surroundings create a new quality of life. Among Ukrainian researchers, O. Sierikova & S. Ivanov (2023) were interested in green building and its impact on the environment. The study analysed the potential of green buildings to reduce pollution in the ecosystem, including air and water pollution. In addition, the research highlighted the importance of green building in the midst of the COVID-19 pandemic, as it not only provides safe spaces for residents, but can also help protect the human environment from contamination.

As can be seen from these broad scientific and bibliographical reviews, research on green building has mainly examined the characteristics of green building and identified the distinctive aspects that allow green building to be identified as a separate sector of the construction industry. However, there are only a few studies on the development of green buildings in individual countries, describing what the authors consider to be the most striking examples. There is an increasing need to synthesise it and develop a coherent picture of current developments in the building industry. The increased level of generalisation about green building in general, and about a particular country that is experiencing rapid development in all sectors of the economy, such as China, allows a comparison to be made between the processes occurring in the sector in general and in its geographically distinct parts. The aim of this study was to present green building from the perspective of all the components of ecology and sustainable development, as a prospective area for the development of environmental innovation, highlighting its specific characteristics in the Chinese construction market.

Materials and Methods

The material for this study consists of scientific research, bibliographical reviews, documents and reports from international organisations, emphasising the main elements of green architecture. The methodological foundation for the study of green building development is the UN Agenda 21 (United Nations, 1992), the fundamental programme of action to achieve sustainable development, and the World Trade Report 2020 "Government policies to promote innovation in the digital age" (World Trade Organisation, 2020), which presents the theoretical foundations and chronology of the development of technological patterns and prevailing economic models, identifying trends in the world economy for the short and long term.

Based on this, a hypothetico-deductive method was applied in which several empirical studies by other authors on different aspects of green building were evaluated in terms of their relevance to current global environmental trends. In this way, it was possible to demonstrate a growing link between the processes taking place in green building and global trends and the movement of countries towards sustainable development.

Theoretical study of a selected subject involved the use of scientific methods such as analysis, synthesis, abstraction, induction, and deduction. The study collected information on current trends in green building worldwide and in China, regulatory organizations, green building material standards, and the use of natural renewable materials in construction, new architectural and engineering approaches to the construction and operation of buildings and their elements, the ways of recycling construction waste, the increasing responsibility of the constructor for the entire life cycle of the building, the new trend of green building towards saving resources and providing a comfortable living environment for people, educational activities, ways of cooperation between different businesses, municipalities and the population, etc.

The main method of this study was the induction method. The study examined primary international documents, theoretical works and research materials containing primary analysis of selected aspects of green building and its key features, identified through the analytical method and the method of literature review. The use of the induction method is specific to research in the empirical phase: it allowed for an integrated vision of green building, demonstrating the links with the environment in which it exists. This study used descriptions and primary analyses of existing green building practices, management and technologies, as well as barriers to their development, as presented in the reviewed studies and as dominant in the scientific literature.

Results and Discussion

Ecological aspect of sustainable development of the construction industry

Green building was a response to global resource depletion and was designed to conserve valuable resources, as construction is one of the most resource- and energy-intensive industries. The main reasons for its development were therefore economic and environmental. Carbon emissions and the contamination of large areas of land with construction waste are health and environmental hazards. Increased attention to this factor has emerged in the context of accelerating climate change. However, green buildings have also begun to take into account the social factor – both the physical and social health of people, their comfort in the buildings constructed and in the planned landscapes in which these buildings are located. The focus on social and environmental factors is what drives the green building sector to create artificial ecosystems in the urban environment, where people do not lose their connection with nature.

Green building, as a sector of the construction industry, is increasingly responding to the demands of sustainable development in society. It has great potential for development as it responds to the need for a clean environment, including air and water, and contributes to the preservation of health. The resource and energy savings of green building contribute to the economic sustainability of society, while environmental and aesthetic factors contribute to its psychological and social sustainability. In green building, as in other industries seeking to meet sustainability requirements, the product life cycle is an essential category, as the manufacturer is responsible for the product throughout its life cycle until disposal. In the case of green building, builders are responsible for the life cycle of the building, from design to operation and demolition, whereas in today's conventional construction, builders are not responsible for the actual operation, let alone demolition, of the building without negative environmental impact.

Green building has gone through several stages in its development. The first stage is defined by the economy of resources, the development of closed-cycle circuits in construction, and using materials of predominantly inorganic origin. This phase is now in progress in China, which is actively preparing itself for the second phase by studying the experience of countries that started it much earlier. This, first of all, countries such as Japan and Germany, and several other developed EU countries. With Germany, China has several cooperation programmes in this field, with Germany transferring to China technologies that promote energy- and resource-efficient construction and operation of buildings and expertise in project management throughout their lifecycle.

The second stage is based as much as possible on the social needs of the people living in the area and the local natural conditions. This includes minimising the environmental impact of the construction and operation of the buildings, landscaping the buildings both vertically and using green roof technology, and designing the areas around the buildings to be as harmonious as possible with the surrounding nature.

Increased accountability requires new approaches to project management methods as a long-term process involving all stakeholders in discussion and decision making. Conceptually new approaches to building construction and operation in green building require new building standards that address both the construction process of buildings, their ecological and energy efficient operation, and the sustainability of materials. Several such standards, such as LEED (Leadership in Energy and Environmental Design, USA) and BREEAM (Building Research Institute for the Environment, UK) are used in many countries. Several national standards are used by some countries in the region or, as in the case of China, are applied domestically (Zhao *et al.*, 2018).

New construction includes technologies such as prefabrication, where all or most of the elements of a building are designed industrially in-house. This makes it possible to use materials more economically, reduce construction waste, recycle it to develop new materials and structures, speed up the construction process and reduce the size of the building site. The use of information technology makes it possible to design such buildings even for individual projects. There is a growing demand for renewable energy production systems for buildings, air and water treatment equipment, dual water supply, new roofing and green roof materials, etc., all of which contribute to the development and improvement of technologies in construction-related sectors. Materials for green buildings must meet several criteria – they must be non-toxic, low-carbon, easily recyclable and largely made from renewable materials, recycled construction waste, agricultural waste and municipal solid waste: the use of local materials and structural elements from houses destined for demolition is encouraged.

The development of the fifth technological paradigm and the spread of the circular economy model involves the widespread use of green and information technologies in all phases of production processes, thereby increasing productivity and saving resources, and the use of green materials that contribute to a healthier human environment and reduce non-recyclable waste that pollutes the environment for a long time. For China, which has a rapidly growing construction market, all of the above issues are most acute, as the energy consumption of buildings and their emissions into the environment are among the highest in the world. As a result, China has set a course to achieve the country's sustainable development and develop green building as the industry that consumes the most energy and resources and generates the most emissions.

All the features of green buildings are inherent in their Chinese variety. However, China has its own specific characteristics. While in most countries the development of green building is the result of government policies aimed at developing market mechanisms, in China green building has developed as a result of straightforward policies and corresponding government regulations. Green building standards are set by government agencies, which issue certificates of compliance, and the government sets mandatory green building levels for public buildings and often publicly subsidised levels for private construction. The desire to achieve quick, government-set quantitative results often has adverse effects – distortion of the real demand for green projects, as they depend almost entirely on government or government-subsidised demand; ignoring the use factor of buildings by developers; and low quality of design, as designers tend to complete the design process quickly and follow standards, overlooking the factor of the interaction of all building systems to achieve resource and energy efficiency, environmental friendliness and social attractiveness of buildings.

The financial resources invested in the green building sector are mainly used for straightforward government regulation of the industry. Investing in the establishment and development of new market mechanisms could increase the efficiency of green buildings and create more incentives for their development. China, which defines green building as one of the technological breakthroughs, is establishing innovation clusters for its development. In particular, urban clusters and demonstration clusters should be highlighted. Urban clusters, developed in the same administrative way, often group cities with similar problems, making their solutions more difficult. In addition, the fact that the boundaries of such clusters are defined administratively rather than naturally makes it difficult to objectively assess the urban clusters performance. As a positive example of cluster development, there are demonstration clusters, where the process of their creation and operation is more clearly elaborated. They are designed to demonstrate the positive effects of green building in synergy with other sectors and are a powerful source of demonstration to educate society and businesses about the benefits of this approach.

The construction industry is the world's largest consumer of energy and various types of resources, such as ores, timber, etc., and is a major source of emissions to the environment. The United Nations Environment Programme (UNEP) estimates that energy consumption in the building sector accounts for about 30-40% of global energy consumption. The researchers describe various aspects of construction and building performance in China in terms of energy consumption and emissions, and assess the state of construction as follows. The energy consumption of industrial buildings alone accounts for 38% of China's total energy consumption. According to Y. Shen & M. Faure (2021), China is responsible for almost 27% of global carbon dioxide emissions. W. Qiao *et al.* (2022) note the high rate of construction in China – 1.6-2 billion square metres per year – with energy consumption per unit area 2-3 times higher than in several Organisation for Economic Co-operation and Development countries, leading to a strained energy supply situation. In 2018, energy consumption during the construction phase of civil buildings in China accounted for 11% of total energy consumption and 23% during the operation phase. Carbon dioxide emissions during the construction phase amounted to about 1.8 billion tonnes, while carbon dioxide emissions during the lifecycle of buildings amounted to 4.93 billion tonnes, or 51.3% of the country's total carbon dioxide emissions. In a situation of scarce resources, reform and modernisation of the construction industry has become inevitable.

There is a need to explore and establish a sustainable development regime for the construction industry to change the current acute situation of high resource consumption and pollution, and green building can be the solution. The US Environmental Protection Agency (USEPA) defines green building as construction that adheres to the principles of environmental stewardship and resource conservation throughout the life cycle of buildings, from design and construction to operation, maintenance and demolition. China uses a narrow definition that takes into account the vector of China's policy orientation. Green building refers to construction designed to maximise the conservation of resources, including energy, land, water, materials, etc., to protect the environment and reduce pollution, to provide a healthy and efficient living environment for people, and to coexist harmoniously with nature throughout the building's life cycle, which is in line with China's national conditions and the concept of sustainable development. Such an approach aims to minimise harmful effects on human health and the environment.

According to A. Ragheb *et al.* (2016), the main characteristics of green buildings include the use of energy-efficient ventilation, heating and cooling systems, lighting and appliances, water-saving devices; planning the layout of buildings in relation to the landscape to maximise the use of passive solar energy; causing minimal damage to the natural environment; using alternative energy sources, non-toxic natural materials, responsibly collected local materials; adaptive reuse of materials and structures from old buildings; recycling and use of construction waste; efficient space management. Green buildings should be constructed predominantly with green building materials, which are generally produced from renewable resources. The selection of green building materials is therefore guided by criteria such as recyclability and reusability, zero or low air emissions, zero or low toxicity, sustainability and rapid replacement, strength, durability and local production.

H. Wang *et al.* (2018) define green building materials as similar to the above, emphasising their innovative nature, renewable sources of origin and environmentally friendly production and processing processes, which are essential for saving energy and resources in the construction process. They define a green building material as a type of building material whose production involves the use of environmentally friendly technologies, a significant content of recycled industrial, agricultural or municipal solid waste, the full or partial use of natural resources and energy, and a high degree of recyclability, which should contribute to the protection of the environment and human health. Examples of such new green building materials are fibre concrete or plant fibre reinforced concrete and building insulation materials using locally available fibres and other composites from agricultural waste.

In addition, green building technologies (GBTS) have their own specific features designed to improve energy efficiency. GBTS include the installation of solar panels, dual water systems (for clean and service water from rainwater collected on the building itself), heat pumps, the installation of green roofs and walls, and the application of appropriate technologies at all stages of the project. Collaboration between different design disciplines is essential to the development and application of GBTS. It increases the importance of the designer's ability to implement environmentally friendly technologies and to develop an architectural design that is best suited to local conditions.

S. Jones (2021) provides an overview of sustainable green building methods. These include lean construction, the use of diverse designs and information technology, the use of sustainable building materials, new standards and new tools for measuring hydrocarbon emissions. Lean construction involves stakeholders working together to optimise a project and minimise potential damage. The industrial approach (use of prefabricated, modular and industrial structures) in the pre-construction phase makes it possible to use fewer natural resources, reduce pollution and optimise materials management. It determines the environmental and economic benefits.

The use of sustainable building materials requires that they are recyclable, contain recycled content and have a minimal impact on the environment. The study of materials is not limited to their environmental performance, but also includes social aspects that are influenced by companies. Circular or closed-loop construction approaches design and construction to reduce the primary use of resources while increasing their recycling and reuse. Developers can use construction and demolition materials intended for recycling, practise source reduction, recycle to reuse existing materials, and purchase used or recycled materials. The role of the developer is essential in this process.

International green building standards and certification

Two sets of material standards are becoming common: environmental product declarations (EPDs) and a second, more recent set called multi-attribute standards (MAS). An EPD is an assessment of the life cycle of materials. MAS, on the other hand, targets specific material classes and is endorsed by special standards groups. Thus, it is a matter of applying material standards that comply with the requirements of sustainable development – environmental, economic and social.

New tools for carbon reduction have emerged as building materials have a high carbon emission rate, requiring a quick and accurate estimation of their carbon content. The Efficiency Carbon Calculation Calculator (ECC), a free and open-access platform, has proven effective in determining the carbon content and therefore the sustainability of materials. Based on third-party verified EPD data, the ECC tool compares the carbon content of materials, allowing for quick selection of carbon efficient purchases. Information technology, in particular BIM (Building Information Modelling), has been used in sustainable construction. It is mainly concerned with design and pre-construction, but benefits all phases of the project life cycle. Through the accuracy of calculations, 3D modelling and the production of precisely fitting structural elements in industrial pre-construction, material savings are achieved and heat loss during the operation of the building is reduced. BIM processes are therefore efficient in that their implementation almost always reduces the environmental impact of a construction project.

In green construction, the use of green roofs is gaining ground. In general, roofs account for about 20-25% of the total urban area. Green roofs are a natural solution to the environmental problems caused by climate change and rapid urbanisation, providing man-made ecosystem services and having a positive impact on human welfare. According to H. Liu *et al.* (2021), in urban areas, green roofs can mitigate the urban heat island effect, help reduce energy consumption of buildings, regulate rainfall absorption and reduce runoff from roofs, extend the life of roofing materials, improve urban water and air quality, reduce noise, enhance urban biodiversity and harmonise urban landscapes. Assessing the economic impact of green roofs on building maintenance, they estimate that green roofs can reduce maintenance costs by between 60% and 100%, based on one parameter of stormwater runoff alone. Future research, they believe, should focus on low-cost and ingenious green roof designs, taking into account climatic conditions and realising environmental, social, economic and other benefits, while striking a balance between costs and results.

Green building management uses the Green Globes™ system, which includes an assessment protocol, rating system and guidelines for applying sustainable design to commercial buildings (What is sustainable..., n.d.). Other well-known standard systems for assessing green building projects are listed in Table 1. All of these systems are designed to assess a building's compliance with green standards and issue a certificate. All of these systems are designed to assess whether a building meets green standards and issue the appropriate certificate.

Table 1. The most widely used green building standards in the world

System	Origin
LEED (Leadership in Energy and Environmental Design)	USA
Green Mark Scheme	Singapore
CASBEE (Comprehensive Assessment System for the Built Environment Efficiency)	Japan
Building Research Establishment Environmental Assessment Method (BREEAM)	UK
Green Building Council of Australia (GBCA)	Australia
Building Environmental Assessment Method (BEAM)	Hong Kong

Source: made by the author

Green building has expanded the scope of the construction industry by placing new energy, resource, environmental and social demands on it. At the same time, the economic imperative to minimise costs has forced the construction industry to explore new materials, develop new technologies for both the construction and operation of buildings, and develop new conceptual models for buildings that take into account their location. Current green building standards unify the requirements for all its phases and components, allowing them to be manufactured on an industrial scale. In addition, the industry is beginning to adapt to the new demand for buildings. New companies are emerging that focus on the production of green materials, design elements made from natural and recycled materials, and innovative equipment for the maintenance of green buildings. In addition, pre-construction techniques are becoming more widespread, where all the structures of the future building are manufactured in an industrial plant. The use of IT (information technology) in this process allows structures to be manufactured on a project-by-project basis, which is particularly important in green construction in order to maximise the specific characteristics of the future building site. For this process to be successful, the chain from the designer to the manufacturer to the constructor of the building must work harmoniously. This overview shows that the development of green building is pushing the construction and related industries towards higher technological sophistication, higher productivity, new technology chains or natural vertical and horizontal clusters. At the same time, it creates the conditions for a better quality of life for the occupants of green buildings.

Faced with growing environmental problems (water scarcity, air, soil and water pollution, accumulation of solid domestic and industrial waste, resource scarcity) exacerbated by rapid industrialisation, China has, over the past decade, adopted an active policy of sustainable development. The material foundation of this policy is the transition to a "green" economy, i.e. a circular or closed-loop economy that incorporates social and environmental elements into economic processes that cannot always be precisely quantified but that improve the quality of life, including the living environment. The cost of financing China's transition to a green economy is estimated at $19.4 trillion, with an additional financing requirement of $6.4 trillion (Here's how China..., 2018). The main areas of transition include energy and resource conservation, renewable energy generation, a shift to electric transport, recycling and a shift to clean industrial technologies. The development of green building is one of the key areas for building a green economy, as it solves a number of the above issues.

In exploring the history of green building development in modern China, Y. Zhang *et al*. (2018) note that as an economic sector, it has developed relatively recently – after the 2005 Beijing International Conference on Green Building. Since then, green building has been in the spotlight of the Chinese leadership, although it has not always been consistently implemented at the administrative level. In 2016, for example, there was a list of more than 4,500 green building projects, representing more than 500,000,000 m^2 of building space. By 2020, it is expected that 50% of new residential buildings will meet the green building standard. In the "National Medium and Long Term Programme for Science and Technology Development (2006-2020)", the key section "Urbanisation and Urban Development", and "Energy-efficient buildings and green construction" are identified as priorities. In addition, scientists note that the national plans for the 11^{th} and 12^{th} Five-Year Plans set a course for energy conservation and use, considering modern architectural solutions, and identified design and construction with green technologies with responsibility throughout the life cycle of buildings as priority technologies.

New materials manufacturing, relevant to green building development, is named among the top ten priority sectors for development in the Made in China 2025 Programme, with this sector being the fastest growing after the new generation IT sector in China during 2016-2018 (Zenglein & Holzmann, 2019). A special office has been established to manage the assessment and identification of green buildings, the adoption of green building assessments and the management of the assessment and identification of green buildings with one and two stars by government agencies (Zhang *et al.*, 2018).

The construction industry is guided in its activities by building standards. Green building as a sector has its own standards, which include environmental and social requirements for all buildings, operational processes and responsibility for them throughout their lifecycle. Examining the implementation of green building standards in China, Y. Shen & M. Faure (2021) note that a green building rating standard has been developed under the leadership of the central government. It has been incorporated into China's national Green Building Energy Label (GBEL). In contrast, the widely used LEED environmental design standard is based on private standards developed in the US. Both LEED and GBEL include basic requirements for energy use, land use, indoor air quality, water and waste management. The original GBEL standard, published in 2006, was quite comprehensive. The later version of the GBEL standard (2019) includes elements such as durability, real-time resource monitoring, building operations, and usability and accessibility for end users during the operational phase.

A peculiarity of using green building standards in China is that the GBEL standard is mandatory for government buildings, but can be used voluntarily in private construction. The LEED standard only applies to private construction in China. China uses the UK's BREEAM certification system, Germany's DGNB (German Sustainable Building Council) and Singapore's Green Mark, but to a much lesser extent than LEED. A total of 19 million square metres of new and existing buildings will be certified by 2020, with the area of certified new green buildings accounting for 2% of all new buildings constructed in China (China green building..., 2021).

In addition, Y. Shen & M. Faure (2021) examine the management and control methods of green building in China, where the main method is explicit government regulation. It determines the peculiarities of its development, with both positive and negative aspects related to government regulation, and therefore requires more detailed consideration. Alongside explicit government regulation, market-based instruments imply financial incentives or disincentives to influence the level of economic activity. These include taxation, subsidies and government support. In addition, persuasion instruments are used, which use information to encourage voluntary compliance and self-regulation in a green building, most often in the form of private certificates. They note that while the use of each of these tools is essential, none of them alone can be sufficient to promote green building due to high up-front costs, lack of reliable information and the influence of private interests. Although green building has been listed as a development priority in Chinese government documents since 2006, its development faces a number of difficulties that researchers have highlighted. Green building still accounts for a minimal proportion (around 1%) of all existing buildings in China. However, priority is given to the rapid construction of new buildings, neglecting the repair and renovation of existing buildings.

China's central government, which plays a leading role in promoting green building, requires all public buildings to be certified as green under China's GBEL system. GBEL is available for certification of residential, commercial and non-residential buildings and can be chosen on a voluntary basis. The number of new green buildings in China is growing rapidly, largely due to policies and regulations that support green building. And while there is a growing number of commercial green building projects using private certificates, the state-owned GBEL still dominates the Chinese market as most laws and regulations refer to GBEL.

The GBEL standards were developed by a government-owned company, and the certification of projects is carried out by a commission linked to the government. Certification to GBEL standards does not always provide a sufficient assessment of a project's green building practices compared to several private standards such as LEED. In addition, the GBEL standards are constantly being updated, which increases the administrative costs of regulating green buildings. The Chinese government encourages the accelerated development of green buildings in a number of ways – through public procurement, subsidies and lax enforcement of laws.

Furthermore, Y. Shen & M. Faure (2021) analysed the positive and negative aspects of each of the instruments used by the Chinese government. For example, government procurement can increase the demand for green building facilities and products in the short term when the state has required all central government agencies to purchase Chinese Eco-Label (CEL) certified building materials. Government subsidies can reduce the up-front cost of green building, thereby providing an incentive for private developers. However, the pursuit of subsidies can create perverse incentives and contribute to increased environmental impacts.

For example, Chinese legislation on green building at the corporate level requires companies to obtain construction permits that include an Environmental Impact Assessment (EIA). China's 2003 EIA law allowed violators to submit an EIA after a project had started. The 2014 Environmental Protection Law abolished post-EIA, but in practice post-EIAs still exist in two of the eight jurisdictions to attract companies that can supplement local tax revenues. However, subsidies and public procurement alone cannot ensure the long-term growth of green buildings without public financial incentives for the market. New green building projects initiated and subsidised by the government do not always reflect the actual demand for these facilities. Some green building complexes become ghost towns and are likely to consume more energy than they save. Too much public spending on green building can crowd out private investment and make the green building market unnecessarily dependent on the state. At the same time, regulatory planning for green buildings encourages more sensible management of urban land and the siting of buildings away from areas of environmental disadvantage.

Sustainable green construction in the Chinese context

Green building is seen as one of the achievements of China's environmental policy. The example of China shows that when green technologies are promoted, construction can be complicated without government intervention (Shen & Faure, 2021). At the same time, the extent of government regulation of green building and private initiative should be balanced. Green building in China has shown that excessive government involvement in the process can lead to negative outcomes, often the opposite of the original purpose, as noted by W. Qiao *et al.* (2022). They suggest that in order to overcome the negative phenomena in green building, it is essential to seek synergies between all stakeholders in the green building market, strengthen market-based influence mechanisms, and explore more efficient methods of public administration tailored to China's specific characteristics. The Chinese government has so far invested a lot of money in subsidies to promote green building, but these often have a short-term effect and create perverse incentives.

For example, the desire to quickly achieve positive externalities in the green building market, and the lack of information for clients about the real state of the market, leads some participants to exaggerate the environmental performance of projects in order to obtain subsidies. Even if developers want to enter the market, they will pay attention to the construction of green spaces and neglect the maintenance during their long life cycle due to high financial costs. Therefore, there is mistrust between developers and consumers, and consumers' willingness to pay is still low (Qiao *et al.*, 2022).

The problems of green building development in China caused by an explicit state regulation are mentioned by W. Wang *et al.* (2018). State management of the green building sector leads to a desire to demonstrate quick external results, regardless of the possible negative consequences of such an approach. In the Chinese green building market, theoretical and scientific research has been emphasised in previous periods, which has allowed some progress to be made. The green outcome and the cost of maintaining the buildings were of interest and value to both the government and society. However, this middle ground between the idea of a "green" building and an understanding of what it should be as an architectural design was ignored by both government and society. This has affected the quality of construction. Research by W. Wang *et al.* (2018) shows that the performance of green buildings is dependent on planning and design. For example, more than 40% of the energy savings of buildings are incorporated at the design stage.

Construction in China prioritises the pace of construction, therefore, designers are always interested in producing a project quickly. They design predominantly to standard, lacking innovation and sufficient environmental support, ignoring the specifics of the area and neglecting the whole process of the building's operation. This leads to an imbalance in the Chinese green building market. In addition, due to the fast pace of work, planners are not eager to learn and master green building design, but rather pay excessive attention to planning results, i.e. quick design production, ignoring planning processes and methods. Due to a lack of awareness of the nature of a green building and its specific design features, there have been cases where green structures and technological equipment have simply been piled into a single project, rather than creating a coherent complex. Providing the wrong incentives and misunderstanding the nature and purpose of a green building leads to the opposite result in terms of additional resource expenditure and increased environmental damage rather than energy and resource savings. Other researchers, such as the author of this article, share this view.

Low levels of governance and lack of transparency in the design, construction and operation of buildings make it difficult to implement truly green building practices. As an industry that highlights both challenges and opportunities in the transition to a new circular economy model, the construction industry and its innovative green building sector face particular barriers to its development. These include high costs for economic actors in the circular economy model compared to conventional models, lack of market incentives and low awareness of green industrial activities (Ogunmakinde, 2019). These barriers are being overcome in many countries through the development of innovation clusters.

Functionally concerning green building in general, the scientific literature distinguishes clusters such as green building technology implementation, material selection, project development, green building project management and the green building itself. The evaluation system can be divided into the technology sector, the management system and the evaluation using cluster analysis, which can be considered as a separate area of green building research. In order to accelerate successful innovative development, many countries encourage the development of various clusters by locating breakthrough points. These include technology parks, industrial clusters and urban clusters. In China, the network of development clusters has grown steadily over the past decade and a half. For example, the first project list of the urbanisation programme in 2005 included 56 enterprises, 13 industrial parks, 7 provinces, 5 cities and 1 town (Ogunmakinde, 2019). Over time, this network has expanded vertically and horizontally, and there has been a conceptual redefinition of the role of clusters in achieving the country's strategic development objectives (Zhanhao, 2022).

Y. Huang *et al.* (2018) in their work explore the development of urban clusters as an essential field of spatial innovation development in China. The 13^{th} Five-Year Plan and the "New National Urbanisation Plan (2014-2020)" have recognised the strategic importance of urban cluster development in achieving China's sustainable development. Urban clusters are becoming the fastest growing and most promising areas for economic development. At the same time, the administrative way in which they are established is developing some complications. They focus on environmental problems, which are exacerbated by the phenomena of similar industrial structure of cluster members, homogeneous competition, homogeneous resource costs and the spread of pollution. At the same time, Y. Huang *et al.* (2018) point out that there is an imbalance between the economic and environmental development of urban clusters. Once several cities form an urban cluster, it becomes crucial for the economic growth of each city in the urban cluster due to human capital accumulation and knowledge diffusion. When analysing the environmental performance of an urban cluster, researchers believe that it is more correct to consider a particular urban cluster as a separate object of study, since both the boundaries and the participants of the urban cluster are defined by the state rather than by an objective assessment. It is difficult to make an objective assessment of the urban cluster, which would not allow the impact of the urban cluster on the environmental performance of its member cities to be assessed. To inform and promote innovation and sustainable development, China has established a network of eco-innovation demonstration parks consisting of technology parks and urban clusters.

Examples of eco-industrial parks in China include Guanzhang National Eco-Innovation Demonstration Park, Nanhai National Eco-Innovation Demonstration Park, Tianjin Economic Development Zone, Suzhou, Sichuan, Tuopai Industrial Eco-Innovation Parks, Xian High Technology Zone and Yantai Eco-Innovation Development Zone. In these eco-innovation parks, waste from one of the participating enterprises serves as a raw material or part of the materials for others. These eco-innovation parks successfully exchange waste, including ash, sludge, plastics, wood and paper. One example is the production of copper from wastewater in the Suzhou park. The Tianjin Economic Development Zone has successfully implemented a symbiotic relationship between companies producing electronics, automobiles, food and biotechnology. In addition, the Xi'an High-Tech Zone has created synergies between automobile manufacturers, cement companies and processors. The issue of greening park areas and the impact of various indicators on ecological diversity in Ukraine has been considered by such scientists as H. Lukashchuk *et al.* (2023).

Several cities and districts, including Shenzhen in Guangdong province, Wuhan, Huashan in Hubei province, Zhenjiang, Guantang in Jiangsu province, Kunming, Chenggong in Yunan province, Sanming in Fujian province and Zhuhai, Hengqin in Guangdong have been identified as low-carbon pilot cities. The purpose of these low-carbon cities was to reduce carbon emissions (e.g. carbon dioxide and methane), collect data on greenhouse gas emissions, and promote green consumption among residents and appropriate management to maintain economic efficiency and economic growth.

For the development of innovative "smart" and "green" technologies, China's "Made in China 2025" programme aims to develop the following industrial clusters: green manufacturing, smart manufacturing, manufacturing and technological innovation, manufacturing and internet integration, and industry leaders (Zenglein & Holzmann, 2019). As the survey shows, cluster development in China is evolving from year to year, encompassing more sectors and areas, and taking on new forms and combinations. All of these processes are aimed at fully transitioning China to a new and innovative economic model and, as far as possible, achieving sustainable development objectives.

An examination of the scientific work on green building shows that the vast majority of it is still at the level of empirical data description and primary analysis of its various aspects. This is a characteristic of the general academic literature on the subject. However, when selected and synthesised, they provide a coherent picture of green buildings and their place in the modern world. Green building has become a fast-growing sector of construction, innovative for the development of the construction industry as a whole. It is in the green building sector that new construction technologies, new materials and new management methods are being tested.

Conclusions

This study covered a wide range of issues related to green building and its specific characteristics in China. Green building is the construction of buildings in an environmentally responsible and resource-efficient manner throughout their lifecycle, minimising their negative impact on human health and the environment. All these trends are designed not only for aesthetic and social aspects, but also as elements of resource conservation in the operation of the building. Non-renewable materials in building structures are gradually being replaced by renewable ones, such as concrete reinforced with plant fibres, which allows the use of local features and the recycling of products or agricultural waste. In addition, the pre-construction sector, which is essential for green building, is developing, using IT technologies along the entire chain from design to structural fabrication and assembly. All this opens up new business opportunities.

Being included later than other industrialised countries in the process of transition to sustainable development with the development of an appropriate model of circular economy, the green economy, as a more extended understanding of it, China concentrates innovative green building technologies primarily in various types of clusters – from industrial to urban and demonstration, which are developed and expanded year after year in China, which is demonstrated by the results of the study. In addition, the study identified several challenges and barriers to the development of green building in China. It has been the focus of Chinese government authorities, which has allowed the legislative and regulatory administrative environment for green buildings to be established and adjusted quickly, financially stimulating its development and preventing green buildings from being located in environmentally disadvantaged areas.

At the same time, over-administration of the sector hinders the implementation of green projects. Encouraging quick results often has short-term effects and can lead to economic and environmental losses in the long term.

The limited use of market mechanisms in the green building sector reduces competition, which affects the quality of construction. In addition, false financial incentives are often created for the rapid construction of buildings, neglecting the whole process of their subsequent use. China is developing rapidly and is quick to learn from and correct its mistakes. Each of the issues discussed in this study could be the subject of separate further research, for example a detailed overview of modern building materials and their classification for green building.

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None.

Conflict of Interest

None.

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Індустріалізація зеленого будівництва: перспективи впровадження кластерного підходу в Китайській Народній Республіці

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Анотація. Зелене будівництво – це спосіб переходу ресурсомісткої будівельної індустрії до сталого розвитку в умовах скорочення невідновлюваних ресурсів, зміни клімату та зростання населення планети. Для Китаю, який має великий будівельний ринок, трансформація цієї галузі до сучасних тенденцій, які охоплюють вплив на навколишнє середовище, економічний і соціальний розвиток, є особливо актуальною. Мета цього дослідження полягала в тому, щоб надати огляд особливостей зеленого будівництва й продемонструвати особливості його розвитку в Китаї. У дослідженні використовувалися емпіричні та теоретичні методи дослідження, такі як абстракція, індукція та дедукція, аналіз та синтез, що дали змогу охарактеризувати технології зеленого будівництва в Китаї та екологічний вплив різних типів будівельних матеріалів на покращення життєдіяльності людини та стану довкілля. Опис емпіричної інформації щодо зеленого будівництва та його первинний аналіз (від теоретичного розуміння питання до представлення зеленого будівництва як узгодженого об'єкта дослідження) в контексті глобальних тенденцій розвитку виконано на основі матеріалу, що включав наукові дослідження, науково-бібліографічні огляди літератури та документів, звітів міжнародних організацій, що висвітлюють ключові елементи розвитку зеленого будівництва. Встановлено, що останнє десятиліття сталий розвиток і зелене будівництво були в центрі уваги китайської держави, допомагаючи прискорити її розвиток, але водночас встановлюючи певні перешкоди через високий рівень централізованого прийняття рішень. Результати дослідження дають комплексне уявлення про розвиток зеленого будівництва, його місце в світових тенденціях розвитку та притаманні особливості, що використовують кластерний підхід у цьому інноваційному сегменті розвитку Китаю. На практиці результати дослідження можуть бути використані для прийняття рішень із питань зеленого будівництва іншими країнами, спираючись на інноваційний досвід Китаю

Ключові слова: зелена архітектура; вплив на довкілля; екологічні будівельні матеріали; екологічні стандарти; сталий розвиток

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