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Fuzzy modelling of the environmental component of social security

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Abstract. Economic growth has several negative consequences for the environment. At first glance, the impact of the environment on the well-being of the population may seem insignificant. Still, several scientific studies demonstrate that the state of the environment has no less impact on the well-being of the population than economic or social factors. This study aimed to assess Ukraine's environmental well-being in comparison with the member countries of the Organisation for Economic Co-operation and Development. The assessment of environmental well-being is based on indicators from the Organisation for Economic Co-operation and Development Better Life Index and the Environmental Performance Index. Fuzzy set theory is used to research and evaluate environmental well-being. During the study, a fuzzy inference system was constructed, which was used to obtain an assessment of Ukraine's environmental well-being compared to the Organisation for Economic Co-operation and Development countries. Three indicators were used in the study: air pollution, sanitation and drinking water, and agriculture. Results indicate that compared to the Organisation for Economic Co-operation and Development countries, Ukraine is on the border between medium and high levels of environmental well-being. The research findings are supported by the Environmental Performance Index, where Ukraine ranked 41st out of 180 countries in 2024, climbing 11 positions compared to 2022. Although Ukraine has already demonstrated progress in the Environmental Performance Index in 2024 compared to the 2022 results, it can maintain such a trend only if it knows which specific environmental indicators need improvement. Therefore, the practical value of this research lies in demonstrating the environmental indicators that require improvement

Keywords: ecology; fuzzy sets; fuzzy inference system; environmental well-being; mathematical modelling

INTRODUCTION

Social security is a fundamental condition for the stable development of society, ensuring social justice and creating conditions for a decent life for every citizen. It requires a comprehensive approach that covers all major aspects of life. One of the main elements of social security is the well-being of the population. Like social security, it also consists of several main components, such as economic, social, and environmental. The environmental component includes aspects that directly affect people's health, life expectancy, labour productivity,

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and psychological comfort. Taking into account environmental indicators when determining the level of population well-being allows for an assessment of not only the current state but also future prospects. This is an approach to sustainable development that is focused on preserving natural resources and ecosystems for future generations while ensuring a high standard of living for the current inhabitants of the planet.

S. Lyndiuk (2022) notes that the concept of "social security" is complex and encompasses various aspects such as economic, political, social, humanitarian, and value-based dimensions. The author highlights all the factors that influence human activity, including living conditions and quality of life. According to this, research aimed at determining the level of population well-being is not only of interest but is also one of the key elements of social security. However, defining the level of population well-being is a multifaceted task. Well-being can also be divided into three categories: economic, social, and environmental. There is also a significant amount of international scientific research on the impact of the environment on population well-being. In the study of C. Li (2022) it is emphasised that with increasing pressure on the global environmental landscape, natural capital has become scarce. The research by E. Kalaidjian *et al*. (2024) explores the active and passive impact of the environment on human well-being. The findings of J. Wang & D. Tang (2023) show that air pollution negatively affects the population's well-being. The authors propose an "environmental tax" to regulate air pollution while simultaneously enhancing well-being. The research of A. Vijaikis & M.S. Poškus (2024) shows that pro-environmental actions by citizens, i.e., individuals who care for the environment in their private lives, can have a positive impact on mental health.

The aforementioned studies are excellent examples of the extent to which environmental indicators influence population well-being. In previous research, the authors considered the construction of a fuzzy mathematical model to determine the level of economic (Sharkadi & Dorovtsi, 2024a) and social well-being (Sharkadi & Dorovtsi, 2024b) of the population. Fuzzy inference systems are also used by many scientists for similar research (Saini *et al.*, 2022). However, the mentioned study is not dedicated to determining the level of environmental well-being of a particular country but to building a fuzzy inference system to determine indoor air quality.

This article proposes the consideration of the third key element in determining population well-being: environmental well-being. The research aimed to develop a fuzzy mathematical model to determine the level of environmental well-being in Ukraine compared to the member countries of the Organisation for Economic Co-operation and Development (OECD). Within the framework of the study, it is proposed to solve the following tasks:

- classification of existing statistical data by country;
- definition of membership functions for the fuzzy inference system;
- construction of a knowledge base.

MATERIALS AND METHODS

The first step in conducting the research was to construct a hierarchical structure. The most typical and simple hierarchical structure is a two-level one, which has only one higher-level coordinating element and *n* subordinate lower-level elements (Fig. 1). Such a structure allows for the construction of any multi-level hierarchies from two-level subsystems, as if from individual modules.

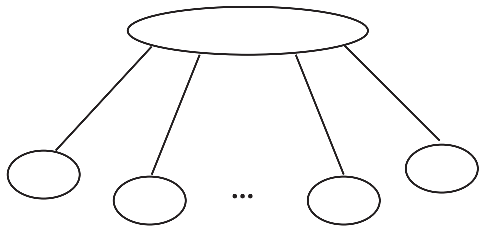

Figure 1. Two-level hierarchical structure
Source: developed by the authors

To achieve the stated goal, it is proposed to use fuzzy set theory. The use of fuzzy mathematics in determining the level of environmental well-being is justified for several key reasons. The level of environmental well-being depends on numerous factors that often have an uncertain or subjective nature. For example, the definition of "clean" or "polluted" air can be ambiguous and depend on the context or regulatory standards, which may also be fuzzy. Also, when determining the level of environmental well-being, it is necessary to consider various sources of information and expert assessments, which may be contradictory or incomplete. Fuzzy mathematics provides tools for integrating such data, allowing for informed conclusions even under conditions of incomplete information.

In previous studies, the authors examined issues of economic well-being and explored the social aspects of population well-being (Sharkadi & Dorovtsi, 2024a; Sharkadi & Dorovtsi, 2024b). This study is the third part of the aforementioned research, examining the third main component of population well-being – environmental well-being. To investigate the level of environmental well-being, three indicators were used: air pollution, sanitation and drinking water, and agricultural activities. The input data for air pollution was the annual average concentration of particulate matter with a diameter of up to 2.5 μm (PM2.5). It is important to note that according to the World Health Organization, the annual average concentration of PM2.5 in the air should not exceed 5 μg/m^3 (European Environment Agency, 2022). Such a level can be achieved by only a few countries. The indicators "sanitation and drinking water" and "agriculture" were composed using data from the Environmental Performance Index. In the course of the study, statistical data for all countries that are members of the OECD were collected and classified for all the aforementioned indicators.

To determine the level of environmental well-being, it is proposed to use a fuzzy inference system. There are several fuzzy inference algorithms, but in this study, the Mamdani fuzzy inference algorithm was used. Besides being the most common fuzzy inference algorithm, the Mamdani algorithm has several other advantages, such as being easy to understand, efficient for manual input, and the rule base is transparent and comprehensible. The Mamdani fuzzy inference system was built in the Fuzzy Logic Designer application of the Matlab software package. The Mamdani algorithm consists of the following steps: formation of a knowledge base; fuzzification of input variables; aggregation of antecedents in fuzzy production rules; activation of consequents of fuzzy production rules; accumulation of consequents of fuzzy production rules; defuzzification – i.e., converting to a crisp value.

RESULTS AND DISCUSSION

In this study, a fuzzy mathematical model was constructed to determine the level of environmental well-being in Ukraine compared to the member countries of the OECD. Determining population well-being is a complex task. The OECD Better Life Index measures the well-being of OECD member countries based on a range of indicators. In this study, the indicators were grouped and a hierarchical system was constructed, dividing the indicators that influence the level of well-being into three main parts. These three main groups include economic indicators, social indicators, and environmental indicators. The constructed hierarchical structure is shown in Figure 2.

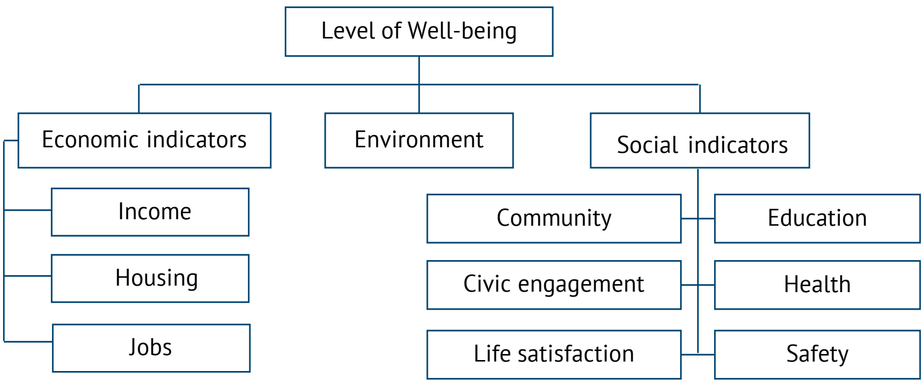

Figure 2. Hierarchical structure for determining the level of well-being
Source: developed by the authors

After gathering the information, the available data (the annual mean concentration of particulate matter with a diameter of up to 2.5 μm (PM2.5) in ambient air, "sanitation and drinking water" indicator of the Environmental Performance Index, "agriculture" indicator of the Environmental Performance Index) were divided into quartiles. Thus, the data was divided into three parts: low, medium, and high. After classifying the data by quartiles, a fuzzy inference system was constructed using the Matlab mathematical programming package. To construct the fuzzy inference system, membership functions were defined and used. Thus, for data belonging to the "low" category, a linearly z-shaped membership function was proposed, generated by the program according to the following formula:

$$f(x,a,b) = \begin{cases} 1, x \le a; \\ \frac{b-x}{b-a}, a < x < b; \\ 0, b \le x. \end{cases} \quad (1)$$

For data belonging to the "medium" category, a triangular membership function was proposed, described by the following formula:

$$f(x,a,b,c) = \begin{cases} 0, x \le a; \\ \frac{x-a}{b-a}, a \le x \le b; \\ \frac{c-x}{c-b}, b \le x \le c; \\ 0, c \le x. \end{cases} \quad (2)$$

For data belonging to the "high" category, a linearly s-shaped membership function was proposed, described by the following formula:

$$f(x,a,b) = \begin{cases} 1, x \le a; \\ \frac{x-a}{b-a}, a < x < b; \\ 0, b \le x. \end{cases} \quad (3)$$

The constructed fuzzy inference system is illustrated in Figure 3.

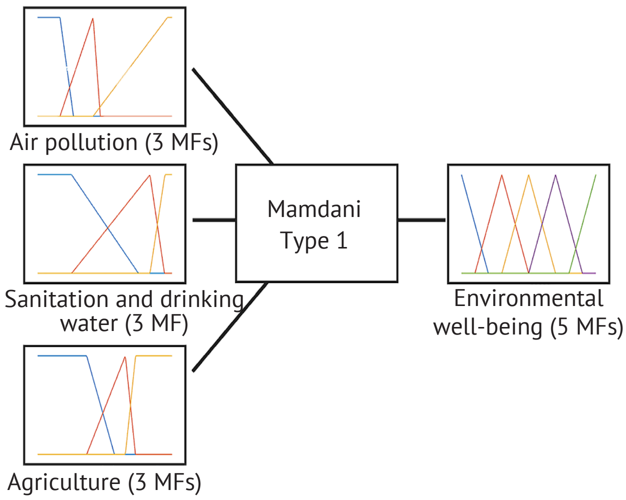

Figure 3. FIS structure for determining the level of environmental well-being
Source: developed by the authors

As shown in Figure 3, the Mamdani algorithm was used in the study. The fuzzy logical inference based on the Mamdani algorithm is formulated according to the following formula:

$$\bigcup_{p=1}^{k_j}\left(\bigcap_{i=1}^{n} x_i = a_{i,jp} \; with \; weight \; w_{jp}\right) \rightarrow \\ \rightarrow y = d_j, j = \overline{1,m}, \quad (4)$$

where $a_{i,jp}$ – the fuzzy term used to evaluate the variable x_i in the row with the number $jp(p = (\overline{1,k_j})$; w_{jp} – the weight coefficient of the rule with ordinal number jp within the range [0,1], which specifies the relative weight of the rule in the fuzzy logical inference; d_j – the fuzzy conclusion of the j-th rule (in the Mamdani-type algorithm, the conclusions of the rules d_j are defined by fuzzy terms); m – the number of terms used for the linguistic assessment of the output variable. Figure 4 shows a typical structure of a fuzzy inference model.

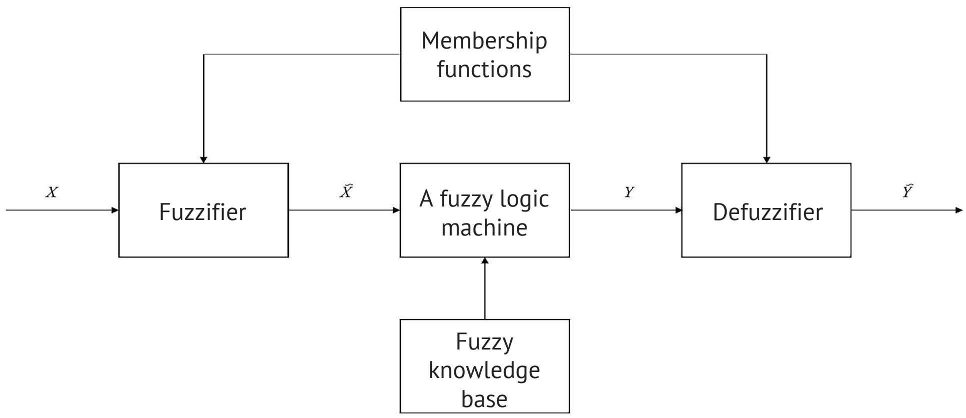

Figure 4. Typical structure of a fuzzy inference model
Source: developed by the authors based on the study A. Abramova (2022)

In the Mamdani algorithm, the construction of a knowledge base is a crucial part. Therefore, the next task was to create a knowledge base. The knowledge base in the Mamdani algorithm consists of logical rules of the "IF-THEN" type. The constructed knowledge base consists of 27 logical rules. The knowledge base constructed during the study is presented in Table 1. Once the knowledge base has been established, the output surface of the constructed model can be viewed in the Control Surface window of the Matlab program. Figures 5 and 6 display the output surface of the fuzzy system in relation to the input values.

Table 1. Knowledge base for the built fuzzy inference system

No. of the rule	Description of the logical rule	Weight	Name of the rule
1	If Air pollution is Low and Sanitation and drinking water is Low then Environmental well-being is Low	1	Rule 1
2	If Air pollution is Low and Sanitation and drinking water is Medium then Environmental well-being is High	1	Rule 2
3	If Air pollution is Low and Sanitation and drinking water is High then Environmental well-being is Very high	1	Rule 3
4	If Air pollution is Medium and Sanitation and drinking water is Low then Environmental well-being is Low	1	Rule 4

Continued Table 1.

No. of the rule	Description of the logical rule	Weight	Name of the rule
5	If Air pollution is Medium and Sanitation and drinking water is Medium then Environmental well-being is Medium	1	Rule 5
6	If Air pollution is Medium and Sanitation and drinking water is High then Environmental well-being is High	1	Rule 6
7	If Air pollution is High and Sanitation and drinking water is Low then Environmental well-being is Very low	1	Rule 7
8	If Air pollution is High and Sanitation and drinking water is Medium then Environmental well-being is Low	1	Rule 8
9	If Air pollution is High and Sanitation and drinking water is High then Environmental well-being is Medium	1	Rule 9
10	If Air pollution is Low and Agriculture is Low then Environmental well-being is Low	1	Rule 10
11	If Air pollution is Low and Agriculture is Medium then Environmental well-being is High	1	Rule 11
12	If Air pollution is Low and Agriculture is High then Environmental well-being is Very high	1	Rule 12
13	If Air pollution is Medium and Agriculture is Low then Environmental well-being is Low	1	Rule 13
14	If Air pollution is Medium and Agriculture is Medium then Environmental well-being is Medium	1	Rule 14
15	If Air pollution is Medium and Agriculture is High then Environmental well-being is High	1	Rule 15
16	If Air pollution is High and Agriculture is Low then Environmental well-being is Very low	1	Rule 16
17	If Air pollution is High and Agriculture is Medium then Environmental well-being is Low	1	Rule 17
18	If Air pollution is High and Agriculture is High then Environmental well-being is Medium	1	Rule 18
19	If Sanitation and drinking water is Low and Agriculture is Low then Environmental well-being is Very low	1	Rule 19
20	If Sanitation and drinking water is Low and Agriculture is Medium then Environmental well-being is Low	1	Rule 20
21	If Sanitation and drinking water is Low and Agriculture is High then Environmental well-being is Medium	1	Rule 21
22	If Sanitation and drinking water is Medium and Agriculture is Low then Environmental well-being is Low	1	Rule 22
23	If Sanitation and drinking water is Medium and Agriculture is Medium then Environmental well-being is Medium	1	Rule 23
24	If Sanitation and drinking water is Medium and Agriculture is High then Environmental well-being is High	1	Rule 24
25	If Sanitation and drinking water is High and Agriculture is Low then Environmental well-being is Low	1	Rule 25
26	If Sanitation and drinking water is High and Agriculture is Medium then Environmental well-being is High	1	Rule 26
27	If Sanitation and drinking water is High and Agriculture is High then Environmental well-being is Very high	1	Rule 27

Source: developed by the authors

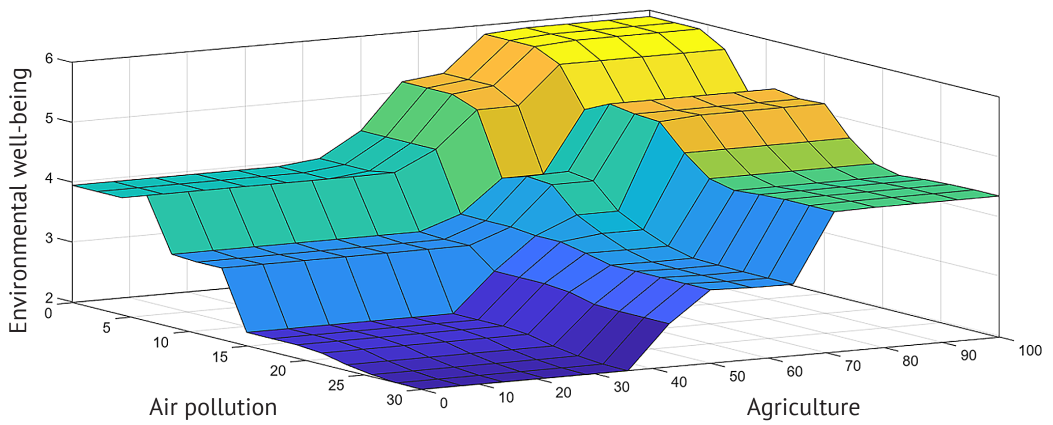

Figure 5. The output surface of the fuzzy system in relation to the input values "air pollution" and "agriculture"
Source: developed by the authors

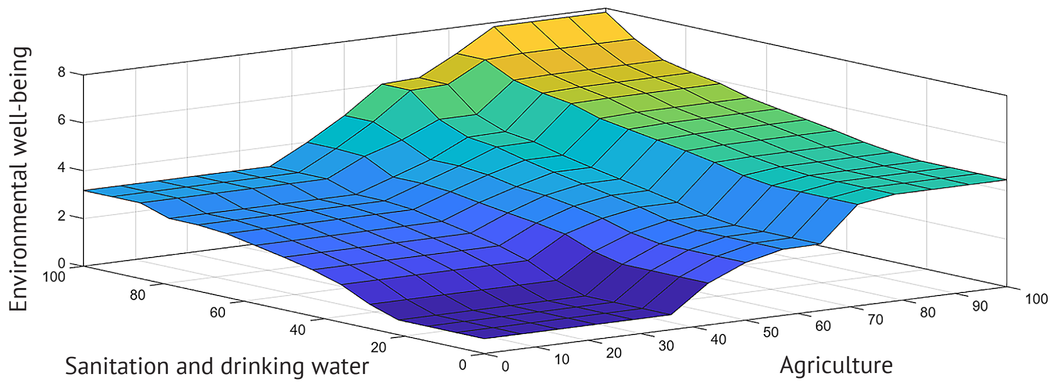

Figure 6. The output surface of the fuzzy system in relation to the input values "sanitation and drinking water" and "agriculture"
Source: developed by the authors

The final step in the research process is defuzzification. The Matlab software package, specifically the Fuzzy Logic Toolbox, offers several methods for defuzzification, including: 1) Centroid – the centre of gravity; 2) Bisector – median; 3) LOM (Largest Of Maximums) – largest of maximums; 4) SOM (Smallest Of Maximums) – smallest of maximums; 5) MOM (Mean Of Maximums) – mean of maximums. Among these, the most widely used method is the centroid or centre of gravity, which is described by the following formula:

$$y = \frac{\int_{min}^{max} x \cdot \mu(x)dx}{\int_{min}^{max} \mu(x)dx}, \tag{5}$$

where y – the defuzzification result; x – the variable corresponding to the output linguistic variable; $\mu(x)$ – the membership function of the fuzzy set corresponding to the output variable after the accumulation stage; *min* and *max* – left and right points of the support interval of the fuzzy set of the corresponding output variable (Butko *et al.*, 2022). The defuzzification result using the centre of gravity method is shown in Figure 7.

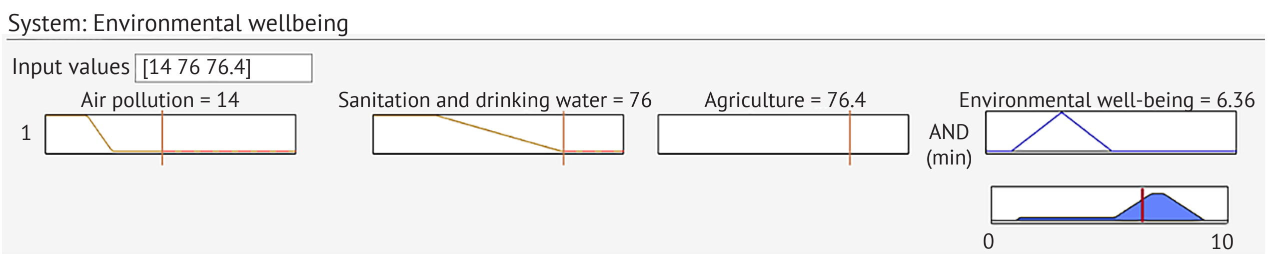

Figure 7. Clarification (defuzzification) of the built model using the centre of gravity method
Source: developed by the authors

As shown in Figure 7, the study not only constructed a fuzzy inference system capable of determining environmental well-being but also tested it on real statistical data for Ukraine. The statistical data used for testing the system includes the following:

- average annual concentration of particulate matter with a diameter of up to 2.5 μm (PM2.5) in the ambient air;
- the "sanitation and drinking water" indicator from the Environmental Performance Index;
- the "agriculture" indicator from the Environmental Performance Index.

Results show that, according to these three indicators, the environmental well-being in Ukraine is at the borderline between medium and high levels. This is confirmed by the Environmental Performance Index, where Ukraine ranked 41st out of 180 countries studied.

As of 2024, there are numerous international scientific studies examining the impact of environmental indicators on the subjective well-being of populations. Primarily, these studies focus on countries where the environmental impact (due to pollutant emissions) is at an extreme level. For instance, the influence of air quality on subjective well-being is examined in the research of L. Yuan *et al*. (2018). Similarly, the study by X. Zhang *et al*. (2017) investigates the effect of air quality on mental health and subjective well-being. These studies demonstrate that air pollution negatively affects the subjective well-being of the population. In this research, similar indicators are used; however, instead of analysing their impact on well-being, a fuzzy mathematical model has been developed to determine the level of environmental well-being.

Besides air quality, sanitation conditions and access to clean drinking water also have a significant impact on well-being. The report by C.N. Mock *et al*. (2017) demonstrates the influence of water supply infrastructure on people's mental and physical health. Furthermore, the research by A. Adukia (2017) shows that water supply infrastructure even affects school attendance, which is also a crucial indicator of social well-being. In the aforementioned studies, only the impact of air quality or water supply infrastructure on subjective well-being was examined. In this research, a broader range of environmental indicators influencing population well-being was analysed, and Ukraine's environmental indicators were compared to those of the OECD member countries.

Previous research has established a strong link between environmental indicators and population well-being, with health serving as a fundamental indicator of social well-being. Without a healthy population, it is difficult to speak of a high level of overall well-being. The studies of E. Ha (2020) and S. Khomenko *et al*. (2021) delve into the impact of air pollution on public health. These authors analysed the impact of various pollutants on public health, while the findings of the present study provide an assessment of environmental well-being. Moreover, a review of the literature reveals that air pollution has a detrimental effect not only on physical but also on mental health. Y. Song *et al*. (2020) and C. Sanduijav *et al*. (2021) explore the impact of polluted air on happiness, a crucial component of social well-being.

As previously mentioned, there is a substantial body of research dedicated to determining levels of environmental well-being. The article of X. Song *et al*. (2022) investigates the impact of the digital economy on environmental well-being. The study utilises panel data from Chinese provinces between 2011 and 2019. In their research, G. Ahumada & V. Iturra (2021) examine the effects of air pollution on the subjective well-being of the Chilean population. In contrast to these studies, this research classifies statistical data for the member countries of the OECD. Following data classification, a fuzzy logic inference system was constructed to determine the level of environmental well-being in comparison to OECD member countries.

The aforementioned studies demonstrate that environmental indicators have a significant impact on the population's well-being. However, research specifically focused on environmental well-being is scarce in the context of Ukraine. The fuzzy inference system developed in this study offers a straightforward and comprehensible method for assessing Ukraine's environmental well-being in comparison to member countries of the OECD.

CONCLUSIONS

This research underscores that human well-being is a far more complex issue than merely economic or even social indicators. By utilising the fuzzy logic system developed during the research, it is possible to easily compute even complex issues such as environmental well-being. The research successfully achieved its goal by creating a fuzzy logic system that assesses the environmental well-being of Ukraine in comparison to the member countries of the OECD. The findings highlight the importance of focusing on environmental protection in addition to economic aspirations. The proposed fuzzy logic system was tested using real statistical data for Ukraine. The results indicate that, according to three key indicators, Ukraine's environmental well-being lies between the medium and high levels. This is further validated by the Environmental Performance Index, where Ukraine ranked 41st out of 180 countries. Although Ukraine has attained a good level of environmental well-being, it is crucial not only to maintain but also to improve this level in the future, particularly concerning harmful air pollutants. The indicator used in this study (the average annual concentration of PM2.5 air pollution) exceeds the World Health Organization's recommended levels by almost threefold. As ecology is a broad concept, further research should include additional indicators that could affect the level of environmental well-being. The prospects for future studies lie in incorporating more environmental factors that influence population well-being.

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CONFLICT OF INTEREST

None.

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Нечітке моделювання екологічної складової соціальної безпеки

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Анотація. Зростання економіки має низку негативних наслідків для навколишнього середовища. З першого погляду вплив навколишнього середовища на добробут населення здається незначним, але низка наукових робіт доводять, що стан навколишнього середовища має не менший вплив на добробут населення, ніж економічні чи соціальні чинники. Мета даного дослідження полягала у оцінці екологічного добробуту України у порівнянні з країнами-членам Організації економічного співробітництва та розвитку. Для оцінки екологічного добробуту використовуються індикатори Індексу кращого життя Організації економічного співробітництва та розвитку та Індексу екологічної ефективності. Для дослідження і оцінки екологічного добробуту використано математичний апарат теорії нечітких множин. У ході дослідження побудовано систему нечіткого логічного виводу, за допомогою якої отримано оцінку екологічного добробуту України порівняно з країнами-членам Організації економічного співробітництва та розвитку. При дослідженні використано три індикатори: забруднення повітря, санітарія та питна вода, сільське господарство. Результати дослідження свідчать про те, що порівняно з країнами-членами Організації економічного співробітництва та розвитку, Україна знаходиться на межі між середнім та високим рівнями екологічного добробуту. Результати дослідження підтверджуються Індексом екологічної ефективності, за яким Україна у 2024 р. посідає 41 місце зі 180 досліджуваних країн, піднявшись на 11 позицій порівняно з 2022 роком. Хоча Україна вже продемонструвала прогрес у Індексі екологічної ефективності у 2024 році порівняно з результатами за 2022 рік, вона може зберегти таку тенденцію лише за умови, що знатиме, які саме екологічні показники важливо покращити. Тож практична цінність даного дослідження полягає в демонстрації екологічних індикаторів, які потребують покращення

Ключові слова: екологія; нечіткі множини; система нечіткого виводу; екологічний добробут; математичне моделювання