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1. MATERIJALI I METODE / MATERIALS AND METHODS

U ovom delu se navodi opis uzoraka koji su uzeti na analizu sa naznakom lokaliteta. Neophodno je navesti oznake opreme, kao i tehnike i metode kojima su obavljene analize. U slučaju originalnih metoda autora treba priložiti opis metoda i opreme.U oblasti društvenih nauka neophodno je napomenuti, šta je predmet istraživanja.

2. REZULTATI I DISKUSIJA / RESULTS AND DISCUSSION

Tabele, slike, grafikoni i dr. mogu da budu u jednoj ili dve kolone. Iznad tabele treba da stoji naziv, npr.

Tabela 1 - Rezultati eksperimentalnih merenja

Ispod ilustracije treba da stoji objašnjenje, npr.: *Slika 1 - Rezultati simulacije procesa*

Nazive tabela i grafikona takođe dati na srpskom i engleskom jeziku.

Formule numerisati rednim brojevima u malim zagradama. Pozivanje na formule u tekstu vrši se navođenjem odgovarajućeg rednog broja u malim (okruglim) zagradama:

$$\overline{R_u} = L_4 + L_3 F_x \left(\frac{\overline{U_{pm}} - \overline{U_{gm}}}{\overline{U_{pm}^2}} \right) \qquad (1)$$

U ovom odeljku se takođe vrši upoređenje rezultata koje su dobili autori s podacima iz radova navedenih u spisku referenci, što predstavlja osnovu diskusije.

ZAKLJUČAK / CONCLUSION

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Zahvalnica / Acknowledgements

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LITERATURA / REFERENCES

Literatura (skorijeg datuma: 2010. i novija) se u tekstu navodi prezimenom autora i godinom publikovanja: (Petrović, 2019), (Janković, Marković, 2020). U slučaju kad postoji više autora u tekstu se navodi samo prezime prvog autora: (Jovanović i dr., 2020) ili (Johnson et al., 2021). Reference u spisku literature se navode azbučnim (abecednim) redom:

Petrović, S. (2019). *Zaštita vodnih resursa*, Naučna knjiga, Beograd, 403 str.

Smith, G. (2020). Title of the article, *Chem. Phys.*, 65 (4), pp. 19-35.

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U sve radove neophodno je uvoditi elemente istraživanja. U radove iz društvenog polja neophodno je uključivati komparativne metode, a takođe analize Studija slučajeva (Case Study).

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Application of AI in big data analytics in the goal of energy transition: a comparative cost-effectiveness analysis of renewable energy sources versus fossil fuels

Primena veštačke inteligencije u analizi velikih podataka u cilju energetske tranzicije: uporedna analiza isplativosti obnovljivih izvora energije u odnosu na fosilna goriva

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Abstract: The analytical processing of big data and AI technologies plays a key role in the energy transition, enabling more efficient utilization of renewable energy sources and the optimization of power systems. The utilization of alternative and renewable energy sources represents the only viable strategy that can ensure a successful energy transition, distancing us from outdated and environmentally harmful energy supply systems based on fossil fuels and high carbon emissions. With the support of artificial intelligence (AI) and big data technologies, this transition becomes more predictable, measurable, and feasible, enabling the anticipation of potential energy supply scenarios. This paper explores the application of AI and big data technologies, while a comparative analysis is employed to examine the use of alternative, renewable, and traditional energy sources within the context of the energy transition. Through a comparative analysis, the study examines the advantages, challenges, and production costs associated with alternative, renewable, and conventional energy sources. The findings underscore the potential of data-driven approaches to accelerate the energy transition while highlighting the economic and technological barriers that must be addressed to ensure a sustainable energy future.

Keywords: Carbon footprint, Sustainable energy, Energy transition, Big data, AI.

Sažetak: Analitička obrada velikih podataka i tehnologija veštačke inteligencije igra ključnu ulogu u energetskoj tranziciji, omogućavajući efikasnije korišćenje obnovljivih izvora energije i optimizaciju energetskih sistema. Korišćenje alternativnih i obnovljivih izvora energije predstavlja jedinu održivu strategiju koja može osigurati uspešnu energetsku tranziciju, distancirajući nas od zastarelih i ekološki štetnih sistema snabdevanja energijom zasnovanih na fosilnim gorivima i visokim emisijama ugljenika. Uz podršku veštačke inteligencije (VI) i tehnologija velikih podataka, ova tranzicija postaje predvidljivija, merljivija i izvodljivija, omogućavajući predviđanje potencijalnih scenarija snabdevanja energijom. Ovaj rad istražuje primenu tehnologija veštačke inteligencije i velikih podataka, dok se uporedna analiza koristi za ispitivanje upotrebe alternativnih, obnovljivih i tradicionalnih izvora energije u kontekstu energetske tranzicije. Kroz uporednu analizu, studija ispituje prednosti, izazove i troškove proizvodnje povezane s alternativnim, obnovljivim i konvencionalnim izvorima energije. Rezultati naglašavaju potencijal pristupa zasnovanih na podacima za ubrzanje energetske tranzicije, istovremeno ističući ekonomske i tehnološke barijere koje se moraju rešiti kako bi se osigurala održiva energetska budućnost.

Ključne reči: Ugljenični otisak, održiva energija, energetska tranzicija, veliki podaci, VI.

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INTRODUCTION

The protection of the natural environment and the provision of sufficient energy will not be achievable without the use of advanced technologies such as big data and artificial intelligence (AI). The analytical processing of big data and AI technologies plays a key role in the energy transition, enabling more efficient utilization of renewable energy sources and the optimization of power systems. The use of big data technology is the key to the solution of multi-dimensional system problems, the improvement of operational efficiency, and the reduction of production costs. In addition, big data technology can also help users to analyze operating conditions and detect potential faults (Hong et al., 2023). The utilization of alternative and renewable energy sources represents the only viable strategy that can ensure a successful energy transition, distancing us from outdated and environmentally harmful energy supply systems based on fossil fuels and high carbon emissions.

With the support of artificial intelligence (AI) and big data technologies, this transition becomes more predictable, measurable, and feasible, enabling the anticipation of potential energy supply scenarios.

1. METHODOLOGY

The research was conducted through a comparative analysis of energy costs from various sources. Costs were presented using the Levelized Cost of Energy (LCOE) and Overnight Cost metrics for different sources - both renewable and conventional - using databases from the International Renewable Energy Agency (IRENA), Lazard, and the International Energy Agency (IEA).

2. MATERIALS AND METHODS

The energy sources included in the analysis are onshore wind, offshore wind, solar photovoltaics, and geothermal energy for renewable energy sources (RES), and natural gas, nuclear energy, and coal for conventional energy sources.

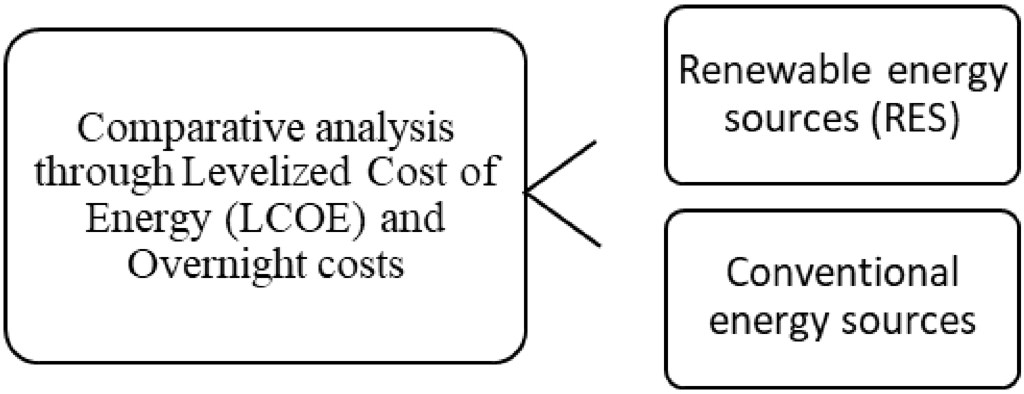

Figure 1. Comparative analysis of energy costs
Source: Author's figure

3. RESEARCH AND DISCUSSION

The comparative analysis of the Levelized Cost of Energy (LCOE) and overnight costs (as provided by Lazard, IRENA, and IEA) offers significant insights into the cost-effectiveness of both renewable energy sources (RES) and conventional energy sources.

Among the renewable energy sources analyzed, onshore wind stands out as the most cost-effective technology, with LCOE values ranging from 0.033 USD/kWh (IRENA) to 0.063 USD/kWh (Lazard). This places onshore wind as the leading renewable energy technology in terms of cost-effectiveness, making it an attractive option for large-scale energy production. In Serbia, where significant wind power capacity is already being developed, such as the Kovačica wind plant, onshore wind represents a critical component of the renewable energy transition.

Following closely in cost-effectiveness is solar photovoltaics (PV), with an LCOE ranging from 0.044 USD/kWh (IRENA) to 0.075 USD/kWh (Lazard). The declining cost of solar PV is a direct result of technological advancements and economies of scale, making it an increasingly viable option for sustainable energy production. With further investment in solar PV technologies, these costs are expected to continue decreasing, enhancing its competitiveness with onshore wind.

Offshore wind, with an LCOE ranging from 0.075 USD/kWh (IRENA) to 0.143 USD/kWh (Lazard), is still more expensive than onshore wind, yet remains an important technology, especially in coastal regions with high offshore wind potential. Despite its higher cost, offshore wind energy is expected to become more cost-competitive as turbine technologies improve and large-scale offshore wind farms continue to develop.

Among the renewable sources, geothermal energy stands out as the most expensive, with an LCOE ranging from 0.071 USD/kWh (IRENA) to 0.217 USD/kWh (Lazard). While geothermal provides reliable baseload power, its higher upfront costs and the need for specific geographical conditions make it less competitive compared to other renewables. Nevertheless, its long-term potential for stable energy production remains valuable, particularly in regions with significant geothermal resources.

When considering conventional energy sources, gas and nuclear still present higher LCOE compared to renewable sources, with values of 224 USD/kWh (gas) and 253 USD/kWh (nuclear), according to the IEA. However, these figures reflect the overnight costs of conventional plants, highlighting the significant capital expenditure involved in building these plants. Gas power plants, despite their relatively lower overnight costs (823 USD/kWe), face challenges related to fuel price volatility and carbon emissions, which reduce their cost-competitiveness in the long run. Nuclear power, with an overnight cost of 3606 USD/kWe, has the highest upfront capital requirements, making it less economically viable compared to renewable energy technologies. Additionally, nuclear plants face challenges related to regulatory approval, construction timelines, and waste disposal, further impacting their economic competitiveness.

Levelized cost of energy comparative analysis coventional versus RES

Table 1. Levelized Cost of Energy Comparison (USD/MWh)

Source	**Type of source**	**Min**	**Max**	**Mean**
Onshore wind	RES	27	73	63,5
Offshore wind	RES	74	139	143,5
Solar Photovoltaics	RES	29	92	75
Geothermal	RES	64	106	217
Gas	Conventional	110	228	224
Nuclear	Conventional	142	222	253
Coal	Conventional	69	168	153

Source: Author's systematization and calculation based on Lazard (2024) data

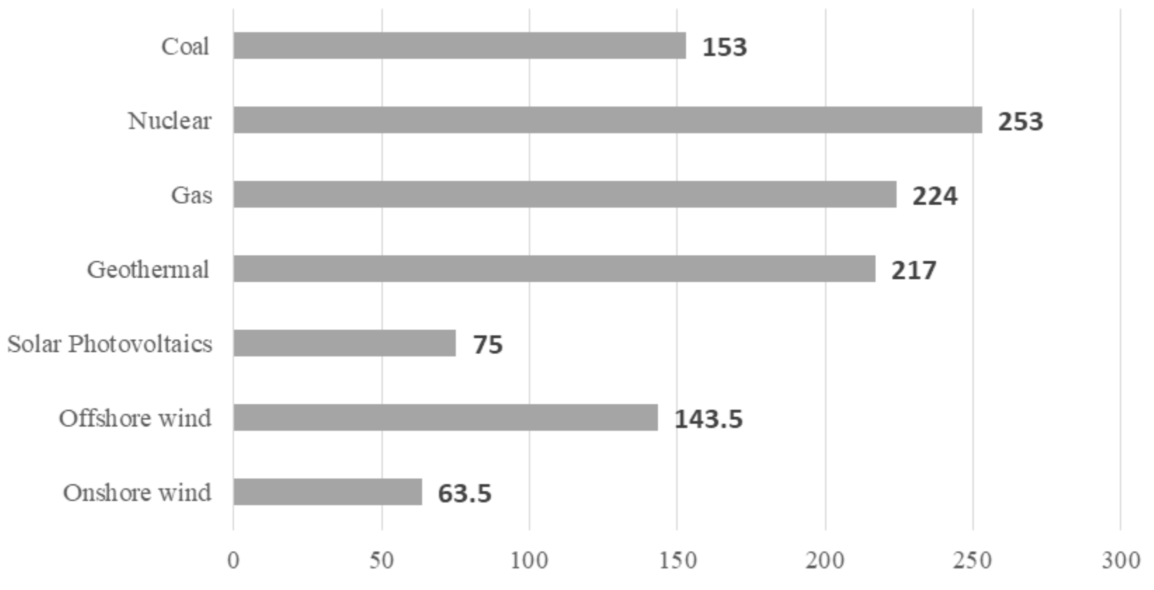

Figure 2. LCOE by source of energy in USD/MWh
Source: Author's figure

Levelized cost of energy comparative analysis RES

Table 2. Total installed costs and Levelized Cost of Energy Comparison (USD/kWh)

Source	Total installed costs	LCOE
Onshore wind	1160	0,033
Offshore wind	2800	0,075
Solar Photovoltaics	750	0,044
Geothermal	4589	0,071

Source: Author's systematization based on IRENA (2023) data

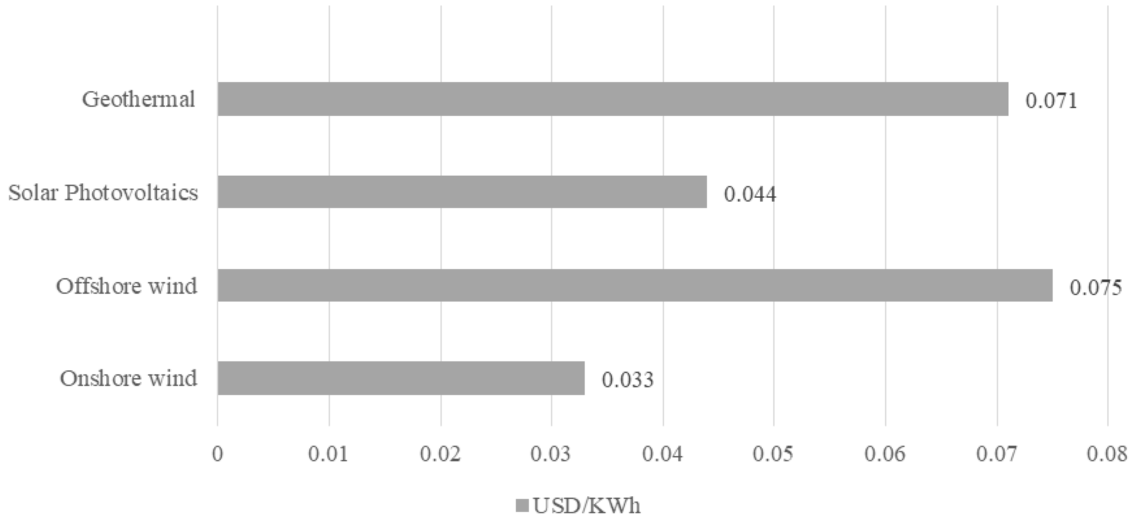

Figure 3. LCOE by source of energy in USD/kWh
Source: Author's figure

Overnight costs of energy comparative analysis coventional versus RES

Table 3. Overnight costs of Energy Comparison (USD/kWe)

Source	Type of source	Min	Max	Mean
Onshore wind	RES	877	3022	1391
Offshore wind	RES	1721	4039	2876
Solar Photovoltaics	RES	534	2006	995
Geothermal	RES	3851	10959	6647
Gas	Conventional	254	1109	823
Nuclear	Conventional	2157	6920	3606
Coal	Conventional	800	4382	1897

Source: Author's systematization based on IEA (2020) data

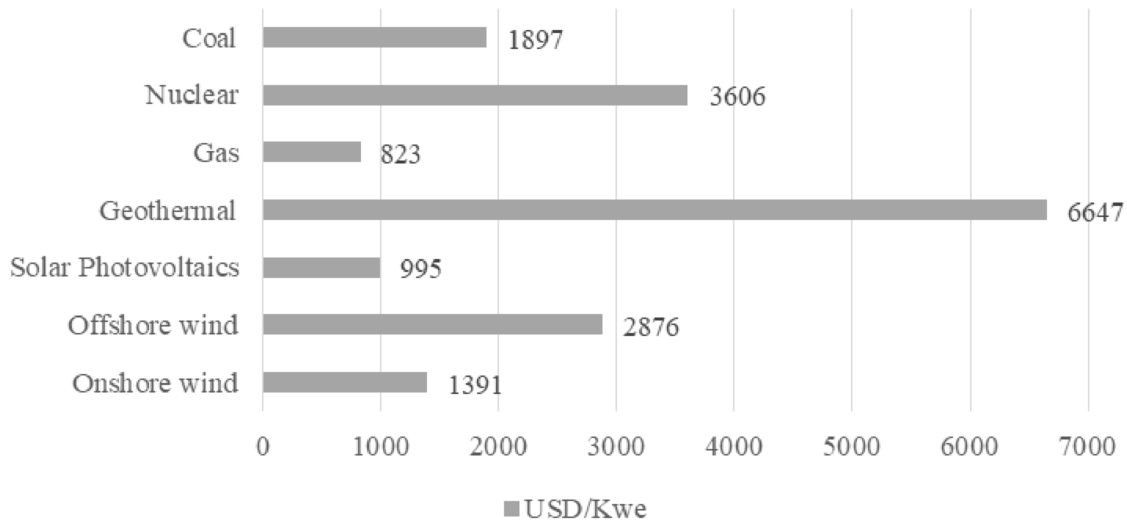

Figure 4. Overnight costs by source of energy in USD/kWe
Source: Author's figure

Synthesis of Comparative LCOE Results for RES

Table 4. Summary of Results from Cross-Comparison of Renewable Energy Cost Data USD/kWh

Source	USD/kWh
Onshore wind	0,048
Offshore wind	0,109
Solar Photovoltaics	0,059
Geothermal	0,144

Source: Author's calculation

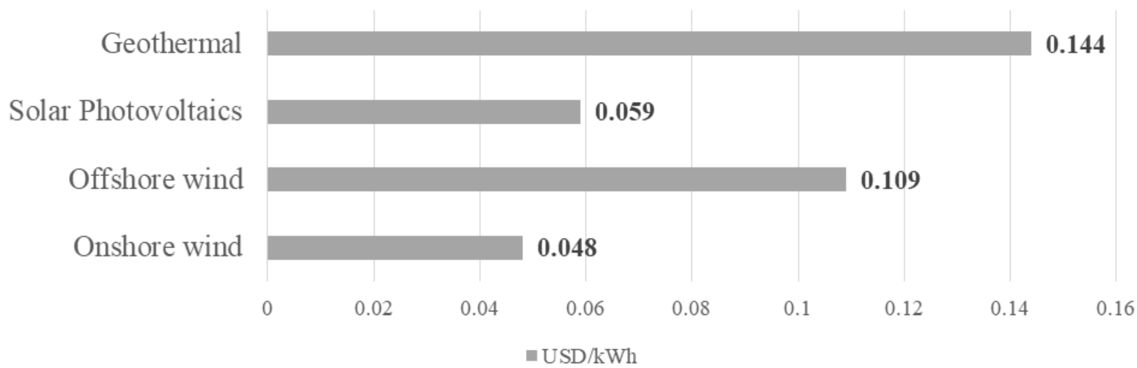

Figure 5. Summary data of Cross-Comparison of Renewable Energy Cost Data USD/kWh
Source: Author's figure

The differences between the LCOE values from Lazard and IRENA demonstrate the variations in assumptions and methodologies used in these reports. While Lazard tends to provide slightly higher LCOE values, especially for offshore wind and geothermal, IRENA's figures generally reflect lower costs, possibly due to different geographical assumptions or the inclusion of additional cost-reduction potential in emerging markets. These variations underscore the importance of using multiple sources of data to obtain a comprehensive understanding of the energy cost landscape.

Based on the comparative analysis of results according to LCOE, onshore wind is confirmed as the most cost-effective renewable energy technology among the sources analyzed, with a levelized cost of 0.048 USD/kWh.

Considering the high cost-effectiveness of these energy sources, which are being developed in Serbia (such as the significant wind power capacity at the Kovačica plant), the application and improvement of big data and AI technologies should be considered particularly in the context of cost-effective technologies. Following wind energy in terms of cost-effectiveness is solar PV – 0.059 USD/kWh, whose investment cost is significantly decreasing, while the cost of wind energy remains high.

In conclusion, renewable energy technologies - particularly onshore wind and solar PV - show great promise in providing cost-competitive solutions for global energy needs. As big data and artificial intelligence (AI) technologies continue to evolve, they can further optimize the performance, maintenance, and efficiency of renewable energy systems, potentially lowering the LCOE even more. The shift towards renewable energy is not only driven by environmental concerns but also by the growing recognition of its economic benefits, which are becoming increasingly clear as technologies continue to advance.

CONCLUSION

The comparative analysis of the Levelized Cost of Energy (LCOE) and overnight investment costs for both renewable and conventional energy sources reveals a clear economic shift in favor of renewable technologies, particularly onshore wind and solar photovoltaics. These sources demonstrate significantly lower LCOE values compared to conventional fossil fuels, alongside a continued trend of decreasing investment costs due to technological advancements and increasing deployment.

Onshore wind, as the most cost-effective energy source in the analysis, highlights the growing maturity and financial viability of renewable energy technologies. Solar photovoltaics, following closely, benefits from continuous innovation and global scaling, further reinforcing the competitiveness of renewables in the global energy mix. In contrast, conventional sources such as natural gas and nuclear energy remain burdened with high LCOE values and substantial upfront capital costs, which pose considerable barriers to long-term sustainability and affordability.

In this context, the integration of AI and big data analytics presents a critical opportunity to enhance the efficiency, reliability, and cost-effectiveness of renewable energy systems. By enabling predictive maintenance, optimizing energy output, and improving grid integration, these technologies can further accelerate the energy transition and support the widespread adoption of clean energy sources.

This study underscores the importance of combining economic feasibility with technological innovation to ensure a successful and sustainable energy transition. As energy systems become more complex and data-intensive, the application of AI and big data analytics will not only support smarter decision-making but also unlock new potentials for cost reduction and performance optimization. Investing in these digital technologies, especially in the context of already cost-competitive renewable energy solutions, represents a strategic pathway toward achieving global decarbonization goals and ensuring long-term energy security.

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European legal framework for sustainable waste management

Evropski pravni okvir za održivo upravljanje otpadom

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Abstract: The amount of produced waste and its inappropriate disposal is a global problem. Waste management aims to prevent waste generation and reduce its harmful impact on the environment. In order to reduce the amount of waste and reduce its harmful impact on the environment, the European Union has set ambitious goals for the realization of which it has adopted a number of different documents and rules. The circular economy is a model of production and consumption that includes sharing, renting, reusing, repairing, restoring and recycling existing materials and products, which aims to reduce the amount of waste to a minimum. In this way, the circular economy tackles climate change and other global environmental problems. The goal of European Union policies is to contribute to the circular economy by extracting resources from waste. The environmental goals of the European Union are ambitious, and their realization is necessary, and it is necessary to invest additional efforts in their realization, and the adoption of new legal rules will certainly be necessary.

Keywords: waste, waste management, sustainability, circular economy, legal framework, European Union.

Sažetak: Količina proizvedenog otpada kao i njegovo neodgovarajuće zbrinjavanje globalni su problem. Upravljanje otpadom usmereno je na sprečavanje nastanka otpada i smanjivanje njegovog štetnog uticaja na životnu sredinu. Kako bi se smanjila količina otpada te smanjio njegov štetni uticaj na životnu sredinu, Evropska unija je postavila ambiciozne ciljeve za čije je ostvarivanje donela niz različitih dokumenata i pravila. Kružna ekonomija je model proizvodnje i potrošnje koji uključuje deljenje, ponovnu upotrebu, popravku, obnavljanje i reciklažu postojećih materijala i proizvoda čime se količina otpada želi smanjiti na minimum. Na taj način cirkularna ekonomija utiče i na klimatske promene i druge globalne ekološke probleme. Cilj politika Evropske unije je da izdvajanjem resursa iz otpada doprinese kružnom gospodarstvu. Ekološki ciljevi Evropske unije su ambiciozni, a njihova realizacija je neophodna te je potrebno uložiti dodatne napore u njihovo ostvarivanje, a donošenje novih pravnih pravila svakako će biti nužno.

Ključne reči: otpad, upravljanje otpadom, održivost, kružna ekonomija, pravni okvir, Evropska unija.

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INTRODUCTION

Inadequately disposed waste in the environment (discharged into rivers, seas, at illegal landfills) is global and one of the biggest environmental poll-ution problems. The consequences of these pollut-ions have a harmful effect on the health of people and animal and plant species. As Herceg points out, inadequately disposed waste affects the quality of surface and underground water, changes and affects the soil, greenhouse gases from waste change local air quality, increase the risk of fires and explosions (Herceg, 2013). Traditionally waste management refers to collecting, transporting, and disposing of waste, where waste generated is collected and sent off to most often landfill sites or incineration facilities (Waste Mission, 2024). Here, the primary emphasis is on waste disposal, but it does not deal with the problems of reducing waste generation. Today, waste management has a broader meaning - it is aimed at preventing waste generation and reducing its harmful impact on the environment. In that sense, waste management can be defined as a set of activities, decisions and measures aimed at:

1. preventing the generation of waste, reducing the amount of waste and/or its harmful impact on the environment,

2. performance of collection, transportation, recovery, disposal and other activities related to waste, and supervision over the performance of these activities,

3. care for landfills that are closed.

The amount of produced waste and its inap-propriate disposal is a global problem. According to data from the European Commission, 5 tonnes of waste is produced by the average European each year (see Figure 1), and only 38% of waste in the European Union is recycled. Also, over 60% of household waste still goes to landfill in some European Union countries (European Commission n/a a). As stated in the Directive (EU) 2018/851, municipal waste constitutes approximately between 7 and 10 % of the total waste generated in the Union (Directive (EU) 2018/851, Preamble, point 6.).

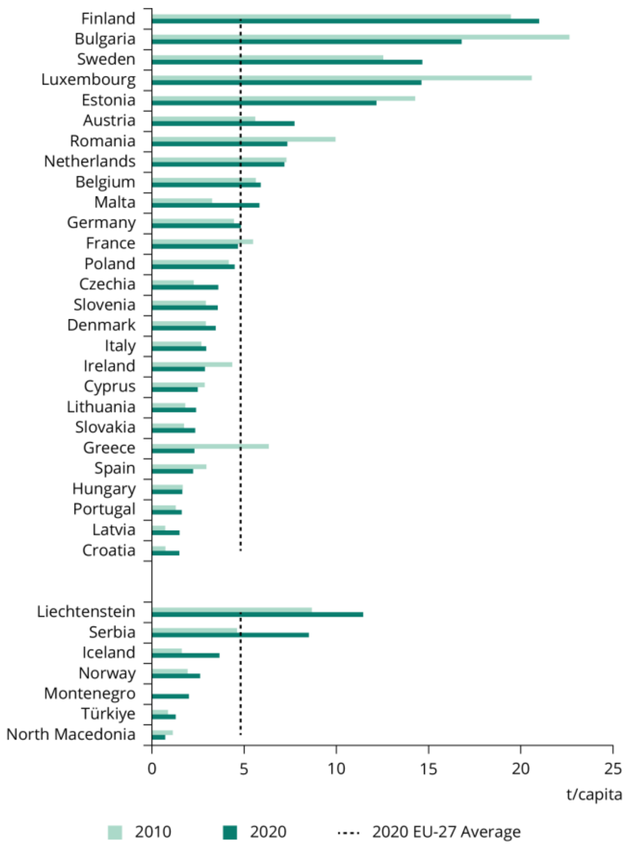

Figure 1. Generation of waste per capita and by European country (2010 and 2020)
Source: European Environment Agency (28.6.2023)

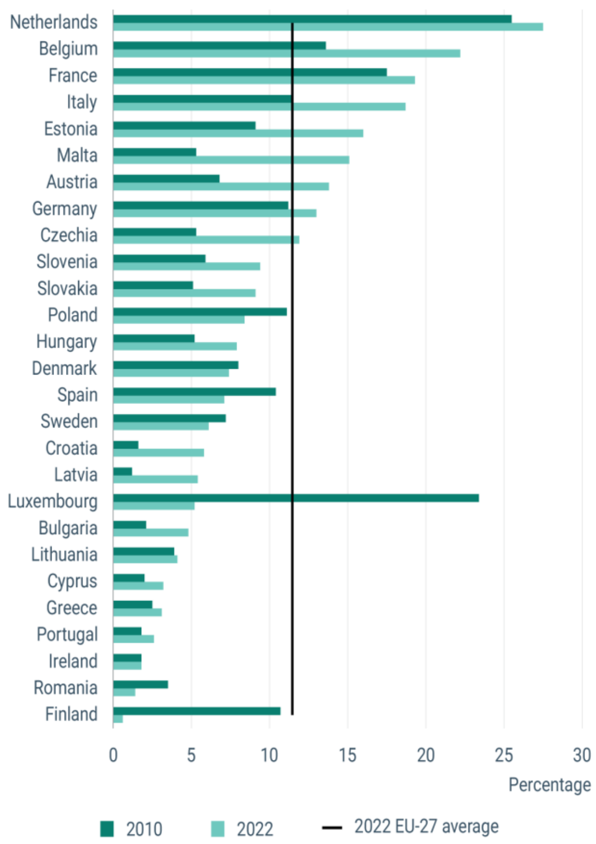

Figure 2. Circular material use rate by EU country (2010 and 2022)
Source: European Environment Agency (2.2.2024)

However, waste is not garbage and it can be a valuable raw material for further production. As described by Herceg, waste consists of discarded things that are sorted and usable. So, those that still have a useful value. On the other hand, litter (garbage) is everything that is discarded and unnecessary but unsorted. It has very little or no use value (Herceg, 2013). Still, there are other definitions of waste (Amasuomo et al., 2016; Dijkema et al., 2010; Van Ewijk et al., 2020). Dijekema et al. point out that a substance is a waste only when it is experienced as or labelled as waste (Dijkema et al. 2010), when the owner labels it as such. Therefore, it is necessary to accurately define and classify waste, because the classification of materials as waste will form the basis for the regulations necessary to protect the population and the environment in which the waste is processed or disposed of (Amasuomo et al., 2016).

It is undeniable that different types of waste and their huge amount represent a global problem of modern times. That is why appropriate waste management is essential for preventing waste, protecting living beings, health and the environment.

Intending to reduce the amount of waste and decrease its harmful impact on the environment, the European Union has set ambitious goals, which will be described in the paper. European Union has adopted a number of different documents and rules. In addition to the Waste Framework Directive, the legal framework includes a whole series of directives related to: waste batteries and accumulators, waste from vehicles, landfill waste, on waste management from extractive industries, packaging and packaging waste, the use of sludge from wastewater treatment plants in agriculture, waste electrical and electronic equipment. European Union waste policy aims to protect the environment and human health and help the EU's transition to a circular economy.

The circular economy is a model of production and consumption that includes sharing, renting, reusing, repairing, restoring and recycling existing materials and products, which aims to reduce the amount of waste to a minimum. In this way, the circular economy tackles climate change and other global environmental problems. European Union policies aim to contribute to the circular economy by extracting resources from waste.

The paper analyses the most important provisions of the Waste Framework Directive (which sets the basic concepts and definitions related to waste management) and other relevant regulations. Although there is a legal framework for waste, the implementation of directives in the European Union Member States differs significantly. The difference between the set goals and the results achieved so far is also visible.

1. OVERVIEW OF EUROPEAN UNION WASTE MANAGEMENT LEGAL FRAMEWORK

Waste management is a complex task, considering that almost every type of waste requires different treatments and regulations. Sustainable waste management seeks solutions that do not harm the environment or human health and aim to reduce the consumption of natural resources. Apart from environmental benefits, it has economic and social benefits as well. European Union targets for waste management are key drivers of increasing recycling rates, and European Union waste legislation includes more than 30 binding targets for 2015-2030 (European Environment Agency, 19.12. 2023).

The regulatory concept of waste comprises environmental principles, the legal definition, legal requirements, and policy implementation (Van Ewijk et al., 2020).

Waste management is based on compliance with generally accepted principles of environmental protection. Herceg enumerates the following principles of waste management: the principle of sustainable development, the principle of proximity and regional approach to waste management, the principle of hierarchy of waste management, the principle of "polluter pays", the principle of liability, the principle of public participation in decision making, the principle of zero waste (Herceg, 2013).

When we talk about European legislation related to waste, the first directives, although ineffective, were adopted in the 1970s, and legislation on waste was fragmented for a long time (Herceg, 2013). Waste management was emphasized as a priority in the first European Union Environmental Action Plan, adopted in 1972, and since then, it has continued to be one of the priority areas (Erceg et al., 2017).

There are many regulations, and most of them are directives. The main purpose of the directives is the harmonization of national legislation. They are binding on the member states regarding the results they need to achieve. However, they are left with a choice of methods by which they will achieve the goals of the European Union within the framework of their existing legal order.

Directives regulating waste can be divided into four groups:

1. Directives related to the waste management framework (e.g., Waste Framework Directive (2008/98/EC);

2. Directives related to special types of waste (Directive on packaging and packaging waste, Directive 2000/53/EC on end-of-life vehicles, Directive on waste electrical and electronic equipment,

Directive 2006/66/EC on batteries and accumulators and waste batteries and accumulators...);

3. Directives related to shipments of waste and the import and export of waste (Regulation 1013/2006 on shipments of waste);

4. Directives related to buildings for the processing and disposal of waste (Council Directive 1999/ 31/EC on landfill of waste) (Činčurak Erceg, 2024).

Nevertheless, the different requirements that certain types of waste require will necessarily require the adoption of new rules for those categories of waste, thus creating some new divisions. For example, Amasuomo lists different classifications and types of waste and explains that "common characteristics used in the classification of waste include the physical states, physical properties, reusable potentials, biodegradable potentials, source of production and the degree of environmental impact". They are most often divided according to their physical state (solid waste, liquid waste, gaseous waste), source (household/ domestic waste, industrial waste, agricultural waste, commercial waste, demolition and construction waste, mining waste) and environmental impact (hazardous waste, non-hazardous waste) (Amasuomo et al., 2016).

For the purposes of European legislation, a European List of Waste was established by Decision 2000/532/EC, which has been amended several times. There is also a Commission notice on technical guidance on the classification of waste whose purpose is to give technical guidance on certain aspects of Waste Framework Directive and List of Waste.

2. WASTE FRAMEWORK DIRECTIVE

The Waste Framework Directive (Directive 2008 /98/EC) was adopted in 2008. It sets the basic concepts and definitions related to waste management. According to Art. 3(1): waste "means any substance or object which the holder discards or intends or is required to discard". The Waste Framework Directive explains when waste ceases to be waste and becomes a secondary raw material, and how to distinguish between waste and by-products. Special conditions apply to hazardous waste, waste oils and bio-waste. Directive 2008/98/EC confirms the prevention principle, the precautionary principle, the "polluter-pays principle", and establishes extended producer responsibility as a key principle in waste management. It also sets out the waste hierarchy as follows: waste prevention, preparing for reuse, recycling, recovery and disposal (Art. 4(1)). This waste hierarchy shall apply as a priority order in waste prevention and management legislation and policy. As emphasized in the literature, waste hierarchy is the most significant instrument of the Waste Framework Directive as it places recycling after waste prevention and preparing for reuse (De Römph et al., 2020). However, "waste hierarchy has been contemplated in the international and national regulations, although there is no indicators for its implementation", although recycling rate is the most widespread indicator (however, recycling rate issues and limitations have also been pointed out) (Pires et al., 2019). It also sets quantity-based targets for the preparation of reuse and recycling for specific waste streams. It is necessary to mention Art. 13, which states that: "Member States shall take the necessary measures to ensure that waste management is carried out without endangering humans health, without harming the environment and, in particular: (a) without risk to water, air, soil, plants or animals; (b) without causing a nuisance through noise or odors; and (c) without adversely affecting the countryside or places of special interest". In accordance with Art. 15(1) original waste producer or other waste holder must treat it themselves or by a dealer or an establishment or undertaking which carries out waste treatment operations or arranged by a private or public waste collector. Pursuant to Art. 23(1) establishment or undertaking intending to carry out waste treatment must obtain a permit from the competent authority. Art. 34(1) stipulates the obligation of periodic inspections for establishments or undertakings which: carry out waste treatment operations, collect or transport waste on a professional basis, produce hazardous waste. Competent national authorities must establish waste-management plans (Art. 28) and waste-prevention programmes (Art. 29).

As part of a package of measures on the circular economy, Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amends Directive 2008/98/EC on waste. The amendment of 2018 did not modify the definition of waste, but added the definition of municipal waste (Art. 3(2b)). The Directive (EU) 2018/851 involved reform of the waste management policy: it changed the subject matter and scope of "the Framework Directive including therein the need to reduce waste generation and the importance of transitioning towards a circular economy, which is essential for guaranteeing the Union's long-term competitiveness. This is a significant modification, as it opens the door to including waste management systems in the global objective of achieving a real circular economy" (López-Portillo et al., 2021). It strengthens rules on waste prevention. The waste hierarchy was not modified in the amended Directive (EU) 2018/851, but as discused, the modification of the subject matter and scope implies the need for a systematic reinterpretation of waste hierarchy (López-Portillo et al., 2021). Reinterpretation "should also be extended to other precepts such as Art. 13, which refers to the adoption of measures to ensure that resource management does not entail a risk to the environment or human health" (López-Portillo et al., 2021). The Directive (EU) 2018/851 introduced the obligation to adopt economic instruments and other measures to provide incentives for the application of the waste hierarchy (Art. 4(3)). Examples of economic instruments and other measures are listed in Annex IVa, and include, for example: charges and restrictions for the landfilling and incineration of; "pay-as-you-throw" schemes; deposit-refund schemes and other measures to encourage efficient collection of used products and materials; use of fiscal measures or other means to promote the uptake of products and materials that are prepared for re-use or recycled; support to research and innovation in advanced recycling technologies and remanufacturing; public awareness campaigns, in particular on separate collection, waste prevention and litter reduction, and mainstreaming these issues in education and training.

Directive (EU) 2018/851 set out of new objectives for the recycling of municipal waste: 55% of all municipal waste by weight should be recycled or prepared for re-use in 2025, 60% in 2030 and 65% in 2035 (Art. 11 (2)). These goals will be challenging to achieve, as can be seen from Figure 3: Municipal waste recycling rates in Europe by country. It prescribes in Art. 9 (1)(g) a target for the reduction of food waste generation by 50 % per capita global food waste at the retail and consumer levels and to reduce food losses along production and supply chains by 2030.

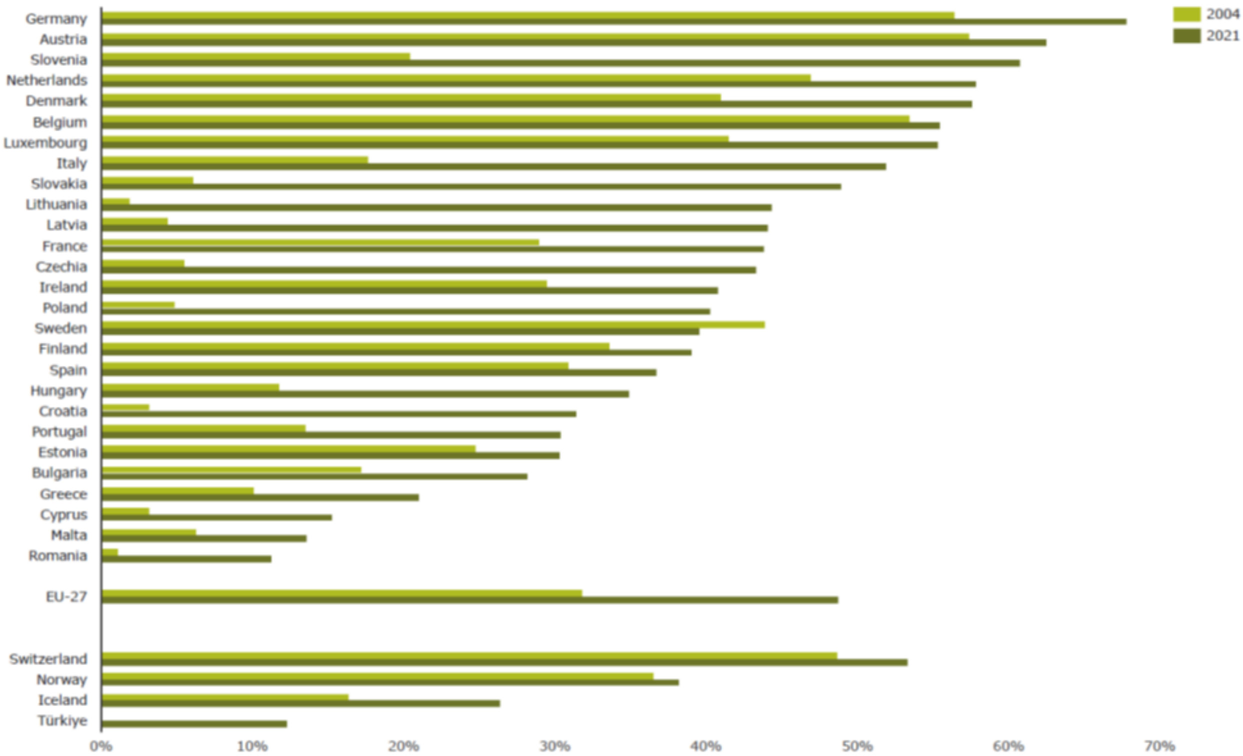

Figure 3. Municipal waste recycling rates in Europe by country
Source: European Environment Agency (19.12.2023)

Furthermore, the Directive obliges Member States to: establish, by 1 January 2025, a separate collection of textiles and hazardous waste generated by households (with the obligation of a separate collection at least for paper, metal, plastic and glass); ensure that, by 31 December 2023, bio-waste is collected separately or recycled at source (for example, by composting).

3. OTHER REGULATIONS REGARDING WASTE

It has already been stated that the European legal framework consists of a large number of special regulations for different types of waste. Their analysis would exceed the scope of this paper. However, some of them will be provided with basic information. Note that they were all amended with the aim of achieving the environmental goals of EU.

Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste (Directive (EU) 2018/850 of the European Parliament and of the Council of 30 May 2018 amending Directive 1999/31/EC on the landfill of waste) by introducing stringent technical requirements it aims to prevent, or reduce negative impact from landfill on surface water, groundwater, soil, air or human health.

European Parliament and Council Directive 94/62/EC of 20 December 1994 on packaging and packaging waste aims at harmonising national measures concerning the management of packaging and packaging waste and improving the quality of the environment by preventing and reducing the impact of packaging and packaging waste on the environment. Directive (EU) 2018/852 (amendment of Directive 94/62/EC) contains updated measures aimed at preventing the production of packaging waste, and promote the reuse, recycling and other forms of recovering of packaging waste, instead of its final disposal, thus contributing to the transition towards a circular economy.

Plastic and plastic waste are particularly significant problems for the environment. Statistics show that around 25.8 million tons of plastic waste is generated in Europe every year, of which less than 30% is collected for recycling (COM(2018) 28 final). Special attention is paid to the problems of microplastics (Činčurak Erceg, 2022). Directive (EU) 2019/904 of the European Parliament and of the Council of 5 June 2019 on the reduction of the impact of certain plastic products on the environment which aims to prevent and reduce the impact of certain plastic products on the environment, and includes an EU-wide ban on single-use plastic products whenever there are alternatives. It applies to the single-use plastic products listed in the Annex, products made from oxo-degradable plastic, and fishing gear containing plastic. In the context of waste management, Art. 9 should be mentioned, which stipulates that the Member States must take the necessary measures to ensure separate collection for the recycling of beverage bottles with a capacity of up to three litres, including their caps and lids by 2025, in an amount equal to 77% of the products placed on the market in a given year by weight (90% by 2029). At least 25% of beverage bottles should come from recycled plastic by 2025, increasing to 30% by 2030.

Figure 4. European Union targets for waste management

Area	**Target**	**Relevant EU Directive**
Municipal waste management	Preparing for reuse and recikling rate of municipal waste: At least 55% by 2025, 50% by 2030 and 65% by 2035 (by weight)	Waste Framework Directive
	Mandatory separate collection of textiles and household hazardous waste (by January 2025)	
	Mandatory separate collection (of recycling at source) of bio-waste	
Landfilling of waste	Share of municipal waste that is landfilled: maximum 10% by 2035	Landfill Directive
	Ban on the landfilling of waste suitable for recycling or other materials or energy recovery (from 2030)	
Packaging waste	Recycling rate for packaging waste, all materials: 65% by 2025 (70% by 2030) Paper and cardboard: 75% by 2025 (85% by 2030) Ferrous metals: 70% (80%); Aluminium: 50% (60%); Glass: 70% (75%); Plastic: 50% (55%); Wood: 25% (25%).	Packaging and Packaging Waste Directive
	Mandatory producer responsibility schemes for all packaging	
	The revised PPWD would bring changes that include: Reuse and refill targets to 2030 and 2040 Mandatory deposit return system (DRS) to ensure the separate collection of at least 90% of single-use plastic botles and beverage containers, by 2029 (possibility of exemption for countries who still achieve the 90% separate collection target)	
End-of-life vehicles	Reuse, recovery and recycling targets Minimum of 95% of reuse and recovery (by weight, per vehicle) by 2015 Minimum of 85% of recycling (by weight, per vehicle) by 2015	End-of-Life Vehicles Directive
Batteries and accumulators	Minimum rate of separate collection: 45% by 2016	Batteries Directive
Electrical and electronic equipment (EEE)	Minimum rate of separate collection: 65% of the awerage weight of EEE placed on the market in the 3 preceding years in the member state, or 85% of WEEE generated on the territory of the member state	Waste Electrical and Electronic Equipment Directive

Source: OECD (2024)

Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators promotes a high rate of collection and recycling of waste batteries and improvement in the environmental performance of all involved in the lifecycle of batteries, including their recycling and disposal. The Directive 2006/66/EC aims to cut the amount of hazardous substances (mercury, cadmium and lead) dumped in the environment by reducing the use of these substances in batteries and treating and re-using the amounts used.

Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles sets out measures to prevent and limit waste from end-of-life vehicles and their components by ensuring their reuse, recycling and recovery.

Directive 2006/21/EC of the European Parliament and of the Council of 15 March 2006 on the management of waste from extractive industries and amending introduces measures for safe management of waste resulting from the extraction, treatment and storage of mineral resources and the working of quarries. Operators must draw up a waste management plan that prevents or reduces waste generation, and encourages waste recovery and safe waste disposal.

In addition to the target listed in this brief overview of the directives, The European Union's targets related to waste include the introduction of economic instruments to reduce landfilling; "the introduction of simplified and improved definitions and harmonized calculation methods for recycling rates across the EU; specific measures to promote reuse and encourage industrial symbiosis, that is, the use of by-products from one industry as raw materials in another; mandatory extended producer responsibility schemes for manufacturers to encourage them to introduce more eco-friendly products to the market and support recovery and recycling systems (e.g. for packaging, batteries/accumulators, electrical and electronic equipment, and end-of-life vehicles)" (Szamek, 2024).

4. PROBLEMS OF IMPLEMENTATION OF THE DIRECTIVES

Although there is an extensive legal framework for environmental protection in the European Union, the problems of applying regulations in the Member States are still the biggest problem. Moreover, Zorpas points out that the European Union has released more than 1,000 legislations and directives related to environmental protection, but the absence of the implementation of those documents contributes to the waste production (Zorpas, 2020). In this sense, he also points out that "whereas most Member States already have a waste management system in place, even the most developed systems have to meet specific methodology and approach in order to advance the quality of life, meets environmental and legal standards, adopts best practices, substantially increases public participation and environmental education, the need for efficiency, and quality management" (Zorpas, 2020). Waste management strategies must comply with United Nations' Sustainable Development Goals., circular economy and industrial symbiosis concept as well as the Waste Framework Directive targets, concept and philosophy (Zorpas, 2020). López-Portillo et al. point out that the European Commission also recognised the implementation gap of the EU's environmental law as well as the European Environmental Agency indicated "the reinforcement of policy implementation and the improvement of its coherence as one of the main action areas to advance in the transition towards a sustainable society" (López-Portillo et al., 2021).

Legal literature usually emphasizes the problems of implementing European directives into national legislation. In this sense, the Waste Framework Directive is no exception. Its transposition into national law and the subsequent policy implementation differ in each Member State. As Van Ewijk et al. point out, "the national context, including government budgets, bureaucratic capacity, political trends, lobbying, established practices, and the inherited policy landscape, leads to distinct waste management arrangements" (Van Ewijk et al., 2020).

Member States must report to the European Commission on the implementation of European Union waste legislation. When European Union laws are not adequately implemented, the Commission can take legal action. However, to avoid reaching that stage, the Commission first offers technical support to Member States to guide them through implementation. Infringements of environmental law account for the largest number of cases dealt with by the European Commission - about 20% of the total. (European Commission, n/a b). According to the European Environment Agency, the European Union is slowly progressing towards more recycling and less landfilling (European Environment Agency, 21.3.2023). As stated in the Communication "Environmental Implementation Review 2022 - Turning the tide through environmental compliance" despite some progress, compliance with the basic obligations of the Waste Framework and the Landfill Directive is yet to be achieved. What is certainly worrying is the fact that the European Commission is pursuing infringement proceedings against 12 Member States for non-compliance with the Landfill Directive as well as there are some Member States that are far from achieving the recycling targets and still operate non-conform landfills. It is clear that there is a big difference between legislative requirements and practice. Establishing a suitable waste management system needs significant resources, cooperation, and time, and waste management approaches and policies are failing in many countries (Čինčurak Erceg, 2024). So, achieving the EU's waste targets requires a significant effort and achieving the goals will be neither quick nor easy.

5. CIRCULAR ECONOMY AND INDUSTRIAL SYMBIOSIS AS A WAY TO REDUCE WASTE

It has already been mentioned that the qualification of waste may change, so what is considered waste today can be a resource in the future. So, the production process can be used for the transformation of waste, and the waste/by-products of one industry can be the raw material of another.

De Römph et al. mention the problem of defining the term circular economy and state that no commonly accepted definition exists. Nevertheless, it can be said that the circular economy "is an economy in which materials are used sustainably, moving away from a linear ('take–make–dispose') economy into a circular one" (de Römph et al. 2020). It is based on the idea that the value of materials is maintained in the economy for as long as possible. It aims at conserving resources, tries to minimise and control the environmental as well as human health impacts of the entire material system (de Römph et al., 2020). It also reduces the production of waste to a bare minimum (López-Portillo et al., 2021).

The European Union has been implementing measures in the circular economy framework since 2014 (Ofak, 2024). Commission's Comunication of 2014 "Towards a circular economy: A zero waste programme for Europe" pointed out the need to evolve towards a more circular economy. In the year 2015, the first European Union Action Plan "Closing the loop – An EU action plan for the Circular Economy" (COM/2015/0614 final) was adopted. It is a set of documents addressing the full material cycle and includes several legislative proposals concerning European Union waste law. In 2020, a new Circular Economy Action Plan was adopted: "A new Circular Economy Action Plan for a cleaner and more competitive Europe" (COM/2020/98 final). The new EU's Circular Economy Action Plan "aims to expand the circular economy to the mainstream economic actors to achieve climate neutrality by 2050 and separate economic growth from the use of resources, as foreseen in the European Green Plan" (Ofak, 2024). However, it should be emphasized that "there is currently no initiative for a 'Framework Directive' on the circular economy that would bring all sectoral measures into alignment, and CEAP, as an action plan, is not legally binding" (Ofak, 2024). Critically analysing the Circular Economy Action Plan, Ofak concludes that the new action plan includes more legislative measures compared to the 2015 plan and that the examination of the advancement in the implementation of legislative measures indicates that the Member States generally support the actions outlined in it. However, Ofak also points out that the suitability of the selected instruments for transitioning the economy from a linear to a circular model is uncertain. She clarifies, citing the results of the research of other authors (Watkins, Van der Ven and Bondi, (2023) The Missing Piece of the EU Green Deal, The case for an EU resources law) that the EU's strategy for moving towards a circular economy does not place sufficient focus on reducing material resource usage through addressing consumption habits.

The industry's negative impact on the environment worldwide is recognised as a serious problem and environmental awareness is growing. A significant part of this impact could be reduced by improving resource efficiency. An important role in the transition towards sustainable development also has an Industrial Symbiosis. Chertow (2000) has defined Industrial Symbiosis as traditionally separate industries engaged "in a collective approach to competitive advantage involving physical exchange of materials, energy, water and by-products. Industrial Symbiosis involves the direct physical exchange of materials, energy and/or by-products" (Chertow, 2000). So, Industrial Symbiosis is the bussines relationship between industrial facilities or companies in which the waste or by-products of one become raw materials for another. Both Circular Economy and Industrial Symbiosis prioritize sustainability, but they have different focuses. Circular Economy is a broader concept, involving sustainable practices for all materials and products. Industrial Symbiosis, on the other hand, specifically targets industrial waste and by-products. So, Industrial Symbiosis also contribute to reuse of waste and by-products. With the concept of Industrial Symbiosis, it is possible to divert waste from landfills and reduce the negative impact on the environment. On the one hand, from a business perspective, Industrial Symbiosis can reduce the need for raw materials and waste disposal costs. From an environmental point of view, the benefits of Industrial Symbiosis are the reduction of consumption of natural resources and waste disposal, as well as the reduction of emissions to air, water and soil resulting from the production of saved raw materials.

CONCLUSION

Waste management was previously aimed at protecting health and the environment from the impact of littering, and more recently, it has been focused on the resource value of waste. Poor waste management is widely recognised as a source of economic costs, health and environmental risks. Waste management has been an essential concern for European Union and Member States legislators. Although numerous documents have been adopted and the goals set are ambitious, the development and progress of waste management and measures for proper treatment and disposal of waste is slow. In this sense, it is necessary to strengthen efforts in order to achieve the set goals. It is necessary to introduce regular activities to raise awareness about waste, practices of prevention, reuse, recycling, recovery of materials, etc. To significantly reduce waste production, prevention is widely acknowledged as the most important approach, taking precedence over recycling and other waste management strategies. In this context, ongoing education and increased awareness about the importance of minimizing waste generation are essential.

As shown in the paper, the European legal framework for waste management contains numerous directives, regulations and policies. A large number of regulations, as well as their frequent changes, are difficult to follow. Also, although there are general targets for waste reduction, precise mechanisms for monitoring and measuring progress are often missing. Also, the implementation of all these different directives can be complex and complicated. In practice, the implementation differs greatly among the Member States, which ultimately leads to the failure to achieve the goals achieved.

Although the circular economy and industrial symbiosis are mentioned as a possible way to reduce waste and environmental pollution, it seems that they are not used enough in practice, and the regulations do not regulate them enough. The environmental goals of the European Union are ambitious, and their realization is necessary, and it is necessary to invest additional efforts in their realization, and the adoption of new legal rules will certainly be necessary.

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Management of green finance through the prism of modern organization and organized green activities

Upravljanje zelenim finansijama kroz prizmu moderne organizacije i organizovanih zelenih aktivnosti

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Abstract: Through the perspective of planned green activities and modern organizations, the main subject of the paper is (some) aspects of green finance. The idea of sustainable development is connected with all aspects of contemporary human activity, especially in the last two decades. Climate change, which is increasingly serious and destructive to the natural environment, has conditioned a new way of behaving. The concepts of sustainable business and sustainable projects must be included in the organization's operations to protect the natural environment, which is necessary for every form of life on Earth, including people. In contrast to the generation of funds in the economy of scale, sustainable initiatives respect the social dimension, i.e., the "human" element, which is essentially the concept of not putting the environment in greater danger, beyond the limit of self-cleaning, but to use renewable energy sources and advanced technologies. Since people are the link between the economy and the environment, they must maintain a healthy lifestyle and engage in healthy and quality activities. Sustainable finance includes the use of green credit lines and other financial instruments to finance sustainability initiatives. Green projects, also known as sustainability projects, involve various investment interventions, including Feed-in Tariffs (FiT), as well as incentives for the use of biomass, solar, hydropower, and aeolian (wind) energy. A large number of international initiatives are being undertaken to raise capital and investments for sustainable infrastructure at the global level. The Clean Technology Fund (CTF), the Global Environment Facility (GEF), and the Clean Development Mechanism (CDM), established by the Kyoto Protocol, are just some of the initiatives promoting green finance. The paper aims to highlight the importance of sustainable development and the implementation of all initiatives, plans, and goals that derive from and support sustainability. One of the sustainable and very important directions is green financing projects, as well as concepts of green economy instruments, to which considerable attention is paid in the paper.

Keywords: Green finance, Sustainable Management, Modern organizations, Organized activities, Sustainable development, Green projects.

Sažetak: Kroz perspektivu planiranih zelenih aktivnosti i savremenih organizacija, glavni predmet rada jesu neki od aspekata zelenih finansija. Ideja održivog razvoja povezana je sa svim aspektima savremene ljudske aktivnosti, posebno u poslednje dve decenije. Klimatske promene, koje su sve ozbiljnijeg i destruktivnijeg karaktera za prirodno okruženje, uslovile su nov način ponašanja. Koncepti održivog poslovanja i održivih projekata moraju biti uključeni u poslovanje kompanija kako bi se zaštitila prirodna sredina, koja je neophodna za postojanje svakog oblika života na Zemlji, samim tim i ljudi. Za razliku od generisanja sredstava u ekonomiji obima, održive inicijative poštuju društvenu dimenziju, odnosno „ljudski“ element, koji je u suštini koncepta da ne dovodi životnu sredinu u veću opasnost – iznad granice samočišćenja, već da koristi obnovljive izvore energije i napredne tehnologije. Pošto su ljudi veza između ekonomije i životne sredine, važno je da održavaju zdrav način života i da se bave zdravim i kvalitetnim aktivnostima. Održive finansije obuhvataju korišćenje zelenih kreditnih linija i drugih finansijskih instrumenata za finansiranje inicijativa održivosti. Zeleni projekti, poznati i kao projekti održivosti, podrazumevaju razne investicione intervencije, uključujući Fid-in Tarife (FIT), kao i podsticaje za korišćenje biomase, solarne, hidroenergije i eolske (vetro) energije. Evidentno je da se preduzima veliki broj međunarodnih inicijativa za prikupljanje kapitala i investicija za održivu infrastrukturu na globalnom nivou. Fond za čiste tehnologije (CTF), Globalni fond za životnu sredinu (GEF) i Mehanizam čistog razvoja (CDM), uspostavljen Kjoto protokolom, samo su neke od inicijativa koje promovišu zeleno finansiranje. Rad ima za cilj da istakne značaj održivog razvoja i primenu svih inicijativa, planova i ciljeva koji proizilaze iz održivosti i podržavaju je. Jedan od održivih i veoma važnih pravaca su projekti zelenog finansiranja, kao i koncepti instrumenata zelene ekonomije, kojima je u radu posvećena značajna pažnja.

Ključne reči: Zeleno finansiranje, održivo upravljanje, moderne organizacije, organizovane aktivnosti, održivi razvoj, zeleni projekti.

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INTRODUCTION

The concept of a green economy gained prominence after the UN Green Economy Initiative, led by UNEP, which was manifested in the Global Green New Deal document of 2008. The deal was a package of public investments, complementary policies, and price reforms aimed at transitioning to a green economy to address global poverty and its permanent eradication (UNEP, 2011).

The definition of a green economy is given in the UNEP Report “Towards a Green Economy”, 2011: “A green economy is an economy that leads to improved human well-being and social equity, while significantly reducing environmental risks and environmental scarcity, and is resource efficient, social and inclusive, and low-carbon” (UNEP, 2011).

The concept of a green economy is based on: a) increasing activities for climate change resilience with low-carbon development; b) sustainable and balanced production, exchange, and consumption; and based on c) economic and social benefits, which are the drivers of green economic growth (Ilic, 2019). The concept of a green economy and green growth is closely linked to the idea of sustainable development, which is manifested in the practical application of a low-carbon economy and a radical transition to a green economy while preserving natural resources and protecting the environment. The hierarchy of the concept of greening the economy according to Adamowicz ranges from a new green deal, green growth, through a green economy, to sustainable development, as the ultimate instance (Adamowicz, 2022). Sustainability implies the harmonization of three pillars: Economy, Ecology, and Social component. The paper aims to explain the concept of green finance as an integral part of modern organizations, through the instruments of the green economy and certain principles of sustainable development. The research methodology used in the paper is based on desk research and literature review.

1. GREEN ECONOMY INSTRUMENTS

According to Agarwal & Jain (2024), the financial instruments used in green financing for green projects are:

1. Green bonds, the sale of which uses the money raised for energy efficiency, renewable energy sources, sustainable infrastructure, and greenhouse gas (GHG) reduction;
2. Green loans, which encourage borrowers to obtain favorable loans for “environmental ventures”;
3. Green equity, which involves buying shares in companies and creating green funds for environmental sustainability;
4. Carbon markets, where companies buy carbon offsets to reduce greenhouse gas emissions;
5. Green insurance, to reduce the risks of environmental hazards due to climate disasters through the use of insurance policies;
6. Green funds and sustainable investment portfolios, which are used for investments in green projects, combining investments from different investors; the investment portfolio applies environmental, social, and governance (ESG) factors, and
7. Green grants and subsidies, offered by governments or international organizations as incentives for environmentally friendly projects (Agarwal & Jain, 2024).

Financial policy and green economy instruments are:

1. Discounted green loans, in connection with which it is necessary to ensure reduced interest rates for green loans;
2. Green bonds, where it is necessary to develop the green bond market by providing incentives to banks and companies to issue them; and
3. Green companies and policies to improve the conditions for the green economy and environmental instruments (Gongsheng et al., 2015).

Green finance instruments are green bonds, through which stakeholders raise money for green business activities and banking services such as cash, insurance, lending, and mortgage insurance. Green bonds are financial instruments designed to finance environmentally sustainable projects and the transition to a low-carbon green economy. An increase in green bond issuance and market development can only be achieved if there is investor confidence, which is possible with bond premiums. To ensure that green bond issuance yields contribute to the transition, standards such as the European Union Green Bond Standard (EU GBS) are important, as they provide incentives for investors (Pietsch & Salakhova, 2022). The International Climate Bonds Standards (ICBS) are applied by the Green Bond Principles for the certification of green projects (CBI - Climate Bond Initiative, 2021).

The international standards define green bonds as having the following characteristics:

1. They are debt instruments, or loans, used to finance projects;

2. They are aligned with the proclaimed principles;

3. They apply best practices for internal control, monitoring, reporting, and verification when used; and

4. The financing is provided to achieve the climate goals of the Paris Agreement.

Green bonds are classified as follows (Inderst, Kaminker & Stewart, 2012):

1. Asset-linked bonds, such as green and infrastructure projects;

2. Corporate bonds issued by green companies; and

3. Bonds issued by institutions such as development, international, or financial institutions to raise funds for green projects, such as the World Bank, the European Investment Bank (EIB), the European Bank for Reconstruction and Development (EBRD), and the International Finance Corporation (IFC) (Inderst, Kaminker & Stewart, 2012).

Green insurance is an important pillar of green finance and bonds, as it contributes to achieving sustainability goals and reducing risks in financial operations through risk management, as it is necessary to respect financial investments and social responsibility. In contrast to the dominant emerging market countries, other countries with underdeveloped financial markets and underdeveloped financial infrastructure have had green bond issuances below potential.

Based on the IFC & Amundi (2024) study of emerging market green bond financing, it was found that China, although recording weaker growth, only 18% compared to the previous year, issued the largest amount of bonds, amounting to USD 89.13 billion, in 2023 (Table 1) (IFC & Amundi (2024). The United Arab Emirates had the largest primary green bond market after China, which is about 50% more than the previous year.

Table 1. Issuance of green bonds

Country	Issuance of green bonds in billions of dollars - billion USD	
	2023	**2012-2023**
China	89,13	292,50
Saudi Arabia	6,70	11,1
India	5,08	5,0
Brazil	4,69	18,1
Turkey	3,30	4,80
Indonesia	2,09	10,1
Poland	2,05	10,0
Mexico	1,65	5,20
Chile	1,61	16,6
Thailand	1,25	4,80
Hungary	1,09	7,80

Source: IFC & Amundi, 2024
(adapted by the author)

Saudi Arabia issued $6.7 billion in green bonds in the emerging financial market, followed by India with $5.1 billion, Brazil with $4.7 billion, and Turkey with $3.3 billion. Some countries, such as Indonesia and Hungary, although they did not have a larger amount of issuance than the previously mentioned countries, had a green bond market that was regularly established and functioning adequately during 2023 (IFC & Amundi, 2024). Among the countries observed, countries that did not issue green bonds are Bangladesh, Bosnia and Herzegovina, Ghana, Nepal, Maldives, Paraguay, Sri Lanka, Honduras, Barbados, Dominican Republic, Cabo Verde, Tunisia, and Samoa. In the green transition process, strengthening financial capital and financial markets in low-income and developing countries requires legal regulation, harmonization of standards with other jurisdictions, adequate management of financial instruments, and cooperation between governments and public and private institutions with international investors. To increase demand for green investments for activities that reduce carbon emissions in emerging markets and developing economies (EMDEs), it is important to ensure greater availability of capital and its affordable price (Monasterolo et al., 2022). The Green Financial Sector Initiatives (GFSI) are of great importance for fiscal policymaking and the low-carbon transition. Initiatives play an important role in fostering green investment for EMDEs, as they have positive implications for regulating social and economic equity in society and for macroeconomic and financial stability. It has been estimated that the need for green investment capital in EMDEs is around 90% in countries with underdeveloped capital markets, which indicates that they have an important role in solving the problem of harmful greenhouse gas emissions and sustainable green development (Monasterolo et al., 2022). Regarding green finance sector initiatives, the activities of the European team "Global Green Bond Initiative" (GGBI) to promote the development of green bond markets in developing countries are significant. GGBI was established by the European Commission and a consortium of European Union development finance institutions, under the management of the European Investment Bank (Đukić, 2024).

The regions and countries covered by the financial support, promotion of green investment and initiative by GGBI are: Asia-Pacific region: Bangladesh, Fiji, India, Indonesia, Kazakhstan, Malaysia, Mongolia, Pakistan, Philippines, Thailand, Uzbekistan, Vietnam; Latin America and the Caribbean region: Bolivia, Brazil, Colombia, Costa Rica, Dominican Republic, Ecuador, Guatemala, Mexico, Panama, Paraguay, Peru, Uruguay; Sub-Saharan Africa region: Benin, Côte d'Ivoire, Ghana, Kenya, Namibia, Nigeria, Rwanda, Senegal, South Africa and Uganda (GGBI - Global Green Bond Initiative, 2021).

The support of the GGBI expert team consists of activities such as:

1. Mobilizing capital from institutional investors to be used for green bonds, climate change mitigation, and environmental projects;
2. Diversifying access to private capital to finance an inclusive green transition;
3. Establishing credibility for green bonds;
4. Reducing investment risks;
5. Attracting investors; and
6. Providing guarantees and establishing investor confidence (GGBI - Global Green Bond Initiative, 2021).

2. GREEN FINANCE

Green finance is a form of lending or investment for energy efficiency, which reduces the use of energy sources that are harmful to the environment and achieves a reduction in greenhouse gases (Greenhouse Gases - GHG). Green finance has positive implications for achieving the climate goal, which is manifested in reducing the increase in average temperatures on Earth below 20°C. According to Ilić et al. (2019), green finance contributes to a sustainable green economy and sustainable development by investing in projects that help mitigate climate change.

The green economy is a generator of new jobs and a driver of the strategy against poverty, according to some authors (Ilić, Đukić, Balaban, 2019). The goals of environmental sustainability and economic progress are linked, as there is increasing evidence that greening the economy affects greater employment opportunities. A green economy is a socially inclusive and low-carbon economy with efficient use of natural resources (Ilić & Stanković, 2023). Damani & Manjrekar (2024) have pointed out that access to green finance is particularly important, as it creates more equitable economic and social development in countries that are less developed and poor and that have problems with climate change. Thanks to access to green finance, a financial "green" product or service is created, which gradually reduces harmful carbon emissions.

The potential is created to transform society with the effect of a "large green multiplier". Green activities covered by green finance are grouped into the following categories (Damani & Manjrekar, 2024):

- Pollution prevention and control;
- Biodiversity conservation;
- Waste treatment and recycling;
- Development of a circular economy;
- Climate change mitigation;
- Sustainable use of land and natural resources;
- Use of renewable sources.

Green finance is supported by financial institutions, green banks, green funds, and innovative financial instruments such as green bonds and carbon markets (Ilić, Stojanovic & Djukic, 2019). Investments include the development of clean and green technologies, national regulatory frameworks, financial incentives for the conservation of natural resources, and the reduction of greenhouse gas emissions. Green finance channels financial flows towards socially and environmentally responsible enterprises. In modern conditions, financial mobilization is one of the most important factors in supporting ecological transformation to mitigate the consequences of climate change and greenhouse gases.

Green infrastructure finance framework is presented on Figure 1. It can be seen that the central part of the financial framework is the financing and advisory interface, which influences financial advisory for the monetization of greenhouse gas emission benefits (regenerated carbon, specialized green funds, bilateral donor aid, concessional export financing and the modified Clean Development Mechanism), as well as for the monetization of local benefits and rebalancing of disruptions with domestic sources (Feed-in Tariffs, specialized green funds, fiscal and tax incentives, direct subsidies, country-specific carbon financing). On the other hand, the analysis of the sustainability gap of green projects is focused on the political environment and the regulatory and institutional framework .

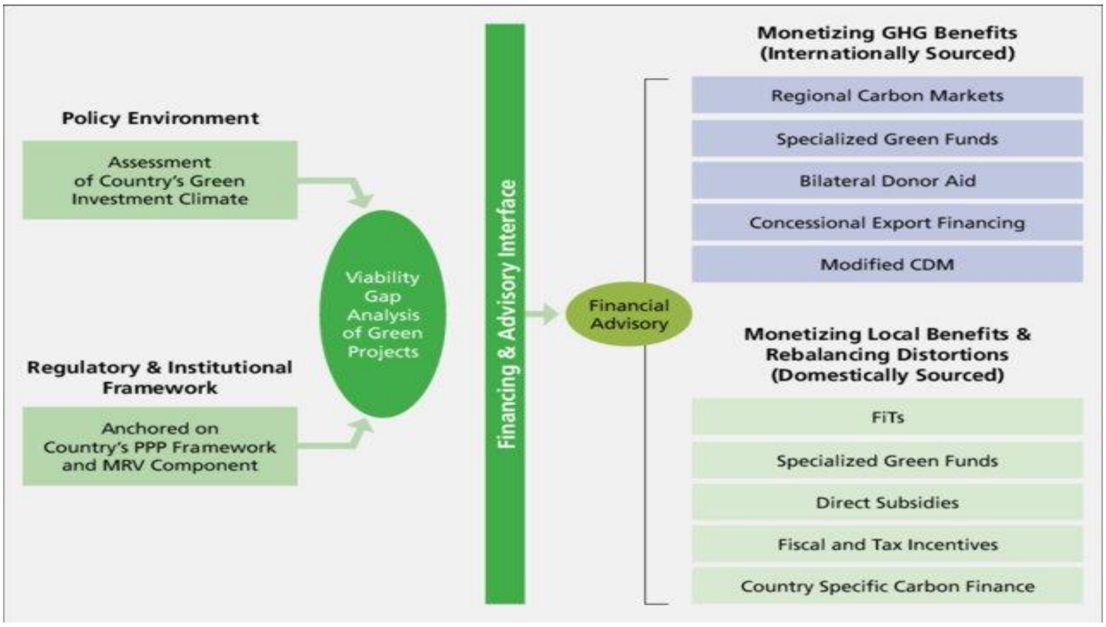

Figure 1. Green infrastructure finance framework
Source: Baietti (2013)

For the economy to be carbon neutral, investments in clean transport, renewable sources, and transition industries are of great importance. Green lending is a form of financing alternative energy sources by banking institutions, with the investment having a 20% savings effect according to certain qualifying criteria. The 20% savings percentage is applied in most banks and international green financing funds. Green lending is characterized by advantages compared to standard loans.

The advantages are:

1. Investments are measurable against costs of at least 20% and energy savings;

2. The rate of late payment of installments by clients is even three times lower compared to the entire loan portfolio; and

3. Green loans are long-term with a term of five years or more, based on which mutual income benefits are achieved for both the client and the bank.

The mechanism of green investment and the development of the green financial market were discussed by Noh (2018).

He advocated the traditional CAPM model (Capital Asset Pricing Model - CAPM) for green investing, based on the theoretical concept of economic return. He revised the traditional model with a new approach because, along with economic return, investors also expect “green value”, so the expected “Rate of Return on Green Investments” is shown in formula (1) (Noh, 2018):

$$TR = R + GR \quad (1)$$

Where:

TR - Total return,

R - Return (economic return),

GR - Green Return.

The rate of return on green investments is the sum of the economic return and the green return. Noh (2018) concluded that “green” investors who are financially oriented will emphasize the utility of economic returns, while other investors will emphasize the green value and benefits of green returns.

3. GREEN FINANCING ORGANIZATIONS

The Global Green Bond Initiative (GBI) is a coalition of development finance institutions and multilateral organizations, that form a consortium, namely: the European Investment Bank (EIB), the European Bank for Reconstruction and Development (EBRD), the Italian Bank (Cassa Depositi e Prestiti), the Spanish Agency for International Development Cooperation (AECID), Germany's KfW development bank, and PROPARCO from the AFD group, which are actively involved in financing under the Green Climate Fund. The consortium has established a strategic partnership with the Inter-American Development Bank (IDB) and the Inter-American Investment Corporation (IDB Invest) to promote a green financial bond market in Latin America and the Caribbean (EIB, 2023). The Finance Summit was held from 4 to 6 September 2023 in Cartagena, Colombia, where the Declaration "Global Green Bond Initiative: A Shared Goal" was signed in partnership cooperation to strengthen the green finance market, which includes international cooperation with local and regional development banks around the world. In this way, opportunities are created to provide financial support and assistance to partner countries for the development of green and infrastructure projects through credible and interoperable green bonds (EIB, 2024).

Multilateral Development Banks (MDBs) have great importance in the financial market for green, social, and sustainability bonds, which they issue with their high credit ratings. The first green bonds were issued by MDBs, which were the only ones to issue them until 2012, while the first issuers of social bonds on the market were multilateral organizations and non-sovereign financial institutions. The EBRD is a financial institution, in other words, the European Bank for Reconstruction and Development, which improves the conditions of the Serbian capital market by issuing dinar bonds, and the first issue in Serbia. The main goal is to enable lending to the Serbian economy in the national currency, thereby contributing to a higher value of the currency, i.e., better dinarization. The focus of the EBRD institution in Serbia is multidimensional (Ostojić, 2022). The EBRD leads to a faster turnover of green energy, emphasizing renewable energy sources, such as solar or wind energy, thereby improving their implementation in district heating systems with its financial instruments. The EBRD provides financial support to sustainable infrastructure, which connects and strengthens regions in the country. Supporting Serbian investment in the environment and ecological infrastructure leads to more efficient management of both pollutants, i.e., waste, and better wastewater management (Dimić et al., 2023). Projects that do not affect air pollution are also financed, as well as irrigation projects, which affect the development of the circular economy. The possibility of attracting private investors is opened, while at the same time promoting sustainable transport, i.e., investment in rail transport, connecting the WBs region with the main corridors of Europe.

The project called "European Union for a Green Agenda in Serbia", in cooperation with UNDP projects and plans, encourages green innovations, but also the energy transition in the WBs, i.e., in Serbia. The regional office of the French Development Agency (FDA), in charge of the WBs, invested more than half a million euros in Serbia over three years (2020-2023), while in other WB countries, it invested twice as much (AfDB, 2024). Through the action of the state and foreign partners committed to sustainable development, it is possible to attract new workers to newly created jobs, in jobs enabled by the green financing program. Every green action, from landfill remediation, air protection, to circular economy and recycling technology using renewable energy sources, requires human resources as the main carriers of the work (Nikolić, 2016). The German Development Bank (KfW) is present as a green financing institution in Serbia, as it allocates significant funds to decarbonization projects and the circular economy. The projects financed by KfW are: a) wind farms using wind energy near Kostolac and within the Trans-Balkan Corridor; b) Serbian municipalities in the treatment of healthy and clean water; and c) wastewater treatment (Djukic & Ilic, 2024). According to certain estimates, for Serbia, it has been determined that in 2022 alone, around two hundred million dollars have been allocated for green investments. The EU initiative "European Union for the Green Agenda in Serbia" has generated around two million dollars in direct co-financing. Within the framework of the Program, more than 20,000,000 USD has been secured through the total investments made in green projects (UNDP Serbia, 2023).

CONCLUSION

A properly designed green finance policy can only lead to the expected results. Conversely, if the policy is inadequate, negative effects and problems occur: insufficient incentives for green investments affect environmental pollution; if an adequate financial assessment of capital investments in green industries is not carried out, there is a "waste of financial resources" and the allocation of investments to industries with polluting emissions; and due to unassessed risks, there is non-payment or bankruptcy.

Three key factors are important for maximizing the social welfare contributed by green projects with green economy instruments: increasing returns from green projects, reducing returns from polluting projects, and increasing awareness among investors, consumers, and businesses, all of which contribute to the most effective green economy policy and its implementation. To achieve the expected benefits of green finance, recommendations were made with a review of the economic mechanisms of green finance and for limiting investments that negatively affect environmental pollution, i.e., increasing carbon emissions. Promoting green financial innovations, with the aim of a more open, liquid, and efficient financial system by taking measures such as: deepening the financial capital market, diversifying financial products and instruments, supporting the participation of institutional investors, promoting competition, financial inclusion for small and medium-sized enterprises and low-income households, establishing financial regulation, and developing financial innovations, thereby improving the business environment.

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Perspectives on the Application of Artificial Intelligence (AI) in the Development of Hydrogen Energy in the Republic of Serbia

Perspektive primene veštačke inteligencije (AI) u razvoju vodonične energije u Republici Srbiji

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Abstract: Green hydrogen has been globally recognized as the fuel of the future, primarily aimed at reducing the footprint of fossil fuels. The concept envisions hydrogen being utilized both as an energy source and as a means of energy storage. Plans include its application in transportation, heating, and various industrial sectors such as the production of copper, iron, aluminum, fertilizers, and cement. Due to its dual role and versatility across different applications, hydrogen energy is gaining prominence and is increasingly acknowledged in the pursuit of a sustainable energy future. To bridge the gap between its high potential and practical implementation. Artificial intelligence (AI) and its applications such as machine learning (ML) are emerging as an indispensable tool in bridging this gap in prediction based on pre-generated variables, and digital twin (DT) as a tool (AI) that provides the possibility of a virtual modeling platform. The Republic of Serbia is facing challenges of a technical, financial and regulatory nature on the hydrogen map, and in order to connect to global development directions in this area, the application of tools (AI) can be a good option related to strategic development. This paper points to the possibility of applying tools (AI) in hydrogen energy at all stages of the life cycle, with a special focus on the optimal design of hydrogen-based (PV) generation systems. As well as the integration of hydrogen systems with wider energy networks and systems. The paper further clarifies the optimal-cost design of a Power-to-hydrogen (PtH) system for hydrogen production. It points to the possibility of application (AI) in this model, and thus gives a recommendation for the application of (AI) and its applications in the strategic development of hydrogen energy in the Republic of Serbia.

Keywords: green hydrogen, artificial intelligence, digital twin, power-to-hydrogen.

Sažetak: Zeleni vodonik je u globalnom smislu proglašen gorivom budućnosti, sa primarnim zadatkom da smanji otisak fosilnih goriva. Ideja je da se vodonik u budućnosti koristi kao energent, ali i kao baterija za skladištenje energije. U planu je da se vodonik upotrebljava za transport, grejanje, industrijske grane kao što su proizvodnja bakra, gvožđa, aluminijuma, veštačkog đubriva i cementa. Zbog dvojne uloge i primene u različitim aplikacijama vodonična energija zauzima primat i postaje sve više priznata u održivoj energetskoj budućnosti. Iz navedenih razloga potrebno je premostiti jaz između visokog potencijala i praktične primene. Veštačka inteligencija (AI) i njene aplikacije kao što su mašinsko učenje (ML) se nameću kao nezaobilazan alat u prevazilaženju ovog jaza u predviđanju na temelju unapred generisnih varijabli, a digital twin (DT) kao alat (AI) koji pruža mogućnost virtuelne platforme za modeliranje. Republiku Srbiju na vodoničnoj mapi očekuju izazovi tehničke, finansijske i regulatorne prirode, a da bi se konektovala na globalne pravce razvoja u ovoj oblasti primjena alata (AI) može biti dobra opcija vezana za strateški razvoj. Ovaj rad ukazuje na mogućnost primene alata (AI) u vodoničnoj

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energiji u svim fazama životnog ciklusa, sa posebnim fokusom na optimalno projektovanje sistema za proizvodnju vodonika na bazi (PV-a, kao i integraciju vodoničnih sistema sa širim energetskim mrežama i sistemima. Rad dalje pojašnjava optimalan-troškovni dizajn sistema Power-to-hydrogen (PtH) za proizvodnju vodonika. Ukazuje na mogućnost primjene (AI) u ovom modelu, te na taj način daje preporuku za primenu (AI) i njenih aplikacija u strateškom razvoju vodonične energije u Republici Srbiji.

Ključne reči: zeleni vodonik, veštačka inteligencija, digitalni blizanac, vodonična energija.

INTRODUCTION

Green hydrogen production is a key factor for decarbonizing the atmosphere and reducing the carbon footprint, and all future climate change mitigation scenarios emphasize the need for hydrogen to account for about 12% of global energy consumption by 2050 (IEA, 2022, 2023; EC, 2020; Department of Energy, 2020). Meeting such energy demand requires an increase in hydrogen production from the current 90 million metric tons (Mt) per year to about 600 (Mt) by 2050 (IEA, 2022; IRENA, 2022). Hydrogen is an energy source, but also an energy carrier that should play a key role in the decarbonization of industry and transport as the branch with the highest carbon emissions (Rissman et al., 2020; IRENA, 2020). Hydrogen is used to store energy from renewable sources of electricity (Terlouw et al., 2022), then as a chemical raw material and precursor of synthetic hydrocarbons for the production of e-fuels (Van der Spek et al, 2022; Ueckerdt et al., 2021). Due to its high calorific value compared to fossil fuels, hydrogen acts as an energy vector, and hydrogen projects and development policies around the world are experiencing great momentum. Hydrogen and fuels derived from it cover a wide range of applications in transportation, heating and industrial production such as production of copper, iron, aluminium, artificial fertilizers and cement. Despite the great potential, green hydrogen production faces the challenges of high capital investments (CAPEX) and operational costs (OPEX). In order to ensure the economic viability of hydrogen production, in addition to finding the optimal combination of renewable energy sources, geographical location, suitable climatic conditions and water electrolysis technologies, it is necessary to find adequate sources of financing, and to adapt the entity government's fiscal policy to development projects. Renewable sources such as wind, water, sun are potential and promising sources of green energy (Terlouw et al., 2022; VanderSpek et al, 2022; Ueckerdt et al., 2021). However, there are still significant limitations to their full development because they are highly variable resources and depend on weather conditions (EU, 2023a), which prevents the optimal use of energy generated by these methods (EU, 2023b). In this context, the need to develop methodologies and strategies to solve these complex challenges becomes imperative. Therefore, it is necessary to optimally design the system for the production of hydrogen from renewable sources, which includes the analysis of the unit costs of hydrogen production (LCOH) as well as the analysis of the costs of energy production (LCOE) (Oliva, Garcia, 2023). This analysis must carefully consider the technology used, the electricity generation environment with meteorology, (CAPEX), (OPEX), the financing rate, the efficiency of renewable and electrolysis systems, as well as the lifetime of these systems (depreciation).These challenges have been addressed by several researchers in the world with a focus on different issues; Hassan et al. (2023) made a detailed review and study on the production of green hydrogen from a techno-economic, ecological and social perspective. Scheepers et al. (2023) determined that the optimal design and operation of the electrolyzer strongly depends on the framework conditions under which the operation takes place, such as the investment costs in the electrolyzer and the price of electricity. A strong dependence (LCOH) on the price of electricity was also found by Superchi et al. (2023) who conducted a techno-economic analysis of green hydrogen production for the decarbonization of steel production. Shams et al. (2021) use a machine learning (ML) algorithm to predict wind and (PV) energy constraints. Based on this, an original planning model was developed to reduce the waste of wind and (PV) energy using battery and hydrogen storage systems. Al-Othman et al. (2022) have comprehensively reviewed the application of (AI) techniques in hybrid renewable energy systems (HRES), especially solar (PV) and wind energy integrated with fuel cells. This study further clarified that the main strengths of the (AI) solution revolved around predicting shortfalls (HRES) during peak load periods as well as intermittent power generation. Al-falahi et al. (2017) conducted a comprehensive review and critical comparison on optimization approaches based on stand-alone solar and wind hybrid energy systems. This study revealed a growing interest in the development of stand-alone optimization algorithms (HRES). To date, reported optimization methods can be roughly classified into classical algorithms, modern techniques, and software tools. Modern techniques, based on some (AI) algorithm, gain an advantage over classical algorithms due to their ability to solve some complex problems. Applications (AI) are powerful tools that could solve the complexity of the energy transition, improve system efficiency, reduce costs, and accelerate the speed of the decarbonization transition (Zhou et al., 2020; Zhou, Zheng, 2020). They are primarily applied to the production of renewable energy sources, demand forecasting, optimization of network operation and energy demand management (Hannan et al., 2021; Abdalla et al., 2021). "The Republic of Serbia is constantly investing in its energy potential, and therefore in renewable sources of sun and wind, so in 2025 it should get new wind power plants with a capacity of 76 megawatts and solar power plants with a power of about 62 MW, which means that it will have wind parks with a power of 684.2 MW on the network, of which the installed capacity of new wind power plants will be 76 MW. The market premium will be used for 94.4 MW, and feed-in tariffs 60.3 MW of electricity will be produced by solar power plants, of which 18.7 MW are new capacities. The projected capacity of the producers is 123.6 MW, of which the new capacity is 61.7 MW. Solar and wind should produce 4.6 percent of the total production. The stated situation is stated in the Energy Balance of the Republic of Serbia for the year 2025, Official Gazette of RS No. 12/2025-28 of February 7, 2025.

The Republic of Serbia currently has two conceptual projects in the field of green hydrogen with the idea of developing experimental facilities on them. The first one is called "Pančevo Hydrogen Valley". It is about a project that would be located on the Danube Corridor 7, one of the most important European roads, which is actually a waterway along the Danube from Germany to the Black Sea. The idea of this project is to use solar and wind energy to produce electricity, in order to further obtain green hydrogen through electrolysis. Floating plants for the production of electricity and hydrogen will be built on the Danube or the Sava, on which mobile wooden platforms would be placed, on which, on the first level, there would be hydrogen tanks, and solar panels or wind generators, or a mix of both, would be placed above the tanks. The Port of Pancevo represents a good technical opportunity to build a pilot plant for the start of hydrogen production from solar panels. The second project is the integration of hydrogen into the existing gas pipeline infrastructure of the pilot project in Sombor. What is important is the percentage of hydrogen that will be released through gas pipeline systems, due to its technical and safety nature. Since hydrogen is technically a different type of gas than natural gas, the existing infrastructure therefore requires certain changes and adaptations. Therefore, it is important to see what those changes are so that hydrogen can be used and transported. In terms of investment, a smaller plant would be developed that would produce hydrogen from solar panels and then inject it into the gas pipeline system. Experiences from Greece, their preliminary tests, showed that hydrogen from 10 to 12% can be mixed with natural gas in certain situations and up to 15% and that it can be used as such in the existing gas system without significant interventions on the system. This is the reason that determines to develop this kind of project, but also to use all the benefits and experiences of this development project". Source, official announcement of the representative of the Ministry of Mining and Energy of the Republic of Serbia in Bloomberg Adria magazine.

The development of such experimental projects requires the use of new technologies and the application of powerful tools for the digitization of engineering systems such as (AI) and its applications such as (ML) and (DT). Artificial intelligence (AI) tools provide the opportunity to model new systems through digitization, work on improving their performance and reducing costs (Tai et al., 2023; Leng et al., 2021). (AI) methods are mainly used to predict variables generated at different stages of the supply chain: renewable sources (wind speed, solar radiation and ambient temperature), system output power, user load and terminal price of electricity. Industry 4.0 marks the transition to interconnected, automated manufacturing, integrating technologies such as the Internet of Things (IoT) and cloud computing. Industry 4.0 represents a significant upgrade in the manufacturing sector, introducing the concepts of a new generation of intelligent manufacturing (Wang et al., 2021). Manufacturing systems have the ability to observe physical processes and generate the corresponding (DT) in the physical domain. These systems are designed to acquire real-time data from the physical environment, facilitating simulation analysis. This strategy aims to improve efficiency and productivity while offering greater flexibility in manufacturing processes, making a step towards more agile and responsive manufacturing systems (Semeraro et al., 2023; He, Bai, 2020). A very important element of this era is (DT) technology, which connects physical and digital entities. In this way, production efficiency and innovation are increased by creating digital versions of physical systems for detailed analysis and optimization. The emergence of (DT) technology has opened new avenues to address this challenge in which production systems possess the ability to observe physical processes and generate the corresponding (DT) in the physical domain. These systems are designed to acquire real-time data from the physical environment, facilitating simulation analysis. This enables the execution of decisions, supported by real-time communication and in cooperation with human operators (Leng et al., 2021).

This paper indicates the importance of hydrogen energy in the context of energy transition globally and in a certain way gives recommendations and achievements for the development of hydrogen energy in the Republic of Serbia. There are many challenges facing hydrogen energy in the Republic of Serbia and they range from producers to regulators to customers, and they are burdened with technical, technological, financial and safety challenges. All these challenges create an opportunity for development in the mentioned areas, these opportunities must be recognized and supported by investors, users, the scientific community, research centers and ultimately the State. Another dimension consists of benefits through the possibility of international financing, access to funds from EU funds, a significant part of which are grants.

The paper aims to identify and propose the best solutions for overcoming the challenges that the green hydrogen sector in the Republic of Serbia should face with the help of (AI) and its applications. In chapter number 2, the system approach is presented and the methodology of design and development (PtH) of the system supported by tools (AI) in order to optimize the process is presented. Chapter 3 provides a brief overview of global challenges in the field of (AI) and green energy to understand the importance of these areas. It further focuses on the regulatory framework and the current situation in the Republic of Serbia in order to identify the entity's potential in future research and development projects..

1. SYSTEM DESIGN METHODOLOGY (PtH) AND THE ROLE OF TOOLS (AI) IN PROCESS OPTIMIZATION

Power-to-hydrogen (PtH) system is shown in Fig.1 (Marocco et al., 2023). The electrolyser is powered by electricity that comes from an on-site solar (PV) system or from the grid. Hydrogen storage is included to reliably cover the end user's hydrogen demand. Battery storage can also be integrated to improve the exploitation of the local solar resource. Finally, excess renewable energy, if not stored, can be fed into the electricity grid to improve the profitability of this business model.

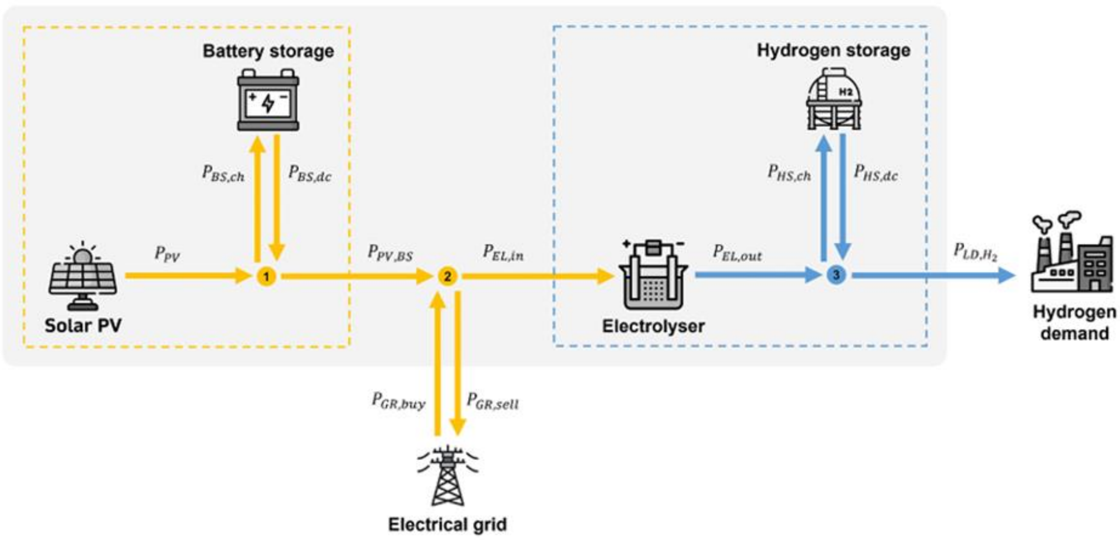

Figure 1. Scheme of the (PtH) system

Here, three different power balances must be satisfied for the simulation time periods. The first power balance (electricity, in kW) is expressed as follows:

$$P_{PV}(t)+P_{BS,dc}(t)=P_{BS,ch}(t)+P_{PV,BS}(t) \qquad (1)$$

Where PPV(t) is the power generated by the (PV) plant, $P_{BS,dc}$ is the battery discharge power, $P_{BS,ch}$ is the battery charge power and $P_{PV,BS}$ is the net power output of the solar/battery subsystem. The battery in the (PV) system is designed as a support for maximizing the exploitation of renewable energy sources on site.

The second power balance (electrical energy, in kW) defines the interaction (PtH) of the system with the electrical network. The electricity required for the electrolyser can be taken from a solar (PV) plant or from the grid. That is, excess renewable energy can be delivered to the grid:

$$P_{PV,\,BS}(t)+P_{GR,buy}(t)=P_{EL,in}(t)+P_{GR,sell}(t) \quad (2)$$

Where $P_{GR,bay}$ is the power purchased from the grid, $P_{GR,sell}$ is the power sold to the grid, and $P_{EL,in}$ is the input power of the electrolyzer.

The third power balance (hydrogen, in kW) refers to the production of hydrogen in the subsystem. It determines the output power of the electrolyser and the power exchange with the hydrogen storage to cover the hydrogen demand of the end user. This can be expressed as follows:

$$P_{EL,out}(t)+P_{HS,dc}(t)=P_{HS,ch}(t)+P_{LD,H2}(t) \quad (3)$$

Where $_{EL,out}$ is the output power from the electrolyzer, $P_{HS,DC}$ is the hydrogen storage discharge power, $P_{HS,ch}$ is the hydrogen storage charging power and $P_{LD,H2}$ is the hydrogen demand that must be covered (which is set as input to the problem).

The modulation range of the electrolyzer is defined according to the following expressions:

$$P_{PL,in}(t) \geq y_{EL,min} \cdot P_{EL,rated,aux}(t) \quad (4)$$

$$P_{PL,in}(t) \leq y_{EL,max} \cdot P_{EL,rated,\,aux}(t) \quad (5)$$

Where $y_{EL,min}$ and $y_{EL,max}$ represent the lower and upper limits of the modulation range of the electrolyzer (they are defined as a percentage of the nominal power of the electrolyzer). $P_{EL,rated,aux}$ is an auxiliary variable introduced to describe the product of the design variable $P_{EL,rated}$, rated (continuous) and the variable variable δ_{EL} (binary);

$$P_{EL,\,rated,aux}(t)=P_{EL,rated} \cdot \delta_{EL}(t) \quad (6)$$

Where δ_{EL} is a binary variable that is in state "1" if the electrolyzer is on and in state "0" if the electrolyzer is off. The partial load performance curve is used to model the operation of the electrolyzer (Marocco et al., 2023). For each point of the modulation range, the curve relates the output power of the electrolyzer (for hydrogen) to the input power of the electrolyzer (for electricity). One of the most striking aspects of the application of (AI) is related to electrolysis for hydrogen production, i.e. (AI)-based electrolyzer performance optimization. They are used in the development of new catalysts for hydrogen production, enabling inventions in energy production techniques (Le et al., 2021). In the field of hydrogen fuel cells, AI enables real-time operational optimization by predicting the performance of solid oxide fuel cells while taking into account other important parameters such as CO_2 hydrogenation and hydrogen power density (Peksen, 2023).

Energy storage technologies, at any time step, the amount of energy in the battery storage can be calculated based on the energy stored in the previous time step and the working power of the battery:

$$E_{BS}(t+1) = (1-\sigma_{BS}) \cdot E_{BS}(t) + \eta_{BS,ch} \cdot P_{BS,ch}(t) \cdot \Delta t - (P_{BS,dc}(t) \cdot \Delta t)/\eta_{BS,dc} \quad (7)$$

Where E_{BS} (in kWh) is the energy stored in the battery storage, and σ_{BS} (in %/h) is the self-discharge coefficient for storage batteries (that is, energy losses expressed as a percentage of the nominal energy in each time step), $\eta_{BS,ch}$ (expressed in %) is the battery charging efficiency, $\eta_{BS,dc}$ (expressed in %) is the battery discharging efficiency and Δt (in hours) is the duration of the time step. Analogously, the behavior of hydrogen storage technology is described by the following linear function:

$$E_{HS}(t+1) = E_{HS}(t) + P_{HS,ch}(t) \cdot \Delta t - P_{HS,dc}(t) \cdot \Delta t \quad (8)$$

Where E_{HS} (in kWh) is the energy stored in the hydrogen storage. It should be noted that, unlike battery storage, the self-discharge coefficient does not appear in the energy balance of Eq. (8) because self-discharge losses for hydrogen storage are negligible. Inequalities (9) and (10) are introduced to limit the amount of energy that can be stored (with j = BS, HS):

$$E_j(t) \geq E_{j,rated} \cdot y_{j,min} \quad (9)$$

$$E_j(t) \leq E_{j,rated} \cdot y_{j,max} \quad (10)$$

Where $y_{j,min}$ and $y_{j,max}$ are min and max state of charge (SOC) values of the jth storage technology (Marocco et al., 2023).

Artificial Intelligence (AI) is becoming an essential factor in optimizing hydrogen storage systems to provide balancing for seasonal electricity needs, reduce energy insecurity for vulnerable communities and lower seasonal price spikes (Izadi et al, 2022). Figure 2. shows multiple approaches to store hydrogen, such as liquid, gaseous and solid fuel, and then using fuel cells can be converted into energy (Yun et al., 2024). One of the obstacles to hydrogen storage is the storage conditions as it requires low temperatures, high pressures and chemical processes. Applications (AI) and (ML) optimize hydrogen storage systems as they can analyze vast amounts of material data and improve the stored density and material properties. By integrating storage monitoring and data collection systems, they enable predictive maintenance as it can track wear and potential failure events to increase safety. Hydrogen can also be separated from natural gas and drawn from the pipeline network for end uses that require pure hydrogen. (AI) can play a constructive role in enabling the use of hydrogen in two ways namely; the first way is to set the appropriate concentration of the mixture considering the real-time data on pipeline characteristics and natural gas composition and the second way is to optimize the locations for injection and withdrawal of pure hydrogen from the natural gas pipeline (Melaina et al., 2013).

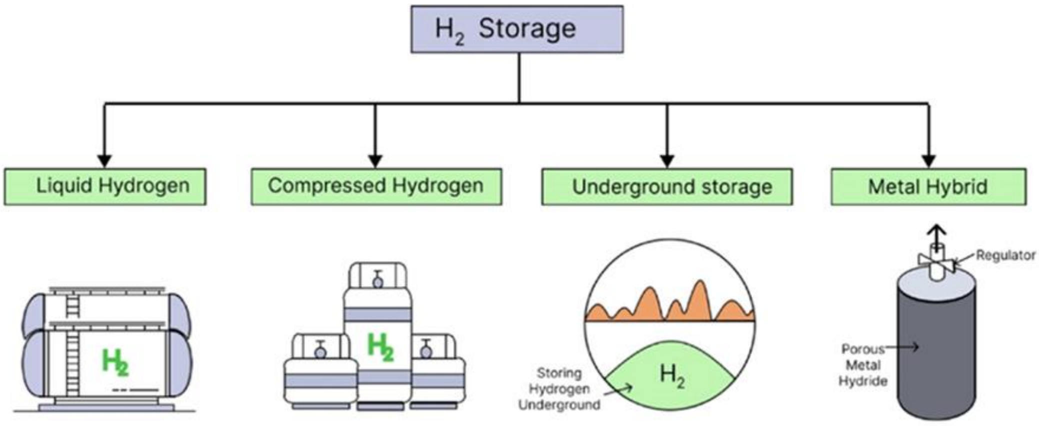

Figure 2. Conductor storage technologies, (Yun et al., 2024)

The function of optimizing the hydrogen supply system during its life cycle includes total net costs (NPC)O. Total NPC ($C_{NPC,tot}$) includes capital (CAPEX) and operating (OPEX) costs:

$$C_{NPC,tot} = C_{NPC,capex,tot} + C_{NPC,opex,tot} \quad (11)$$

The term $C_{NPC,capex,tot}$ is the investment in the project which is the sum of all the capital investments in the (PtH) system, including the (PV) generator, storage batteries (PV), electrolyser, hydrogen storage and infrastructure network equipment for (PV) and conductor.

$$C_{NPC,capex,tot} = C_{capex,PV} + C_{capex,BS} + C_{capex,EL} + C_{capex,HS} \quad (12)$$

The $C_{NPC,opex,tot}$ term is instead calculated according to the following expression (with j = PV, BS, EL, HS):

$$C_{NPC,opex,t} = \sum_{n=1}^{N} \frac{\sum_j C_{opex,j} + C_{GR,bay}}{(1+d)^n} \quad (13)$$

Where N (expressed in years) is the lifetime of the project, $C_{opex,j}$ is the annual operating cost of the jth component, $C_{GR,buy}$ is the annual cost due to electricity purchased from the grid and d is the discount rate (expressed in %). $C_{opex,j}$ is calculated as part (CAPEX) of the jth component. It also includes replacement costs in case the jth component has to be replaced during the nth year. It is important to point out that the target is the function of $C_{NPC,tot}$, it does not include revenues from the sale of surplus (PV) energy. This exclusion aims to prevent the (PtH) system from being oversized for the purpose of selling electricity to the grid, which is not even its primary goal (Marocco et al., 2023).

Artificial intelligence (AI) and its algorithms are key in enhancing the accuracy and efficiency in the performance of various power generation systems. By integrating historical data with meteorological forecasts, AI systems can develop highly accurate predictive models for energy output parameters (Sarma, Parmar, 2024).

In order to provide general criteria for the design (PtH) of the system and to describe its techno-economic and environmental performance, it is necessary to introduce different indicators, namely; System design indicators, energy indicators, economic indicators and environmental indicators and indicators.

Power ratio (PV) ratio (R_{PV} is defined as the ratio between (PV) rated power and electrolyzer rated power:

$$R_{PV} = P_{PV,rateo}/P_{EL,rated} \quad (14)$$

Electrolyzer ratio (R_{EL}) is defined as the ratio of electrolyzer power to the average hydrogen load:

$$R_{EL} = (P_{EL,rated} \cdot \eta_{EL,rated})/P_{LD,H2,avg} \quad (15)$$

Where $\eta_{EL,rated}$ (expressed in %) is the efficiency of the electrolyzer under nominal conditions, and $P_{LD,H2,avg}$ (in kW) is the average hydrogen load that should cover the power.

Autonomy of hydrogen storage (A_{HS}, in h) means the time period during which the hydrogen storage is able to cover the average hydrogen demand. It can be defined as the ratio of HS size to average hydrogen demand:

$$A_{HS} = E_{HS,rated}/P_{LD,H2,avg} \quad (16)$$

Battery storage autonomy (A_{BS}, in h) shows how long battery storage is able to cover the electrolyzer's energy needs under nominal conditions. It is determined by the ratio of the storage size of the battery to the nominal power of the electrolyzer;

$$A_{BS} = E_{BS,rated}/P_{EL.\ rated} \quad (17)$$

It is important to note that battery storage autonomy is defined in relation to the load that the battery (rated capacity) should meet, especially the rated power of the electrolyzer.

Energy indicators, Utilization (U_{PV}, in %) indicates the share (PV) of energy used by the electrolyser for hydrogen production, the remaining share (PV) of energy can be limited or delivered to the grid. This indicator is thus defined from the perspective of the (PtH) business case:

$$U_{PV} = \frac{\sum_{t=1}^{T}(P_{EL,in}(t)\Delta t - P_{GR,buy}(t)\Delta t)}{\sum_{t=1}^{T}(P_{PV,BS(t)\Delta t})} \quad (18)$$

Electrolyzer utilization (U_{EL}, in %) measures the energy utilization of the electrolyzer compared to the maximum amount it can use without any interruption:

$$U_{EL} = \frac{\sum_{t=1}^{T}(P_{EL,in}(t)\Delta t)}{\sum_{t=1}^{T}(P_{EL,roted}\Delta t)} \quad (19)$$

The share of the grid (y_{GR}, in %) represents the part of the electricity consumed by the electrolyser that comes from the grid, and the rest is produced locally by the (PV) plant:

$$y_{GR} = \frac{\sum_{t=1}^{T}(P_{GR,buy}(t)\Delta t)}{\sum_{t=1}^{T}(P_{EL,in}(t)\Delta t)} \quad (20)$$

The Share (PV) expressed as (y_{PV}, in %) represents the part of the electricity consumed by the electrolyser that comes from the (PV) plant on site. It can be calculated based on network participation as follows:

$$Y_{PV} = 100\% - y_{GR} \quad (21)$$

Economic factors, the levelized cost of hydrogen (C_{H2}, price per kg) indicates the average net present cost of hydrogen production for a (PtH) system over its lifetime. It can be expressed by the following expression:

$$C_{H2} = \frac{C_{NPC,tot} - C_{GR,sell}}{\sum_{n=1}^{N}\frac{M_{H2}}{(1+d)^{n}}} \quad (22)$$

Where $C_{NPC,tot}$ is the NPC of the (PtH) system during its lifetime, calculated by formula (11), and C_{GR} is the annual revenue from the sale of excess electricity to the grid, and M_{H2} (kg in y) is the amount of hydrogen produced annually by the (PtH) system.

Environmental indicators, carbon footprint of hydrogen (ε_{H2}, in $kg_{CO2,e}/kg_{H2}$) indicates kilograms of CO_2 equivalents (CO_2,e) emitted per kilogram of hydrogen produced:

$$\varepsilon_{H2} = \frac{\sum_{t=1}^{T}(P_{GR,buy}(t)\Delta t\varepsilon_{GR}10^{-3})}{\sum_{t=1}^{T}(P_{EL,out}(t)\Delta t\Delta h_{H2}^{-1})} \quad (23)$$

Where ε_{GR} (in $g_{CO2,e}$/kWh) is the carbon intensity of electricity (ECI), i.e. how many grams of CO_2 are released per kilowatt-hour of electricity drawn from the grid (refers to the country mix) and Δh_{H2} (in kWh/kg_{H2}) because the heating value (LHV) of hydrogen is lower (Marocco et al., 2023).

Levelized cost of energy production (LCOE) per megawatt is the sum of investment in electricity production assets and operating costs during the life of the project, divided by production capacity in the same period, discounted at a financing rate that recognizes the time value of money (Burdack et al., 2023). To determine levelized energy costs:

$$LCOE = \frac{I_0 + \sum_{t=1}^{n}\frac{At(1,15)}{(1+i)^{t}}}{\sum_{t=1}^{n}\frac{M_{tl}}{(1+i)^{t}}} \quad (24)$$

Where different variables are considered: (I_0) represents the initial investment of the project, which includes mainly (CAPEX), i.e. investment in fixed assets, (A_t) indicates (OPEX) operating costs of the project, among which maintenance costs and profit tax (in the Republic of Serbia at a rate of 15%) are distinguished. The financing rate is denoted as (i), and (t) corresponds to the analysis period, usually set at 25 years, (Mt) represents the electricity generated in megawatt hours (MWh). The LCOE decreases over the years because the initial investment is reduced due to the fact that the technology has come down in price as it progresses and becomes more widely used, making it feasible to undertake projects involving this type of energy.

The levelized cost of hydrogen production (LCOH) represents the total cost of producing one kilogram of green hydrogen, taking into account both the initial investment and the operating and asset-related costs involved in the production process (Burdack et al., 2023):

$$LCOH = \frac{I_0 + \sum_{t=0}^{n-1}\frac{At(1,15)}{(1+i)^{t}}}{\sum_{t=1}^{n-1}\frac{P_t}{(1+i)^{t}}} \quad (25)$$

Where (P_t) represents the production of hydrogen per year in kilograms (kg). This cost is an encouraging prospect, as it is predicted to decrease significantly over the years, which will allow a competitive price to be achieved compared to fossil fuels.

It is applications (AI) such as machine learning (ML) architectures integrating technologies such as the Internet of Things (IoT) and cloud computing that can connect complex interdependencies in large data sets, but also simulate human cognitive processes to improve system efficiency. In parallel, (ML) algorithms autonomously continue to improve their predictive accuracy in a self-learning algorithm by importing new data into the models, which helps to model the complex physical and operational properties of energy systems (Sarma, Parmar, 2024; Burdack et al., 2023). Thus improving production performance with decreasing costs at the same time. These multi-domain applications (AI) are essentially illustrative of the revolutionary capabilities of (AI) in redefining hydrogen-based energy systems to support sustainable energy technologies (Kalinci et al., 2015). These technologies enable condition-based monitoring for fault removal, condition-based maintenance, and control of other variables to achieve optimal hydrogen production with the least amount of energy consumed, while offering real-time monitoring of the electrolysis process (Oladosu et al., 2024; Lv et al., 2024; Abdelkareem et al., 2022; Shoaei et al., 2024).

2. GLOBAL CHALLENGES AND REGULATORY FRAMEWORK IN THE FIELD (AI) and (OIE) in the REPUBLIC OF SERBIA

2.1. Global perspectives on artificial intelligence (AI) and green energy

The hydrogen-based economy has attracted the attention of more than 75 countries around the world to address the challenges of energy security, climate change and carbon emissions. The economies of these 75 countries account for more than half of the world's GDP, and their governments are investing billions of dollars in green hydrogen projects. Total hydrogen investment globally is likely to reach $300 billion by 2030, accounting for 1.4% of the global energy stock. In order to achieve net zero emissions by 2050, CO_2 emissions must be reduced by 45% by 2030 (Raman et al., 2022). Tools (AI) are recognized as being able to contribute to change, providing new ways to maximize the utility of energy systems operation, automation and control. A competitive policy framework related to the circular economy should be developed, adapting to new trends, forming sustainable development, which will improve the circular economy (Danish, Senjyu, 2023).

2.2. Regulatory framework in the field of Artificial Intelligence (AI)

The current projection shows that the value of the artificial intelligence market at the world level is more than 184 billion dollars, and that by the end of 2030 this market will reach the value of 826 billion dollars. According to the report of the European Commission: artificial intelligence will significantly contribute to the automation of 14% of jobs, while another 32% of occupations will experience major transformations. The Government of the Republic of Serbia has adopted the Strategy for the Development of Artificial Intelligence for the period from 2025 to 2030. This strategy will continue the accelerated development of artificial intelligence in Serbia, as a continuation of the strategy adopted in 2019. Serbia, as the first in the region of Southeast Europe, made a step forward in the management of the development of artificial intelligence and positioned itself as a leader in the region, which was also recognized through the chairmanship of the Global Partnership for Artificial Intelligence. The strategy includes further development in the areas of the legislative framework, investments in education, innovation and infrastructure, as well as increased application in the public sector. By adopting this strategy, the plans are aligned with the latest developments in the field of artificial intelligence, while the further development and application of this technology traces the path to the modernization of the state and society as a whole, following the goals of the "Leap into the Future 2027" program. The strategy was created as a result of a wide range of consultations of the professional community with the expert opinion of the Government Council for Artificial Intelligence.

2.3. Integrated energy and climate plan as a basis for development (OIE)

It is important to note that in the Republic of Serbia, progress has been made in the field of the legal and political framework for the implementation of projects to reduce emissions and decarbonize the atmosphere, because on March 23, 2021, the Law on Climate Change (Official Gazette of RS No. 26/2021) was adopted, which more closely defines the area of decarbonization, reduction of carbon dioxide emissions and fulfillment of obligations under the Paris Agreement and other acts of international law (EU regulations). Also, in the Republic of Serbia, there is a noticeable increase in collective awareness of environmental protection and pollution reduction, which primarily relates to air quality, which is threatened by the emission of carbon dioxide and other harmful substances.

In addition to the above, the following strategic documents were also adopted: Decision on determining the Energy Balance of the Republic of Serbia for the year 2025 (Official Gazette of RS No. 12/2025-28 of 07.02.2025); Energy Development

Strategy of the Republic of Serbia until 2040 with projections until 2050; Initial basis of the energy infrastructure development plan until 2028 with projections until 2030; Integrated national energy and climate plan of the Republic of Serbia for the period up to 2030 with a vision up to 2050. "By adopting the Integrated National Energy and Climate Plan for the period up to 2030 with projections up to 2050, we have defined a "road map" in the process of energy transition. In accordance with the imperative of decarbonization, the most significant changes are foreseen in the way of electricity production, where the determination is to significantly increase the capacities that use RES (Andrejević Panić et al., 2024).

Our goal is to provide 3.5 GW of new green energy from solar and wind power plants by the end of the decade, which means that almost every other megawatt-hour of electricity produced must be from RES". This was announced by the Ministry of Mining and Energy of the Republic of Serbia and published on the official website.

CONCLUSION

Artificial intelligence (AI) is the fastest growing branch of computer science and engineering, and hydrogen energy is the most important area in achieving energy security with a positive impact on climate change. Hydrogen energy acquires a special importance and role in the decarbonization of industry and transport as the branch with the highest carbon emissions, then in balancing the power and capacity of electric power networks, scientific and technological development, the development of innovative financing models, the influence on the creation of the profile of the optimal price of electricity and ultimately the development of the entity's economy. On the other hand, artificial intelligence (AI) plays a key role in modeling different energy systems, with a special focus on (OEI). (AI) methods enable more intelligent planning, management, forecasting of variables in supply chains, more convenient configuration, optimization, control and prognostic maintenance of both individual and integrated energy systems.

The paper provides a methodological approach to the development of hydrogen energy through development (PtH) model and brings examples of good practice of application (AI) globally in all phases of development, implementation, production, transport and storage. It further focuses on the energy market, the price movement of energy equipment and the analysis of the economic justification of hydrogen energy production with examples from the environment. The Republic of Serbia is constantly investing in the energy sector, with a focus on renewable energy sources, but also in the field of (AI) where significant progress has been achieved. This paper points to good practices and in a certain sense recommends the synergistic action of the energy sector and (AI) which should jointly generate benefits and give strong momentum to the development of hydrogen energy. Only the synergistic action of these sectors, the transfer of knowledge and scientific and technological achievements can contribute to the development of hydrogen energy. The development of hydrogen energy in the Republic of Serbia should certainly be adapted to the existing electricity and gas development plans in order to avoid multiplying resources and costs. This approach would create a well-founded scientific platform for adopting a hydrogen strategy as a key document for the future development of hydrogen energy. Global trends and scientific research show that challenges in the hydrogen energy sector exist with goals up to half a century, and the development chance should be based on such a platform. While the challenges in the sector (AI) and green energy there are opportunities for growth and development is based on realistic assumptions for the realization of multiple benefits, which is ultimately reflected in GDP growth. The recommendation for future research can be directed to the analysis of the state of the existing power and gas infrastructure, the technical and economic justification of the establishment of new production capacities, the possibility of integrating hydrogen energy into existing energy capacities, prognostic maintenance, security and resilience of energy networks and capacities.

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Intelligent visualization and modeling of phytogeochemical profiles of industrial dumps in Donbass

Inteligentna vizuelizacija i modeliranje fitogeohemijskih profila industrijskih deponija u Donbasu

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Abstract: The paper contains information on the features of phytogeochemical profiles for industrial sites in Donbass – coal mine dumps. The studies were conducted using a multi-stage system of using statistical techniques in mathematics and elements of artificial intelligence in making decisions on the selection of priority pollutants and reference chemical elements to restore missing data. Intelligent visualization of analytical control data of biogeochemical processes is a unique profile of information reflecting similar series for the nature of technogenic pollution of the environment. For the first time, gradients of accumulation of individual elements in the tissues of an indicator plant were established, which is considered in the future as a remediant in the restoration of disturbed ecotopes of Donbass.

Keywords: technogenesis, intelligent data visualization, statistical methods, phytogeochemistry, phytoindication, environmental monitoring, Donbass.

Sažetak: Rad sadrži informacije o karakteristikama fitogeohemijskih profila za industrijske lokacije u Donbasu - odlagališta rudnika uglja. Studije su sprovedene korišćenjem višestepenog sistema korišćenja statističkih tehnika u matematici i elemenata veštačke inteligencije u donošenju odluka o izboru prioritetnih zagađivača i referentnih hemijskih elemenata za obnavljanje nedostajućih podataka. Inteligentna vizuelizacija analitičkih kontrolnih podataka biogeohemijskih procesa je jedinstven profil informacija koji odražava slične serije za prirodu tehnogenog zagađenja životne sredine. Po prvi put su utvrđeni gradijenti akumulacije pojedinačnih elemenata u tkivima biljke indikatora, što se u budućnosti smatra remedijantom u restauraciji poremećenih ekotopa Donbasa.

Ključne reči: tehnogeneza, inteligentna vizuelizacija podataka, statističke metode, fitogeohemija, fitoindikacija, monitoring životne sredine, Donbas..

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INTRODUCTION

The system of quantification of natural environment objects under technogenesis conditions involves the use of certain analytical procedures and methods of secondary synthesis if the set of information on the state of a local ecosystem represents large arrays of quantitative results (Ermakov, Jovanovic, 2012; Korniyenko, Kalaev, 2022; Rouhani, Skousen, 2023). For most of the territory of Donbass, the introduction of methods for restoring disturbed ecotopes is a priority environmental task due to significant transformations as a result of increasing anthropogenic activity (Dogadkin et al., 2024; Nespirnyi, Safonov, 2024; Safonov et al., 2024).

The purpose of the work is to visualize a model of several phytogeochemical profiles characteristic of the waste heaps of Donbass using methods of mathematical statistics based on elemental analytical control data. At the same time, an important stage in the advancement of scientific research is the approach of using the capabilities of artificial intelligence for: 1) restoring missing data, 2) reconstructing historical processes of nature management in the region, 3) modeling those patterns that are characteristic of the industrial environment, 4) making decisions about the belonging of a specific sample of the phytogeochemical environment to a specific system of the geochemical province in a technogenically disturbed region.

Previously conducted studies (Safonov et al., 2023, Safonov et al., 2024; Zinicovscaia et al., 2024) obtained some patterns of migration and accumulation of chemical elements (including toxic and man-made) for the Donbass ecosystems under conditions of intensive economic activity.

Professor V.V. Ermakov (1939-2025 years of life) contributed greatly to the development of such research; he is the author of the experimental ideology and the beginning of work on collecting plant materials at man-made sites in the modern conditions of Donbass. The Vernadsky Institute of Geochemistry and Analytical Chemistry greatly helps scientists in Donbass, taking into account the difficult material conditions that arose during the military events.

The task has been completed within the framework of the youth laboratory “Diagnostics and mechanisms of adaptation of natural and anthropogenically transformed ecosystems of Donbass”, Azov-Black Sea Mathematical Center. Part of this work performed at the Vernadsky Institute of Geochemistry and Analytical Chemistry was supported by the Ministry of Science and Higher Education of the Russian Federation, within the budget theme of the Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences.

1. MATERIALS AND METHODS

The work uses analytical control metdods: atomic absorption, mass spectrometry with inductively coupled plasma, and the neutron activation analysis method. The importance of such studies is due to the fact that there is no data on modern pollution in the region, and military events are also underway, which also adversely affects the sustainability of ecosystems. At the same time, it becomes possible to conduct an examination in a partially remote format using a database and artificial intelligence programs to restore a holistic environmental picture in dynamics and modern development.

For cases when the results of analytical control and structural-botanical examination represent fragmentary information, a special method of restoration (imputation) of missing information in a specific series (sequence) of features has been developed.

The presented work functionally combines methodological techniques for assessing the ingredient composition of plants (using the established remediant Phleum pratense L. as an example) as part of the programs for phytochemical assessment of raw materials, and takes into account cenotic patterns using the example of successional processes of vegetation formation under the impact of accumulated damage objects. The main objective of the study was to visualize the data, the correct interpretation of which is possible with a more detailed examination and accumulation of information.

Geophysical and geochemical parameters in industrially developed regions are characterized by a certain dynamism of variability if specific interventions are observed (Jovanović et al., 2023; Kolesnikov et al., 2022; Yeprintsev et al., 2023), which is relevant for the territory of Donbass during military events (Dogadkin at al., 2024; Safonov et al., 2024). Some phytogeochemical features of coal mine dumps in Donetsk and Makeyevka were determined. The results obtained are in the stage of constant supplementation with new information, which determines the need for their ordering. Phytogeochemical series of contrasting conditions of Donbass were formed for different taxa and zones of ectopic confinement, for example, using indicator species of bryophytes (Zinicovscaia et al., 2024). The work uses methods of geochemical control and the possibility of using data for remediation of disturbed soils, ecotopes in an industrially tense region (Fernández-Braña, Salgado, 2023), which is typical for places and areas of mineral extraction, construction of coal mines, landscape disturbance and high levels of environmental pollution (Křibek et al., 2028; Massante, 2015; Zheng et al., 2024).

2. RESULTS AND DISCUSSION

The classical approach to the analysis of data on geochemical provinces and migration flows in geosystems is the pair correlation analysis of a set of digital data, which is an array of information and highlights the pattern of joint entry into the environment. Figure 1 shows the results of the general diagram of the ratio of concentrations and the specificity of accumulation of elements in plant tissues of the indicator species, which is the primary link in the food chain and plays the role of a remediant in the formation of a stable striking cover. This approach ensures success in the processes of greening and preventing erosion of the soil horizon.

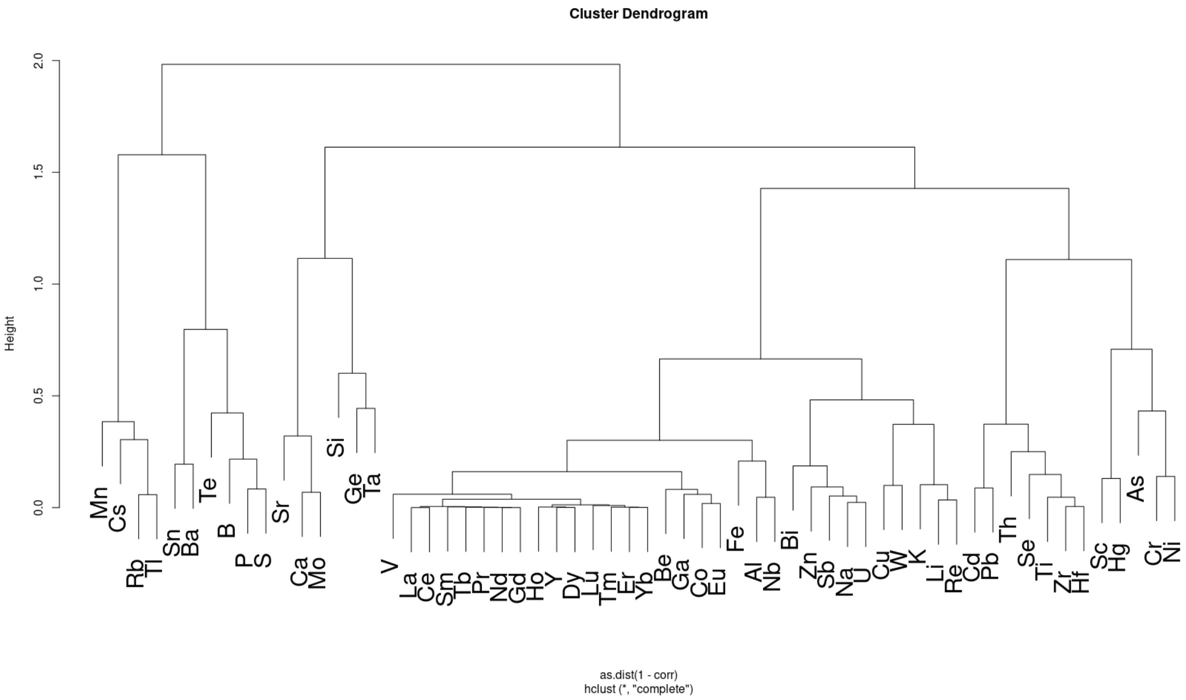

Figure 1. Correlation links between elements in the composition of an indicator plant that forms a stable population during remediation processes in the dumps of coal mines in Donbass

The obtained results confirm that the plant has a high level of accumulation of chemical elements entering the environment precisely with technogenic intervention – during the extraction of minerals and the construction of a waste heap as a place for the accumulation of hazardous waste and requiring optimization of the environment. By means of such analysis, we have established toxic and mobile elements that are of the greatest importance in the migration flows of matter as a result of technogenesis. In general, 2 large groups of elements are separated, antagonizing each other (left and right parts of grouped values, see Figure 1 - dendrogram). Within each group of accompanying elements, there are also groupings of elements that reflect the joint entry into the plant organism. This was proven with the help of the mathematical apparatus used - statistical data on arrays of values for seven waste heaps of Donbass.

The significance of such data proves that technogenic elements are not only in the geological environment (the dead part of nature), but also enter into biogeochemical cycles, which leads to their entry into the cycle of active components of living nature. In response to such pollution, a plant can form various structural modifications and even change its life strategy, for example, to reproduce more by seeds under stress conditions or to form additional shoots in order to survive and occupy more free space to capture territory.

The specificity of studying accumulation in a plant organism is important, since the fate of each pollutant element of technogenic nature can differ significantly: some elements can have high concentrations in the soil horizon or parent rock, but do not pose a danger to biological objects, i.e. are not involved in biogeochemical cycles. Nevertheless, as practice shows, most new geochemical provinces in a contrasting environment of disturbances, explosions, quarrying or mining have an active characteristic of penetrating into the plant organism and further moving along the food chain, ultimately getting into the human body, which is desirable to prevent.

Figure 2 contains information from a more advanced intellectual approach – using the principal component method to analyze patterns obtained in field studies and using analytical control methods. That is, here (Fig. 2) in the projection of the first two principal components, the entire set of established elements is distributed both in relation to each other and in relation to seven geographic points (test sites) that represent different geochemical sources of environmental pollution as a result of the storage of coal production waste in Donbass.

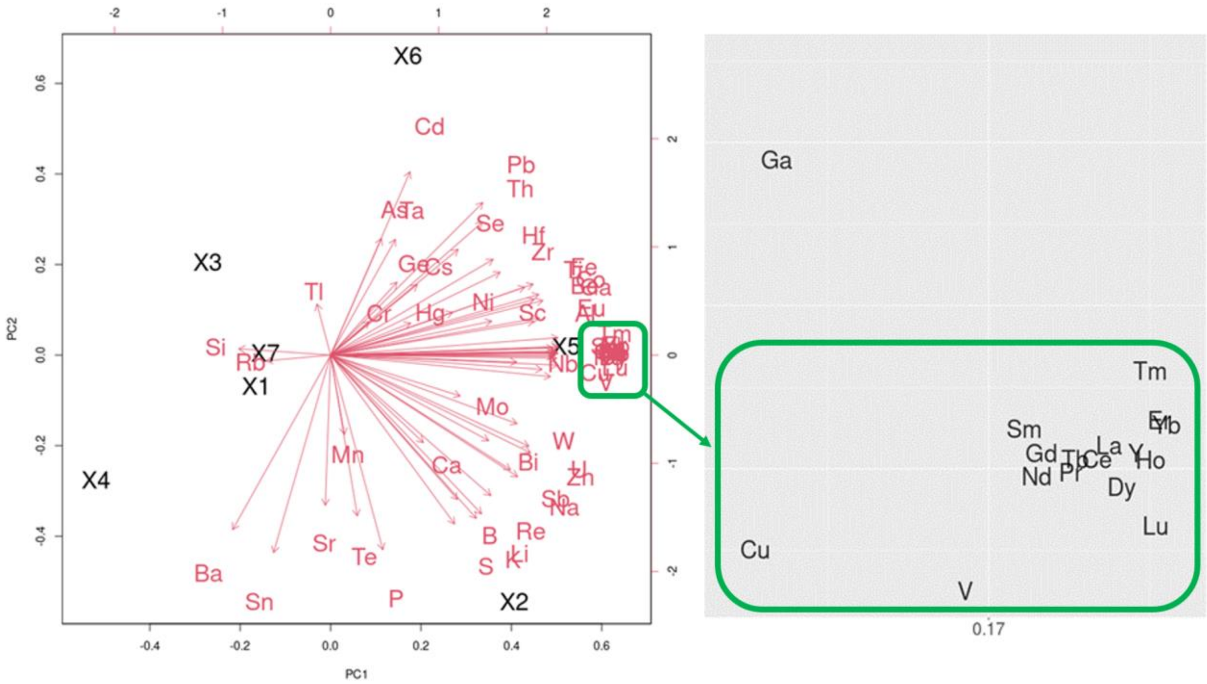

Figure 2. Results of using the principal component method in relation to elements of specific waste heaps in Donbass (decoding of a denser data sector), X1-X7 – localization of waste heaps relative to each other in the projection of the first components

For a more convenient examination of the patterns and results of the analysis, Figure 2 (on the right) contains a detailed diagram of an enlarged section of the primary analysis between the accompanying elements that have a close correlation relationship, which is also proven by the method of paired correlation comparison (Fig. 1) and verified by a secondary intelligent program using the principal components.

Such information has additional characteristics in the analysis of the specificity of pollution and the mechanisms of pollutant entry into the environment. However, the main thing is that the analysis of the principal component method proves the individual geochemical characteristic for the plant collected on individual waste heaps. This allows us to establish a geochemical profile for each waste heap and identify the dominant processes of contamination of harmful substances in the plant organism.

It has been established that the historical processes of the formation of an industrial region are also reflected in the nature of the economic use of the area. Each individual waste heap was built at different times and was created because of mining in a specific layer of underground rock, so it has its own specifics. Since many archival data have been lost because of military actions, scientists of modern research are faced with the task of reconstructing some processes to restore information about the environment. At the same time, only observational methods are not suitable, the system needs to process a large amount of experimental data and methods of intellectual capabilities of calculation systems can solve such a problem.

In the next series of experiments, an attempt was made to specifically develop a program and calculation algorithm for restoring (imputing) missing data that may arise when it is necessary to save reagents during chemical analysis or when restoring the complete profile of each sample of plant material according to the biogeochemical profile in order to have a complete picture of pollution or compliance with normal living conditions.

From the data set it has been established that for particularly toxic elements their concentrations can be of significant importance in the life of plants even in a small range of variation of their values. Whereas macroelements with a large range of concentrations usually constitute a general background value, ensuring the functioning of the basic physiological needs of the plant, but not radically changing the process of survival in unstable environmental conditions. In most cases, those plant populations were analyzed that have a high adaptation to stress conditions of industrial pollution and military impacts. However, even for such adapted forms of plants, modifications constantly arise that can block the process of development and life of a separate phytocenosis.

We tested the method of an intelligent approach to identifying paired values of conjugate characteristics (Fig. 3). It was necessary to answer the question: are there samples of plant material similar to the seven previously established profiles for waste heaps? Based on the data of the experimental block of industrial botany, it was suggested that the waste heaps of the Kalininsky district of the city of Donetsk and the Krasnogvardeisky district of the city of Makeyevka have a single source of mineral extraction and a common coal seam mined at a depth of 600-800 meters in the 50-70s of the 20th century, can these characteristics of geochemical profiles coincide and how many values are sufficient to reconstruct a geochemical profile based on the absorption capacity of an indicator plant under stressful growing conditions at man-made sites.

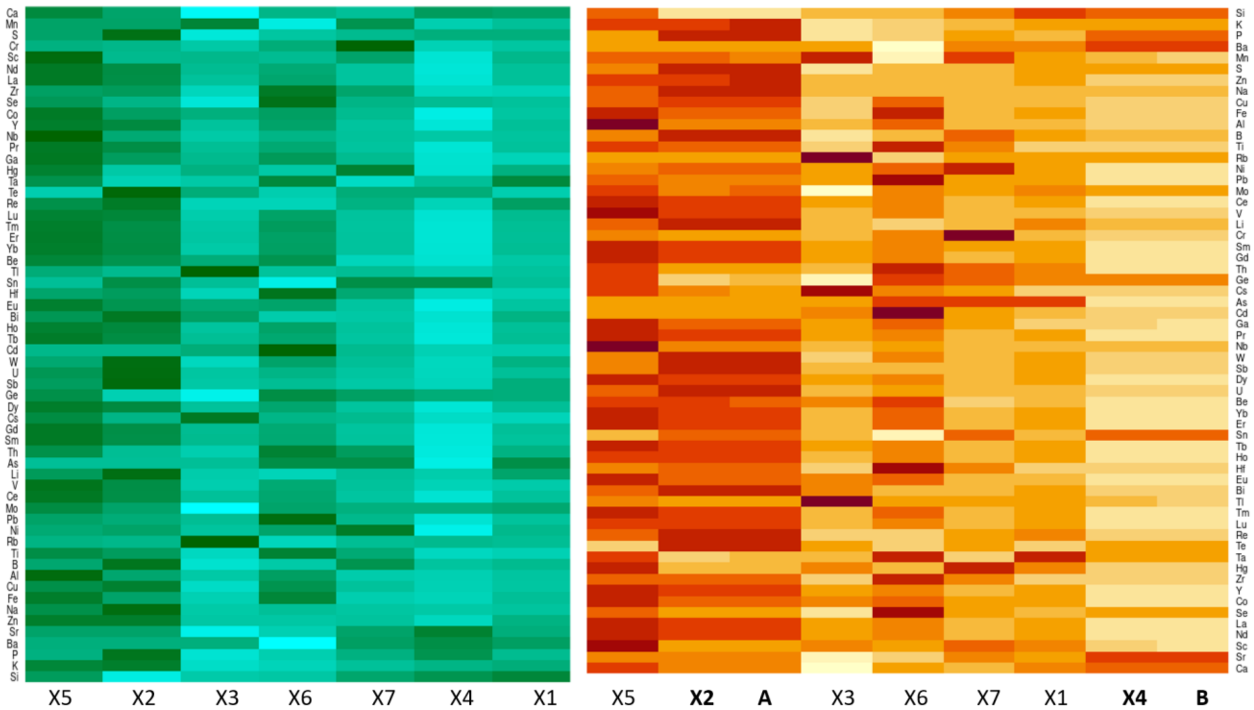

Figure 3. Solution of the problem of determining the associated geochemical profiles in plants using the principal component method and amputation of missing data (as an analogue of the intelligent system for calculating the results of field experiments),
X1-X7 - profiles of the waste heaps of Donetsk and Makeyevka, the profile of waste heap A is characteristic of X2, for waste heap B - X4

In the sequence of conjugated characteristics of individual chemical elements, when new series of the sequence are added (for example, A and B, see Fig. 3), the sequence of the entire series of elements also changes (right part of the figure). However, this does not change the tendency of the mutual relationship between the basic technophilic elements in their interaction and joint entry into the plant organism. Whether such a pattern will be observed for other indicator species must be established experimentally.

The used samples of plant materials of the same species were analyzed for 5, 10, 20, 30, 40 and 50 data available from 60 chemical elements previously established for seven waste heaps of Donbass. In this case, it is fundamentally important to include in such a list (even with 10 values of their available 60), so that different categories of elements reflecting a large information space within the cluster group are involved in the statistics. That is, with the help of an intelligent system, it was obtained that the minimum sufficient values for reconstructing the entire profile are sufficient if there is information about at least eight chemical elements, provided that each value belongs to a separate cluster group of the most conjugated features established by previously conducted studies in the pair correlation of values. Of course, the number of available samples and analyzed elements increases the accuracy of the experiment.

However, if we are talking about identifying the ecological profile of the territory or the phyto-geochemical profile for the obtained sample in the diagnostics of wildlife, then it is enough to use the values (indices) of contrasting cluster groups.

Examples of such cluster representations can be the following combinations of values (depending on the specifics of the applied methods of analytical control and chemical analysis): 1) Mn-Rb-P-Mo-Ce-Na-Cd-Cr, 2) Cs-S-Ca-La-Fe-Zn-Cu-Ni. For field diagnostics and identification of the kinship of the geochemical profile, such combinations of information on the concentration of the specified elements are complementary in order to conduct an examination, assess the impact on the environment, diagnostics and even use the data in forensics if a sample of plant material is obtained in the area that needs to be established as a result of the investigation. If less than 8 individual concentration values are used, the system does not show the relationship between the profiles and it is not possible to carry out diagnostics and examination in this case.

The 12-component series of data availability on the concentration of elements in a plant (for example, Tl-Ba-P-Mo-Sm-Dy-Eu-Al-Zn-Na-Pb-Hf) provides the possibility of 95-98% accuracy in reconstructing the existing phyto-geochemical profile if the sample was taken under the conditions that were previously studied - from microclimatic features to the specifics of pollution as a result of industrial activity of individual enterprises, for example, metallurgical or metal processing significance.

Therefore, using the capabilities of artificial intelligence application elements, it is possible to optimize the model of geochemical and spatial data visualization and obtain a visual example for full use in the practice of environmental research.

CONCLUSION

Of particular interest is the diagnostics of ecosystems by the specifics of the impact factor of military events, while it has been proven that the concentration of zinc, chromium and lead increases. These three elements are under the close attention of geochemists conducting examinations in places of military disturbances of ecosystems.

In the future, it is important to obtain data not only on the geochemical profile, but also on structural and physiological transformations in plants depending on the specific nature of pollution. The evolutionary biological process allows us to form adaptive mechanisms for the survival of species in contrasting stressful conditions. The accumulated information on plant structures at the present stage undergoes the procedure of quantification and digitalization of data that have qualitative characteristics and recalculated indices in environmental monitoring. For cereal species, data on the microstructures of the periosteal apparatus, terate forms of inflorescences, embryonic modifications during fruit formation, pubescence of leaf parts adjacent to the stem, and the work of the intercalary meristem are promising.

Based on the obtained primary data, a close correlation was found between the elements, which means that a hypothesis can be formulated and further investigated about their joint entry into the plant organism in the following groups: 1) La-Ce-Sm-Tb-Pr-Nd-Gd; 2) Ho-Y-Dy; 3) Lu-Tm-Er-Yb; 4) Co-Eu; 5) Zr-Hf; 6) Rb-Tl; 7) Ca-Mo; 8) Cr-Ni. Technophile elements migrate according to individual scenarios: Mn, Zn, Cu, Cd, Al. Coincidences of the profiles of waste heaps A and X2, B and X4 are noted in addition to the previous descriptions. In new works, cumulative antagonism of pollutants with Ba, Si, Sr and Sn was revealed. In targeted programs for the remediation of damaged systems, it is fundamentally important to operate with the obtained data on the involvement of toxic elements in biogeochemical processes, which allows freely migrating pollutants to be converted into a bound state in the environment.

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Legal mechanisms for reducing microplastic pollution: an analysis of policy gaps and regulatory solutions

Pravni mehanizmi za smanjenje zagađenja mikroplastikom: analiza nedostataka u zakonodavstvu i regulatorna rešenja

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Abstract: Microplastic pollution has emerged as a critical environmental challenge, posing significant risks to ecosystems, human health, and biodiversity. Regulatory frameworks for microplastic pollution prevention are evolving globally, addressing sources, distribution, and impacts of microplastics in marine and terrestrial environments. These regulations focus on controlling the production, use, and disposal of plastic products that break down into microplastics. key strategies include implementing restrictions on single-use plastics, promoting circular economy principles, and enhancing waste management practices. Moreover, the regulation of microplastics in industrial applications, such as cosmetics, cleaning products, and textiles, is becoming increasingly stringent. International bodies, including the United Nations and the European Union, have initiated collaborative efforts to harmonize regulations, improve scientific understanding, and establish monitoring standards for microplastic contamination. This paper explores the current regulatory framework, particullary in republic of serbia, identifies gaps in enforcement, and proposes strategies for a more effective response to microplastic pollution, emphasizing the need for cross-sectoral coordination and comprehensive public engagement.

Keywords: waste, plastic, microplastic, pollution.

Sažetak: Zagađenje mikroplastikom se pojavilo kao kritičan ekološki izazov, koji predstavlja značajan rizik za ekosisteme, zdravlje ljudi i biodiverzitet. Regulatorni okviri za prevenciju zagađenja mikroplastikom se globalno razvijaju, baveći se sa izvorima, distribucijom i uticajima mikroplastike u morskom i kopnenom okruženju. Ovi propisi se fokusiraju na kontrolu proizvodnje, upotrebe i odlaganja plastičnih proizvoda koji se raspadaju u mikroplastiku. Ključne strategije uključuju primenu ograničenja na plastiku za jednokratnu upotrebu, promovisanje principa cirkularne ekonomije i unapređenje praksi upravljanja otpadom. Štaviše, regulisanje mikroplastike u industrijskoj primeni, kao što su kozmetika, proizvodi za čišćenje i tekstil, postaje sve stroža. Međunarodna tela, uključujući Ujedinjene Nacije i Evropsku Uniju, pokrenula su zajedničke napore na harmonizaciji propisa, poboljšanju naučnog razumevanja i uspostavljanju standarda za praćenje kontaminacije mikroplastikom. Ovaj rad istražuje trenutni regulatorni okvir, posebno u Republici Srbiji, identifikuje nedostatke u primeni i predlaže strategije za efikasniji odgovor na zagađenje mikroplastikom, naglašavajući potrebu za međusektorskom koordinacijom i sveobuhvatnim angažovanjem javnosti.

Ključne reči: otpad, plastika, mikroplastika, zagađenje.

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INTRODUCTION

According to the United Nations Environment Programme (UNEP), microplastics are defined as solid plastic particles measuring less than 5 millimeters in diameter. These particles are characterized by their persistence in the environment, as they are neither biodegradable nor soluble in water.

Microplastics can be generally classified into two categories based on their origin: primary and secondary microplastics. Primary microplastics are intentionally manufactured for use in a variety of products, including cosmetic formulations and cleaning agents, where they serve specific functional purposes. In contrast, secondary microplastics are formed unintentionally as a result of the degradation and mechanical breakdown of larger plastic materials. These particles typically arise as by-products during waste management processes such as the separation, storage, washing, grinding, and extrusion of plastic waste.

This paper examines the development of policies addressing microplastics derived from waste, with the aim of identifying effective legislative and regulatory strategies to mitigate plastic pollution.

The first section provides an overview of EU policies and trends in microplastic pollution, the second section focuses on existing policies in the Republic of Serbia, while the third section offers recommendations for policy reforms in Serbia aimed at enhancing the prevention of microplastic generation.

In the course of writing the paper, comparative method was employed, with observation serving as the primary research tool.

1. EU WASTE POLICIES IN MICROPLASTIC PREVENTION AND REDUCTION

Policies aimed at the prevention of secondary microplastic pollution are increasingly recognized as essential components of comprehensive plastic governance frameworks. Unlike primary microplastics, which can be regulated at the point of production, secondary microplastics present a greater regulatory challenge due to their diffuse and often unintentional formation during the degradation of plastic products. Current policy approaches typically address secondary microplastics through broader waste management and environmental protection legislation, with particular emphasis on improving plastic collection systems, encouraging material recovery, and minimizing plastic leakage into terrestrial and aquatic environments. Measures such as mandatory extended producer responsibility (EPR) schemes, the development of product design standards that reduce fragmentation, and investment in advanced waste treatment technologies have shown potential in mitigating secondary microplastic release. However, despite these advancements, significant gaps remain - particularly in the areas of enforcement, monitoring, and the integration of microplastic-specific criteria into existing permitting and environmental impact assessment procedures. As such, a more targeted policy framework is required, one that includes specific provisions for identifying high-risk plastic applications, regulating key industrial processes (e.g., mechanical recycling), and promoting innovation in alternative materials and closed-loop systems.

The European Union has been at the forefront of addressing microplastic pollution through a series of directives and regulations aimed at reducing plastic waste and controlling the release of microplastics into the environment.

The EU's European Strategy for Plastics in a Circular Economy (2018) is a comprehensive policy initiative designed to address the entire lifecycle of plastics. It includes a commitment to reducing plastic waste, promoting recycling, and curbing microplastic pollution. The strategy is framed within a broader push toward a circular economy, where materials are reused, recycled, and kept in use for as long as possible.

The Directive on Single-Use Plastics (SUP Directive) aims to reduce the environmental impact of plastic waste, particularly single-use plastic products. It includes measures to reduce plastic waste in aquatic environments, addressing secondary microplastic pollution caused by, for example, plastic litter.

Waste Framework Directive (2008/98/EC) lays out the EU's waste management policies and encourages waste prevention, the reuse of materials, and recycling. While not specifically focused on microplastics, it establishes a foundation for addressing waste management more broadly and can indirectly help reduce microplastic pollution by promoting better waste handling practices and recycling methods.

Also, the UNEP has been actively involved in raising awareness and guiding global actions to tackle microplastic pollution. The UNEP's work focuses on promoting international cooperation and policy harmonization, as well as improving scientific understanding of the issue.

In 2016, UNEP released a comprehensive global report on marine litter and microplastics, which offered scientific evidence on the extent of microplastic contamination and its environmental and health impacts. The report provides guidelines for the prevention and reduction of microplastic pollution in the marine environment, recommending policies and strategies such as banning microplastics in cosmetics, personal care products, and household cleaners and strengthening public awareness and education on the dangers of microplastics and plastic waste.

Both the EU and UNEP frameworks address secondary microplastic pollution through a combination of preventative measures (e.g., reducing plastic waste generation and promoting circular economy models) and mitigation strategies (e.g., improving waste treatment infrastructure, recycling technologies, and product design). Key policy components relevant to secondary microplastic pollution include stronger waste management policies aimed at preventing plastic fragmentation during collection and treatment.

2. WASTE POLICIES IN REPUBLIC OF SERBIA

Serbia's waste management system is governed by a comprehensive set of national laws, regulations, and policies designed to improve waste disposal practices, promote recycling, and mitigate environmental harm. These policies are part of a broader framework aligned with the country's ambitions for European Union (EU) integration. Serbia's efforts to harmonize its legal and regulatory structures with EU standards, particularly in the context of the EU acquis communautaire - a body of EU legislation that is binding on member states - reflect the country's commitment to adopting internationally recognized environmental practices. This alignment process has gained momentum following Serbia's signing of the Stabilization and Association Agreement (SAA) with the EU in 2008, which laid the foundation for cooperation in environmental protection and waste management. Serbia's commitment to EU integration underscores its ongoing legal and institutional reforms, particularly in the management of plastic waste and the broader goal of achieving sustainable environmental practices.

One of the cornerstone pieces of legislation in Serbia's waste management framework is the Law on Waste Management (2023). This law serves as the primary national legislation governing waste disposal, recovery, and recycling processes. The law stipulates procedures for the reduction, reuse, and recycling of waste materials, aligning Serbia's practices with EU directives aimed at minimizing waste generation and promoting the circular economy. Moreover, the law emphasizes compliance with EU standards on waste management, such as the Waste Framework Directive and the Packaging and Packaging Waste Directive, which establish common goals for waste reduction and recycling across EU member states.

In tandem with this legislative framework, Serbia adopted the Waste management program of the Republic of Serbia for the period 2022-2031, a strategic document that sets national objectives for waste reduction, recycling, and overall environmental protection. The program establishes a clear roadmap for achieving higher recycling rates, including specific measures to reduce plastic waste, with a strong emphasis on promoting the circularity of materials. The national plan aligns with the EU's overarching objectives of reducing single-use plastics, increasing recycling rates, and minimizing environmental harm caused by plastic waste. Notably, Serbia's recycling targets for plastic waste are modeled after those set by the EU, aiming for substantial increases in recycling rates and reductions in the volume of plastic waste sent to landfills.

Another significant piece of legislation in Serbia's efforts to address plastic waste is the Law on Packaging and Packaging Waste, which introduces the principle of Extended Producer Responsibility (EPR). Under this law, producers are held accountable for the entire lifecycle of their products, from design to post-consumer waste. This includes the management of plastic packaging waste, which constitutes a major portion of plastic pollution in Serbia. The law mandates that producers take responsibility for the recycling or disposal of packaging waste, either by joining collective recycling schemes or by paying fees that contribute to the proper management of plastic waste. These initiatives align Serbia with the EU's directives, which require member states to enforce producer responsibility for plastic packaging.

Additionally, Serbia has made strides in reducing the consumption of single-use plastic bags, a significant source of plastic waste. Through regulatory measures, including a ban on free distribution of plastic bags in retail environments, Serbia has begun to curb the widespread use of plastic bags, which are a notorious contributor to plastic pollution. These efforts are in line with the EU's Single-Use Plastics Directive (2019), which seeks to reduce the environmental impact of single-use plastic products across member states.

Despite these advancements, plastic waste remains a considerable challenge in Serbia. The country continues to face significant barriers in waste management, primarily due to an underdeveloped waste collection and sorting infrastructure. Although waste separation at the source is encouraged, it is not consistently practiced, particularly in rural areas, where the infrastructure for separate collection is often inadequate. This lack of comprehensive waste segregation hampers the effectiveness of recycling programs and contributes to the inefficient management of plastic waste.

Furthermore, a substantial portion of Serbia's waste is managed informally, often by waste pickers and through illegal dumpsites, particularly in rural and underserved regions. This informal sector complicates waste management efforts by circumventing official waste disposal channels, thus preventing the proper recycling of plastic materials. The lack of proper waste treatment facilities in these areas exacerbates environmental degradation and poses significant public health risks.

While Serbia has made notable progress in increasing its recycling efforts, the country still heavily relies on landfills for the disposal of waste, including plastic materials. Although landfill diversion strategies are part of the country's long-term waste management plans, the infrastructure for such diversion remains underdeveloped. Modern landfill diversion technologies, such as waste-to-energy systems and composting facilities, have not been widely implemented, which impedes the reduction of waste volumes directed to landfills. The slow adoption of circular economy principles - which emphasize reducing waste, reusing products, and recycling materials - further limits the potential for sustainable waste management practices.

In addition to infrastructure challenges, public awareness and participation in waste management programs remain critical issues. While urban areas have seen some success in promoting recycling practices, rural communities are less engaged in waste segregation efforts, primarily due to limited access to recycling bins and lack of educational campaigns. Consequently, significant volumes of recyclable plastic waste continue to end up in landfills, contributing to the ongoing environmental and ecological challenges posed by plastic pollution.

Serbia also faces challenges in monitoring and enforcement, particularly in relation to the proper implementation of waste management policies. The lack of effective monitoring mechanisms, coupled with inconsistent enforcement of regulations, allows for loopholes in compliance, especially in relation to producer responsibility schemes and the management of packaging waste. Strengthening the oversight of waste management systems and improving the capacity of environmental agencies to monitor plastic waste disposal are essential to achieving the country's long-term waste reduction goals.

To address these challenges, it is imperative that Serbia continues to invest in waste management infrastructure, particularly in rural areas, to ensure that plastic waste is effectively segregated, collected, and recycled. Expanding EPR schemes, improving the coordination of waste management systems, and increasing public education on the environmental impacts of plastic waste are critical to reducing the burden of plastic pollution. Moreover, Serbia must prioritize the implementation of waste diversion technologies and circular economy practices to reduce its reliance on landfills and increase the sustainability of its waste management systems.

3. LEGAL REFORMS FOR PLASTIC WASTE MANAGEMENT IN SERBIA

The primary recommendation concerns the adoption of amendments to the Law on Waste Management. It is essential that plastic waste be recognized as a distinct waste stream within the legal framework. The amended law should establish a comprehensive legal foundation for the development of a by-law that will provide specific regulations on the management of plastic waste, ensuring consistency and clarity in implementation. Recognizing plastic waste as a separate waste stream will enable more targeted regulations, tailored to the specific challenges posed by different types of plastics, thus optimizing waste management efforts. Additionally, such a designation will facilitate the tracking of plastic waste generation and disposal, enabling policymakers to measure progress in the reduction and recycling of plastic materials.

One of the key provisions in this legal framework should address the collection, transportation, and storage of plastic waste. The methods for collecting plastic waste must be designed in such a manner that they prevent the dispersion of microplastics into the environment during transit or storage. Microplastics are highly mobile and can easily become part of the broader environmental system if not carefully contained. Therefore, the legislative framework must mandate the adoption of best practices for the safe and controlled management of plastic waste, especially considering the risk of microplastic contamination. This would include guidelines for the secure sealing of plastic waste containers, regular monitoring of collection routes, and the establishment of dedicated storage facilities equipped to prevent leakage of microplastic particles.

The treatment of plastic waste is one of the primary contributors to microplastic formation. During the treatment process, plastic waste is initially sorted based on material type (e.g., polyethylene terephthalate (PET), polypropylene (PP), polyethylene (PE), polystyrene (PS), etc.), after which it is washed to remove contaminants. It is at this stage that microplastics can be generated, particularly in the form of fine plastic particles that may be released into wastewater. Given the potential environmental impact, it is of critical importance that each facility engaged in plastic waste treatment possess modern wastewater treatment plants capable of separating and managing microplastic particles. The failure to implement these technologies can result in the uncontrolled release of microplastics into water systems, contributing to the growing pollution of rivers, lakes, and oceans.

Moreover, companies operating such treatment plants should be legally required to ensure that technological wastewater - which results from the washing and processing of plastic materials - undergoes appropriate treatment. This treatment process must focus on the separation of microplastic particles from the effluent. Facilities should be mandated to adopt advanced filtration systems or other technologies capable of removing these minute particles before they are discharged into the environment. Technologies such as membrane filtration, advanced oxidation processes, or sedimentation tanks could be implemented to capture microplastics before the water is released. Furthermore, a legal requirement should be established to ensure that no treatment plant operates without a dedicated technological wastewater treatment system, and that these systems are subject to regulatory oversight through the issuance of a water permit that guarantees compliance with environmental standards. This oversight should be performed by an independent body to ensure transparency and accountability in the wastewater treatment process.

In addition to the treatment of wastewater, the proposed by-law should introduce provisions requiring facilities to manage the residuals that emerge from the waste treatment process. These residuals, often in the form of plastic fines or contaminated sludge, must be handled in accordance with the principles of environmental protection and resource recovery. The by-law should outline clear and enforceable guidelines for the disposal, recycling, or repurposing of these residual materials, ensuring that they do not contribute to further environmental degradation. In particular, plastic fines should be treated as a potential resource rather than waste, encouraging the development of processes for their safe incorporation into new products or their transformation into alternative materials, such as building aggregates or energy sources.

Furthermore, the amended law and the accompanying by-law should mandate regular reporting and transparency from facilities that handle plastic waste. This would ensure that both governmental agencies and the public are informed about the types and quantities of plastic waste being treated, as well as the effectiveness of the waste treatment and recycling processes. Such transparency will facilitate the identification of bottlenecks or inefficiencies in the waste management system and help optimize the allocation of resources for waste management operations.

In addition to facilitating better waste management practices, the legal framework should also emphasize public engagement and education. Public awareness campaigns on the importance of plastic waste separation, proper disposal, and recycling could contribute significantly to reducing plastic waste at the source. This would foster a culture of responsible plastic use and waste management, particularly if individuals understand the role they play in reducing microplastic pollution. The implementation of extended producer responsibility (EPR) schemes should be accompanied by public outreach programs that encourage consumers to participate in recycling efforts and make informed choices about their plastic consumption.

One critical aspect of the proposed legal changes is ensuring the enforcement of compliance with the amended laws. The government must allocate sufficient resources to environmental inspection agencies, enabling them to conduct regular audits of plastic waste treatment plants and facilities involved in the recycling process. Failure to comply with the updated regulations should result in severe penalties, including fines, mandatory closures, or the suspension of operations for repeat offenders. The robust enforcement of these regulations will be essential for ensuring that facilities adhere to the environmental standards necessary for mitigating microplastic pollution.

Finally, the development of innovation in alternative materials and technologies should be actively promoted through the amended waste management framework. Incentives could be offered to companies that invest in biodegradable or non-toxic alternatives to conventional plastics, as well as in the development of more efficient recycling technologies. Additionally, the legal framework should encourage the implementation of circular economy principles, where plastic products are designed with their end-of-life disposal in mind. Products designed for ease of recycling and resource recovery would reduce the amount of plastic waste generated and help minimize the creation of microplastics during waste processing.

CONCLUSION

The EU's directives and UNEP's guidelines provide a robust framework for addressing both primary and secondary microplastic pollution through regulatory measures, public-private collaboration, and a focus on lifecycle management. While EU regulations are highly targeted to specific sectors (such as cosmetics and plastics manufacturing), UNEP's global approach emphasizes coordination across borders and sectors to tackle microplastic pollution comprehensively. Both frameworks highlight the importance of integrated policies that combine prevention, innovation, and sustainable waste management to reduce the environmental and human health impacts of microplastics.

Serbia is making significant strides toward improving its waste management policies, particularly with regard to plastic waste. The country has adopted key legal frameworks, including the Law on Waste Management and the National Waste Management Program, that are aimed at reducing plastic waste and improving recycling rates. However, challenges such as inadequate waste sorting infrastructure, informal waste management systems, and public awareness must be addressed for Serbia to effectively tackle plastic pollution. Continued efforts to align with EU directives and invest in recycling technologies, combined with enhanced public education and industry collaboration, are essential for achieving long-term sustainability in plastic waste management.

Where competent authorities prescribe specific, legally binding conditions within the permitting framework - particularly concerning the segregation of plastic waste, mandatory pre-treatment procedures, storage and treatment standards, and wastewater management requirements - combined with provisions ensuring procedural transparency and public access to environmental information, it is foreseeable that such regulatory measures will contribute to the progressive reduction of microplastic pollution.

In conclusion, the adoption of amendments to the Law on Waste Management, alongside the establishment of a supporting by-law, is crucial for improving the management of plastic waste and preventing the proliferation of microplastic pollution. The implementation of these regulatory measures will provide the necessary legal infrastructure to ensure that Serbia's waste management practices align with contemporary environmental standards and contribute to global efforts in tackling plastic pollution. By addressing critical issues such as plastic waste collection, treatment, and residual management, as well as enhancing transparency and public participation, Serbia can significantly reduce its contribution to microplastic pollution and move towards a more sustainable, circular economy model. This integrated approach will not only benefit Serbia's environment but also enhance its reputation on the global stage as a responsible actor in the fight against plastic pollution.

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Application of AI in environmental protection: corrosion and biosorption

Primena VI u zaštiti životne sredine: korozija i biosorpcija

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Abstract: Artificial intelligence (AI) plays an important role in the field of scientific research. This paper aims to review the application of AI in corrosion and biosorption. The use of AI can advance the research process in terms of prediction, environmental and cost management, optimization and determination of the influence of parameters. Corrosion is a highly complex process that depends on many factors. Studying the interaction of these factors using AI enables better corrosion control. By applying AI, it is possible to determine the diverse influence of factors under real conditions using the database of numerous researches. In addition to the prevention and monitoring of corrosion and biosorption processes, it is important to focus the application of AI on environmentally friendly methods and chemicals. In this way, it is possible to identify compounds and materials of natural origin that can serve as substitutes for toxic compounds for corrosion protection or heavy metal removal. The importance of using non-destructive methods and monitoring data in real time is particularly emphasized, in order to avoid statistical errors. Optimization with the RSM method for corrosion and biosorption processes is widely used, determining process parameters where the best effect of corrosion protection and biosorption is achieved.

Keywords: AI, corrosion, biosorption, optimization.

Sažetak: Veštačka inteligencija (VI) ima važnu ulogu u oblasti naučnih istraživanja. Cilj ovog rada je pregled primene VI u oblasti korozije i biosorpcije. Primena VI može unaprediti proces istraživanja u smislu predviđanja, upravljanja životnom sredinom i troškovima, optimizacije i određivanja uticaja parametara. Korozija je veoma složen proces koji zavisi od mnogo faktora, ispitivanje interakcije ovih faktora primenom VI omogućava bolju korozionu kontrolu. Primenom VI je moguće utvrditi višestruki uticaj faktora u realnim uslovima prema bazi podataka mnogobrojnih istraživanja. Pored prevencije i praćenja procesa korozije i biosorpcije, važno je usmeriti primenu VI na ekološki prihvatljive metode i hemikalije. Na ovaj način je moguće identifikovati jedinjenja i materijale prirodnog porekla, koja mogu biti zamena za toksična jedinjenja koja se koriste za zaštitu od korozije ili za uklanjanje teških metala. Posebno je naglašen značaj primene nedestruktivnih metoda i praćenja podataka u realnom vremenu, kako bi se izbegle statističke greške. Optimizacija primenom RSM metode za procese korozije i biosorpcije se često koristi, pri čemu se određuju parametri procesa u kojima se postiže najbolji efekat zaštite od korozije i biosorpcije.

Ključne reči: VI, korozija, biosorpcija, optimizacija.

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INTRODUCTION

The possibility of using artificial intelligence in science facilitates the work of researchers (Zawacki-Richter et al., 2019). In the field of research, two types of studies are conducted: analytical and experimental. Experiments are becoming more expensive because they require more time, material and energy to achieve adequate results. Soft computing techniques are helpful to reduce the cost (Sharma et al., 2022). Machine learning, deep learning and artificial intelligence are in a relation. Machine learning focuses on enabling computers to perform tasks without explicit programming. Deep learning is based on artificial neural networks (ANN) as a subset of machine learning. By applying artificial intelligence, machines are taught to think and act like humans (Rajendran et al., 2022). Other AI applications such as pattern recognition, evolutionary computation, neural networks, expert systems, discriminant analysis, metaheuristic optimization, swarm optimization, image processing, and computer vision, are also used (LeCun et al., 2015). RSM is similar to adaptive neuro-fuzzy inference systems (ANFIS), which represent an AI modeling tool integrated with neural networks for data prediction (Onu et al., 2022; Onu et al., 2021). Studies related to the comparison of different methodologies used for prediction of complex nonlinear systems, including RSM and ANFIS, show that none is superior to the other (Okwu et al., 2021; Onu et al., 2022; Emembolu et al., 2022). The response surface methodology (RSM) is widely used in engineering, such as materials engineering, food engineering, chemical engineering, bioprocess engineering and pharmaceutical engineering, to evaluate the impact of individual factors or their interactive effects (Goh et al., 2008). The statistical tools used to design experiments in RSM enable the prediction and optimization of the processes studied (Veza et al., 2023). The application of artificial intelligence for environmental protection is of great importance and has great potential. It can be applied towards environmental health protection and sustainability (Nti et al., 2023). Recent scientific research has focused on the application of artificial intelligence in the field of corrosion protection and biosorption (Anadebe et al., 2023; Lin et al., 2023).

A very important application of AI in the field of corrosion detection can be divided into predictive maintenance (PdM) approaches for corrosion detection and computed vision and image processing techniques. PdM can be done with a knowledge-based model, a physic-based model, a data-based model and with a hybrid model. Computer vision and image processing approaches for corrosion detection can be divided into infrared thermography, texture analysis and non-destructive methods (Imran et al., 2023). Many researches focus on the protection of materials from corrosion by using environmentally friendly chemicals (Nazeer, Madkour, 2018; Rani, Basu, 2012). Natural materials and plant waste are often the starting components for obtaining environmentally friendly additives in coating applications, corrosion inhibitors and biosorbents (Ong et al., 2021; ElShami et al., 2020; Khaled et al., 2025; Falade et al., 2025; Rasheed et al., 2025; Marković et al., 2023; Zdravković et al., 2023). The application of environmentally friendly materials in corrosion protection and biosorption can be a circular process, in which the waste from the process of obtaining the plant corrosion inhibitor can be used as a biosorbent (Zdravković et al., 2024).

Environmental pollution is a serious problem in the modern world. Heavy metal pollution is reaching dangerous levels, with these metals being major pollutants in lakes, oceans, rivers, marines, industrial and even treated wastewater (Ghorbani et al., 2007). Biosorption, i.e. sorption using biological, low-cost adsorbents derived from plant waste, has emerged as a promising alternative to conventional methods to combat this problem. Multivariant statistical methods have gained attention in recent years and are used to identify the optimal combinations of factors as well as their interaction. These tools are also useful in reducing the cost and time of these studies. An experimental design consists of estimating the coefficients in a mathematical model used to predict the response and testing the adequacy of the model. Factorial experimental designs are the most commonly used experimental designs to determine response surfaces and the more complex RSM (Bingol et al., 2012). RSM is a collection of mathematical and statistical techniques that can be used to analyze the effects of different independent variables on system response (Amini et al., 2008). RSM has been applied in recent years to optimize many heavy metal removal processes using low-cost materials as biosorbents, including the removal of Cu^{2+} ions using raw chicken eggshell (Marković et al., 2023), calcined chicken eggshell (Marković et al., 2025) and bean shells (Marković et al., 2023). ANN are considered a promising tool because of the simplicity towards simulation, predict and model. ANN models are able to describe adsorption systems better than general rate models (Prakash et al., 2008). Recently, response surface methodology has been constantly compared with ANN in terms of their predictive capabilities for various processes. ANN use learning algorithms to evaluate the relationships between the input and output variables and can also be used to model the water management processes (Enyoh et al., 2023).

The aim of this article is to demonstrate the possibilities of applying AI in the field of corrosion protection and biosorption by identifying risks and methods of corrosion control and biosorption.

1. CORROSION PROTECTION

The degradation and destruction of materials caused by environmental influences is known as corrosion. The combined effects of chemical, electrochemical, mechanical, and/or biological variables can cause corrosion (Hoang et al., 2020, Kumari, Lavanya, 2024). The oil and gas industry is directly related to corrosion under insulation. The lack of adequate inspection technologies contributes to this well-known industrial challenge. However, an AI-enhanced inspection tool can provide better corrosion control under these conditions (Amer et al., 2020). Corrosion prevention and protection methods are crucial for sustainability, cost efficiency and safety. Various corrosion control techniques are used: environmental control, material selection, protective coatings, surface treatments, alloying, cathodic protection, design optimization and corrosion inhibitors (Kumari, Lavanya, 2024). The corrosion management system encompasses design, construction and operation and remains the main focus in ensuring the integrity and safe operation of the asset. The application of AI to predict corrosion rate offers advantages where real high-frequency data streams from sensors using machine learning algorithms, enabling predictions based on historical experience with specific assets (Alias et al., 2024).

A corrosion inhibitor is a chemical compound that is introduced in trace amounts to a corrosive medium. Corrosion inhibitors work by interfering with the electrochemical reactions that drive the corrosion processes on metal surfaces (Lavanya et al., 2024; de Souza Morais et al., 2023). Industrial corrosion is a challenge due to material wear and high maintenance costs, which is why effective corrosion inhibitors are very important. Identifying the most efficient compounds in corrosion inhibitors can be time-consuming (Putra et al., 2025). Some inhibitors are specific for certain metals. One example is the corrosion inhibition of copper by tannins, so the identification of plant extracts or expired pharmaceutical products containing these compounds is of great importance (Shah et al., 2013; Kusmierek, Chrzescijanska, 2015). However, tannins also act as corrosion inhibitors for other metals such as steel, iron and aluminum (Rahim, Kassim, 2008; Proença et al., 2022; Zelinka, Stone, 2011). The application of AI can facilitate the identification of the corrosion inhibitor that acts best on the corresponding metal (Lin et al., 2023). Another environmentally friendly way of corrosion protection is the use of plant extracts (natural additives), which have the same functions as synthetic additives (Ong et al., 2021). AI can be used to predict costs, workforce and other variables to be considered for protective coating management (Correa, Mariano, 2022). Prevention is also important to protect the environment from corrosion damage. An example is the application of AI for crack detection in nuclear power plants (Allah et al., 2024). Stress corrosion cracking (SCC) poses a significant challenge to the integrity and longevity of conventional and advanced alloys used in aerospace, marine and nuclear energy applications. Conventional alloys (steel, aluminium, and titanium) and advanced materials (additive-manufactured and high-entropy alloys) exhibit unique SCC behaviour that is affected by corrosive environments, mechanical stress, and temperature variations. Using extensive data sets from experiments and field studies, AI can identify patterns and correlations that traditional methods may miss (Mathew, Adu-Gyamfi, 2024). In addition to the application of AI for the corrosion of metals and metal alloys, AI methods have also been used to predict the corrosion of cement and sulphur concrete in sewage systems. AI-based techniques: adaptive neuro-fuzzy inference system (ANFIS), genetic programming (GP) and multi-expression programming (MEP) were used. Two sets of chemical experiments in acidic solutions and biological tests with *Thiobacillus thiooxidans* were conducted to investigate corrosion in concrete samples. The results show that machine learning-based models can help engineers to estimate the corrosion of concrete pipes in sewer systems (Sabour et al., 2021).

Corrosion protection in marine conditions is very important (Lawal et al., 2024). Adequate choice of corrosion protection can reduce the corrosion rate of metals and protect the environment (Bardal, 2004). The application of AI can be very useful in the prediction and detection of marine corrosion (Imran et al., 2023). Pattern recognition (PR) is one of the AL techniques applied for the prediction of marine corrosion (Imran et al., 2023). This method has also been used to detect corrosion under the coating (Ali et al., 2016). The electrochemical method (electrochemical noise, EN) was used to detect the corrosion and passivation of 304 steel. The results show that the PR accuracy was higher than using only statistical parameters and parameters selected by principal component analysis (Legat, Dolecek, 1995).

The predictive maintenance approaches can provide a mechanism to prevent external corrosion for effective corrosion control (Jimenez et al., 2020). An example is the PdM with a data-based model where the mathematical model from the real-time data was applied to predict corrosion damage to the ship structure (Makridis et al., 2020). The most appropriate mathematical model was proposed for long-term corrosion in physical infrastructure and ship corrosion using the PdM with physic-based model (Bouzaffour et al., 2021). The PdM with hybrid model was used for structural health monitoring, for hull structure maintenance and corrosion detection (Jimenez et al., 2020).

RSM can be used to determine the conditions under which the corrosion inhibitor slows down the corrosion process the most (Ahmadi, Khormali, 2024). Using the RSM results optimization of corrosion process can be performed. By optimizing the corrosion process, it can be determined at which parameters the highest inhibition efficiency is achieved with the minimum dose of corrosion inhibitor, which is investigated when several parameters are changed simultaneously (Emembolu et al., 2022). The most common combination of parameters for the optimization of the corrosion process using corrosion inhibitors are the temperature, the immersion time of the metal in the electrolyte and the concentration of the inhibitor (Ahmadi, Khormali, 2024). Inhibitor concentration, electrolyte concentration and metal immersion time can also be used as variables (Edoziuno et al., 2020; Udunwa et al., 2022; Gu et al., 2015). AI enables to quickly discover and optimize new corrosion inhibitors (Lin et al., 2023).

However, in addition to the numerous advantages of applying AI, it also has its limitations. AI methods are compared to black boxes that merely attempt to map a relationship between output and input variables based on a training dataset. This raises concerns regarding the ability of the tool to generalize to situations that were not well represented in the dataset. The solution may lie in combining or integrating multiple AI paradigms in a hybrid solution or coupling AI paradigms with more traditional solution techniques. Another limitation of using AI-based search methods to solve a problem is that it is often difficult to gain true insight into the problem and the nature of the solution, as is possible when using mathematical programming methods, for example (Chowdhury, Sadek, 2012).

2. BIOSORPTION

Heavy metal pollution associated with wastewater originating from industrial activity, is a serious environmental problem. The growing demand for clean water around the world demonstrates the importance of water purification, i.e. the removal of hazardous heavy metals. The problem of pollution will worsen in the coming years, which will lead to an increase in demand for clean water and thus increase pressure on wastewater treatment (Babu et al., 2023; Jendia et al., 2020). At the industrial level, many conventional methods are used for wastewater treatment, including precipitation, reduction, oxidation, ion exchange and sorption (Bingol et al., 2012). Biosorption is a method that offers itself as a possible alternative for the removal of heavy metals. It is a user-friendly process, so to speak, as it offers many advantages, including a simple design, a specific affinity for certain pollutants and low cost. Industrial and agricultural by-products are used as biosorbents as they are very practical due to their favorable physical, chemical and surface properties, abundant availability and low cost (Marković et al., 2023).

RSM consists of statistical and mathematical techniques that can be used to develop an adequate functional relationship between a response and a number of input (or control) variables. Two major groups of models are commonly used in RSM, namely first-degree and second-degree models. First-order experimental designs include the 2^k factorial experimental design, the Plackett-Burman experimental design, and the simplex experimental design. Second-order designs include the 3^k factorial design, the central composite design (CCD) and the Box-Behnken design (BBD) (Khuri, Mukhopadhyay, 2010). The RSM coupled with the BBD and the CCD has been used as a tool to optimize biosorption processes in a large number of papers in recent years. These statistical models are used to optimize the biosorption processes considering the operational variables that affect the metal uptake efficiency, such as the pH of the aqueous phase, initial sorbate concentration, biosorbent dose, contact time, and others. The modeling coupled with ANOVA statistical analysis to evaluate the significance of the model and to show the influence of the individual variables and their interactions (Choinska-Pulit et al., 2018; Fawzy, 2020).

ANN is a mathematical model that attempts to simulate the structure and functionalities of a biological neural network. ANN are build of blocks, each of which represents an artificial neuron, that is, simply put, a simple mathematical function (model). By combining two or more artificial neurons, an artificial neural network is created. Artificial neural networks are capable of solving complex problems by processing the input information in their basic artificial neurons in a parallel, distributed, non-linear and local way (Suzuki, 2017). The application of

ANN in modeling biosorption processes has increased significantly in recent years. Artificial network models have been used to correlate and predict isotherms, kinetics, breakthrough curves and other responses of many adsorbents, biosorbents and adsorbates, in the field of water treatment, including biosorption. A variety of models are used to analyze, correlate and predict biosorption processes. However, these models are usually based on restrictive theories and assumptions, which limits their applications. ANN help overcome the disadvantages of traditional models by providing better predictions at various operating conditions. In mathematical terms, the performance of a biosorption system is described as a nonlinear function that depends on the properties of the biosorbent, the chemistry of the adsorbate(s), the fluid properties, the operating conditions and the equipment configuration. This nonlinear function can be modeled using an artificial neural network, as there are no limitations to incorporate all independent variables affecting the analyzed system. Environmental factors, such as the pH of the aqueous phase, the initial sorbate concentration, the contact time, the biosorbent dosage and others, have a significant impact on the efficiency of the biosorption process. In order to achieve the highest removal, optimal conditions must be met, and the influencing factors mentioned must be optimized using suitable modeling and simulation methods. ANN can be used to understand the complex interactions between the experimental factors and the uptake of metal ions. Artificial neural networks can also predict the performance of multicomponent biosorption systems by including performance metrics, such as adsorption capacity, as output variables. Moreover, ANN has significant potential over traditional models for the analysis of real fluids in which multiple adsorbates are present, leading to different removal behavior (Reynel-Avila et al., 2022; Fawzy et al., 2018).

Recently, RSM and ANN methods have been jointly applied by researchers to predict the biosorption processes. By applying both techniques, the results can be compared to gain a better understanding of the process. The combination of RSM and ANN, where the experimental RSM data is used to train and validate the ANN, provides more accurate results (Dulla et al., 2018; Ghosh et al., 2015).

CONCLUSION

The application of AI in the field of corrosion and biosorption has proven to be an effective and fast way to analyze results and optimize processes to make them less expensive and time-consuming. Numerous AI techniques allow researchers to adapt their research to achieve the most realistic results possible. By applying AI, it is possible to predict corrosion processes, improve the process of corrosion protection and identify new environmentally friendly compounds that have not yet been tested as corrosion inhibitors. The use of non-destructive methods is another advantage of AI. AI techniques are also used to optimize the biosorption process by analyzing the response of the system to different environmental conditions. The influence of many different variables on the efficiency of the process and their interactions can be studied using AI. However, AI also comes with certain disadvantages in the form of errors that can occur when experimentally obtained data is used for modeling. Process optimization has proven to be one of the most important applications of AI for both corrosion and biosorption.

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Economic indicators of effectiveness and efficiency with a focus on the development of organic production in the Western Balkans

Ekonomski indikatori efektivnosti i efikasnosti sa fokusom na razvoj organske proizvodnje na Zapadnom Balkanu

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Abstract: Organic agriculture represents a farming system that, beyond its environmental dimension, carries substantial economic relevance. Although the development of organic production in the Western Balkan countries has progressed more slowly than in most European Union member states, it nevertheless demonstrates encouraging economic performance and growing strategic relevance. When guided by principles of efficiency and supported by a dedicated institutional framework, this sector yields dual benefits: promoting environmental sustainability while simultaneously facilitating integration into expanding and profitable markets. More than merely the avoidance of synthetic inputs, organic agriculture entails the harmonization of farming practices with natural ecosystems and the respectful treatment of living organisms. By rejecting synthetic fertilizers and pesticides, genetically modified organisms, growth hormones, antibiotics, and artificial additives, this approach proactively addresses ecological and social externalities. Instead, it embraces a holistic paradigm that fosters biodiversity, reinforces natural cycles, and revitalizes soil fertility. For Serbia and the other countries analyzed in this study: Albania, Bosnia and Herzegovina, Montenegro, and North Macedonia, organic agriculture emerges like a pathway toward sustainable economic transformation. This paper explores key economic indicators related to the effectiveness and efficiency of organic sector development in the Western Balkans.

Keywords: Organic agriculture, Western Balkans, Economic performance, Effectiveness, Sustainable development, Agro-ecosystem, Serbia, Comparative analysis.

Sažetak: Organska poljoprivreda predstavlja poljoprivredni sistem koji, pored svoje ekološke dimenzije, nosi značajan ekonomski značaj. Iako je razvoj organske proizvodnje u zemljama Zapadnog Balkana napredovao sporije nego u većini zemalja članica Evropske unije, on ipak pokazuje ohrabrujuće ekonomske performanse i rastući strateški značaj. Kada se vodi principima efikasnosti i podržava ga poseban institucionalni okvir, ovaj sektor donosi dvostruke koristi: promociju ekološke održivosti, a istovremeno olakšava integraciju u rastuća i profitabilna tržišta. Više od pukog izbegavanja sintetičkih inputa, organska poljoprivreda podrazumeva harmonizaciju poljoprivrednih praksi s prirodnim ekosistemima i poštovanje prema živim organizmima. Odbacivanjem sintetičkih đubriva i pesticida, genetski modifikovanih organizama, hormona rasta, antibiotika i veštačkih aditiva, ovaj pristup proaktivno rešava ekološke i društvene eksternalije. Umesto toga, on prihvata holističku paradigmu koja podstiče biodiverzitet, jača prirodne cikluse i revitalizuje plodnost zemljišta. Za Srbiju i druge zemlje analizirane u ovoj studiji: Albaniju, Bosnu i Hercegovinu, Crnu Goru i Severnu Makedoniju, organska poljoprivreda se pojavljuje kao put ka održivoj ekonomskoj transformaciji. Ovaj rad istražuje ključne ekonomske indikatore vezane za efikasnost i efikasnost razvoja organskog sektora na Zapadnom Balkanu..

Ključne reči: Organska poljoprivreda, Zapadni Balkan, ekonomski učinak, efikasnost, održivi razvoj, agroekosistem, Srbija, komparativna analiza.

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INTRODUCTION

The growing demand for sustainable agricultural practices has brought organic farming to the forefront of environmental and rural development strategies. As global concerns about soil degradation, water scarcity, and chemical overuse in agriculture intensify, organic production systems have emerged as a viable alternative that aligns with ecological and socio-economic priorities. In contrast to conventional agriculture, organic farming promotes the conservation of essential natural resources, particularly soil and water. Additionally, it plays a direct role in fostering various complementary activities within rural economies.

In the Western Balkan region, sustainability has historically not been a core focus of agricultural policy. This has led to a range of environmental and infrastructural constraints for the development of organic production. As noted by Pavlović et al. (2024), “Croatia and Serbia have numerous deposits of lignite, which is used for electricity production and household heating. Combustion of lignite leads to significant pollution of the environment with heavy metals and other phytotoxic elements. That is why significant areas of land in Croatia and Serbia are not suitable for organic production.” This observation underscores how legacy energy practices can limit the ecological viability of certain territories for organic agriculture. The production of fruit dominates in Serbia, followed by the production of cereals with constant growth in the production of industrial plants, oilseeds and animal feed Fodder production, it has also seen growth in recent years (Jovanović & Pavlović, 2023).

The ecological dimension of organic agriculture can serve as part of the solution to challenges addressed by the European Green Deal and the Green Agenda for the Western Balkans. In addition to its contribution to environmental sustainability and the preservation of public health, its economic significance is substantial. Given that Western Balkan countries possess longstanding experience in conventional agricultural practices, hold the status of developing economies, and are geographically situated in Europe with aspirations toward EU accession, the economic potential associated with the development of the organic sector appears promising.

1. METHODOLOGY

This study employs a descriptive, analytical, and comparative research approach. The primary data sources include The World of Organic Agriculture (Statistics and Emerging Trends) reports for 2021, 2022, and 2024, published by the Research Institute of Organic Agriculture (FiBL), Frick, and IFOAM (Willer et al., 2021, 2022, 2024), alongside official national statistics. The comparative analysis focuses on the state of organic agriculture in selected Western Balkan countries: Albania, Bosnia and Herzegovina, Montenegro, and North Macedonia and Croatia, like EU member state from the same region.

To assess the market performance of the organic agriculture sector across these countries, a Market Efficiency Index (MEI) is introduced. The MEI is defined as the ratio of total organic food exports (in metric tons) to the total certified organic agricultural area (in hectares). This index serves as a proxy indicator for evaluating the degree of market integration, export productivity, and the economic output per unit area of organic land.

2. RESEARCH AND DISCUSSION

A survey of organic production effectiveness and efficiency was conducted in the observed countries of Western Balkans (Albania, Bosnia and Herzegovina, Montenegro, North Macedonia and Serbia) and Croatia (EU member). The indicators analyzed: Organic share; Organic area; and Export data (EU and USA). Based on the analyzed indicators assessing the market performance of the organic agriculture sector across selected countries, a Market Efficiency Index (MEI) is calculated to provide a comparative measure.

Overview of Organic Share in the Western Balkan Countries and Croatia

The organic share serves as a key indicator of the development and integration of organic farming within national agricultural systems. Among the Western Balkan countries, this share remains relatively low compared to EU averages, yet it shows gradual progress. As shown in Table 1, organic share is in progress (2019-2022) in selected countries.

Table 1 – Organic share change (2019-2022) in selected countries, with trend

Country	Organic share % (2019)	Organic share % (2022)	Trend
Albania	0.1	0.1	No variation
Bosnia and Herzegovina	0.1	0.1	No variation
Montenegro	1.8	1.5	- 0.3
North Macedonia	0.3	0.7	+0.4
Serbia	0.6	0.7	+0.1
Croatia	7.2	8.6	+1.4

Source: Author ‘s research based on Willer et al., 2021 & 2024

Albania and Bosnia and Herzegovina maintained a consistently low organic share of 0.1%, with no recorded growth during this period. Montenegro saw a slight decline from 1.8% to 1.5%. North Macedonia more than doubled its organic share, growing from 0.3% to 0.7%, showing promising momentum. Serbia experienced modest growth, increasing from 0.6% to 0.7%. Croatia stands out with both the highest organic share overall and notable growth: from 7.2% in 2019 to 8.6% in 2022. This suggests a more mature and better-supported organic considering EU membership.

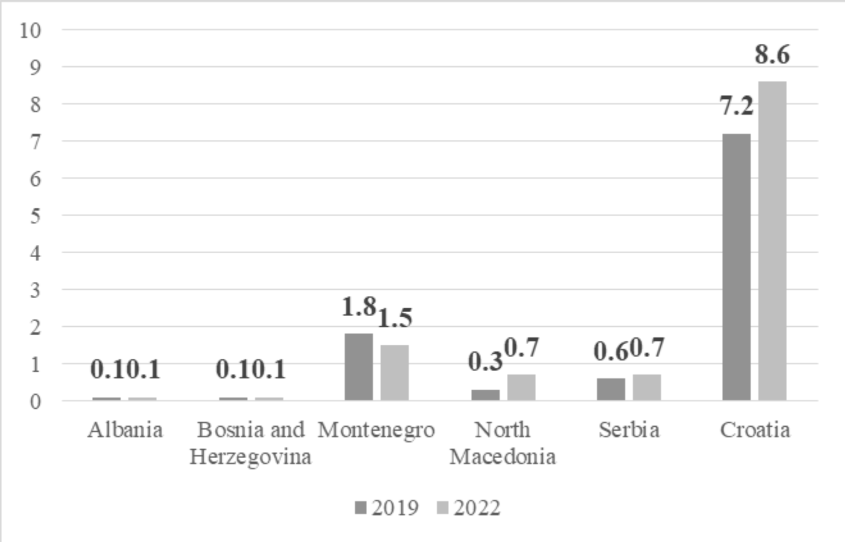

Figure 1 – Organic share change (2019-2022) in selected countries
Source: Author 's figure

Organic area in selected countries

The comparative analysis of organic agricultural land across selected countries between 2020 and 2022 reveals marked variations in growth dynamics, reflecting distinct national trajectories in the development of the organic sector (Table 2).

Table 2 – Areas under organic production in selected countries 2020 and 2022 in ha, with trend and growth rate

Country	Area under organic production (2020) in ha	Area under organic production (2022) in ha	Trend in ha	Growth rate in %
Albania	887	674	-213	-24.02
Bosnia and Herzegovina	1692	2495	+803	+47.45
Montenegro	4823	3966	-857	-17.76
North Macedonia	3727	8724	+4997	+133.99
Serbia	19317	25035	+5718	+29.60
Croatia	108610	129374	+20764	+19.14

Source: Author 's research based on Willer et al., 2022&2024 database

Croatia recorded the most substantial absolute increase, with an expansion of 20,764 hectares under organic production, underscoring the country's consolidated regulatory framework and relatively advanced institutional support for organic farming.

Serbia and North Macedonia also exhibited significant positive developments, with respective increases of 5,718 and 4,997 hectares.

Bosnia and Herzegovina demonstrated moderate growth, adding 803 hectares to its organic agricultural area during the observed period. In contrast, Albania and Montenegro experienced reductions of 213 and 857 hectares, respectively. Taken together, these findings point to a general regional tendency toward the expansion of organic farming.

Although the total areas under organic production (still remain below the levels seen in EU countries, and are even several times smaller), the value of organic product exports has generally shown a steady increase.

The calculated growth rates reveal considerable variation across countries. North Macedonia experienced the most dynamic expansion, with a 133.99% increase in organic agricultural area, followed by Bosnia and Herzegovina (+47.45%) and Serbia (+29.60%). Croatia saw a steady growth of 19.14%, despite already having the largest organic area in absolute terms. In contrast, Montenegro (-17.76%) and Albania (-24.02%) recorded contractions.

Organic exports in selected countries

Table 3 – Exports to EU and USA

Country	Exports to EU and USA (2020) in MT	Exports to EU (2022) in MT	Exports to USA (2022) in MT
Albania	1834	1440.3	1.4
Bosnia and Herzegovina	1582	10489.8	-
Montenegro	56	24.1	-
North Macedonia	361	447.1	-
Serbia	15847	14323.6	62.2
Croatia	28 (USA)	EU country	20.8

Source: Author ‘s research based on Willer et al., 2022 & 2024 database

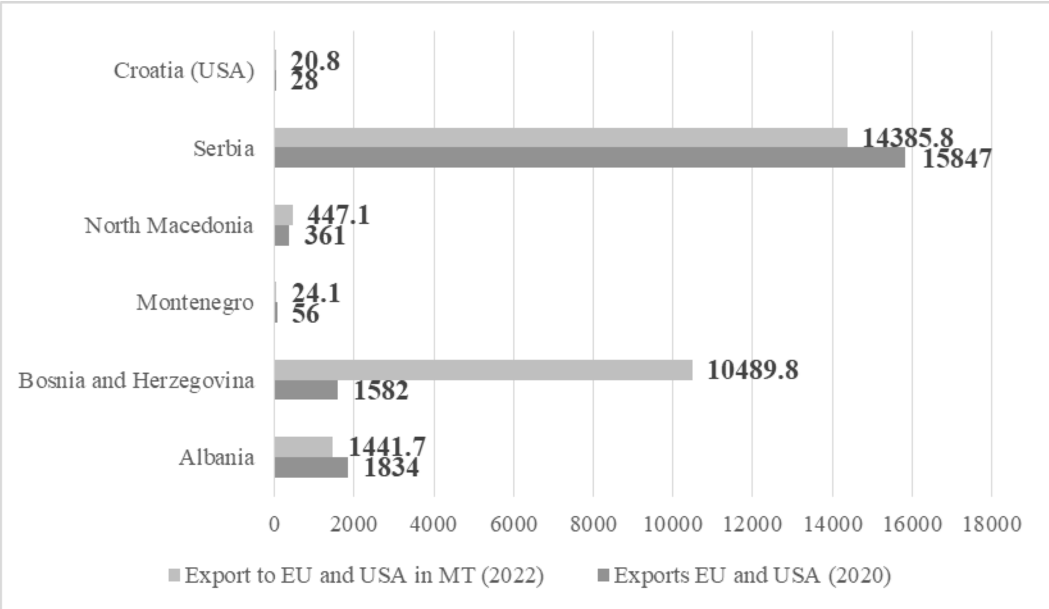

Figure 2 – Exports to EU and USA
Source: Author ‘s figure

The export of organic agricultural products from the Western Balkans to the European Union and the United States represents a growing segment of economic potential for the region. In particular, the European market has demonstrated a consistent and significant demand for such products, positioning itself as the primary destination for exporters from countries like Serbia, Bosnia and Herzegovina, and North Macedonia. Empirical data supports this trend: in 2022, Serbia exported approximately 14,323 metric tons (MT) of organic products to the EU, compared to a modest 62.2 MT to the United States. Bosnia and Herzegovina experienced a remarkable increase in exports to the EU, rising from 1,582 MT in 2020 to over 10,000 MT in 2022. In contrast, countries such as Montenegro and Albania exhibited notably smaller volumes, indicating structural limitations or underdeveloped supply chains in organic production.

This uneven distribution suggests a high degree of heterogeneity in the capacity of Western Balkan states to engage with international organic markets. Serbia has emerged as a regional leader, owing to its more developed production infrastructure, diversified export portfolio, and institutional support for organic farming. Meanwhile, the limited engagement with the U.S. market across the region may reflect logistical challenges, regulatory differences, or strategic prioritization of the geographically closer and more accessible EU market.

Importantly, the positive trajectory in export volumes - particularly toward the EU - illustrates the increasing competitiveness of the region's organic sector, even in the face of global disruptions such as the COVID-19 pandemic. This growth can be interpreted not merely as a commercial success but as an indicator of the sector's adaptive capacity and alignment with international quality standards. Nevertheless, the proportion of land dedicated to organic farming in most Western Balkan countries remains marginal. Tripković, Arsić, and Dobričanin (2023) emphasize that the continued expansion of organic agriculture holds the potential to strengthen the sustainability of small and medium-sized enterprises, provided that they harness emerging opportunities and maintain a focus on healthy food production principles. This underscores both the potential for expansion and the necessity of targeted policy interventions, including technical assistance, farmer education, and improved certification processes.

In sum, the organic export sector holds significant promise as a driver of rural development and economic diversification in the Western Balkans. While current performance varies across countries, the overall trend points to an upward trajectory that, if strategically cultivated, could bolster not only export revenues but also the environmental sustainability and international integration of the region's agri-food systems.

Market Efficiency Index of the Organic Sector in selected countries

A Market Efficiency Index (MEI) was calculated by dividing the total quantity of organic exports, measured in metric tons, by the total certified organic agricultural area in hectares. This ratio provides a standardized indicator of export productivity per unit of organic land area. This metric serves as a proxy indicator for assessing the intensity of market integration, export productivity, and the economic output per unit area of organic land.

Table 4 – Market Efficiency Index of the Organic Sector in selected countries (2022)

Country	Organic area (ha, 2022)	Exports to EU+USA (MT, 2022)	MEI (MT/ha)
Albania	674	1441.7	2.14
Bosnia and Herzegovina	2495	10489.98	4.20
Montenegro	3966	24.1	0.006
North Macedonia	8724	447.1	0.05
Serbia	25035	14385.8	0.57
Croatia	129374	N/a (partial data)	-

Source: Author 's calculation

The MEI reveals significant divergence in market integration among the countries studied. Bosnia and Herzegovina exhibits the highest index value (4.20 MT/ha), suggesting a strong export orientation and efficient conversion of organic land into marketable output. Conversely, Montenegro and North Macedonia display very low MEI values, indicating weak export performance relative to their organic area. In the case of North Macedonia, although the number of organic producers is relatively high, holdings are highly fragmented - typically not exceeding 2 hectares - which further limits export capacity (Jovanović & Pavlović, 2024). Moreover, the accessibility of official certification systems remains a key barrier. As Janković et al. (2023) note, 'For small-scale farmers, the cost of accessing official certification systems is often burdensome. As a result, the procedures required to obtain formal certification can represent a significant obstacle. Serbia presents a moderate level of efficiency, while data limitations prevent conclusive analysis for Croatia.

When addressing the importance of organic agriculture - particularly from an economic standpoint - it is relevant to consider Demeter certification, which reflects a more rigorous and advanced standard of organic production rooted in the biodynamic farming system. As a holistic agricultural approach, biodynamic farming builds upon the principles of organic agriculture while incorporating ecological, ethical, and spiritual dimensions of land management. Globally, 7,087 farms are certified under the Demeter standard. Within the Western Balkans and the countries examined in this study, Serbia stands out with two Demeter-certified farms, followed by Bosnia and Herzegovina with one. Currently, no certified farms operate under this standard in Albania, Montenegro, or North Macedonia. The presence of biodynamic practices in Serbia demonstrates that the foundational conditions for implementing more advanced organic systems are already in place, providing a promising platform for future sectoral development.

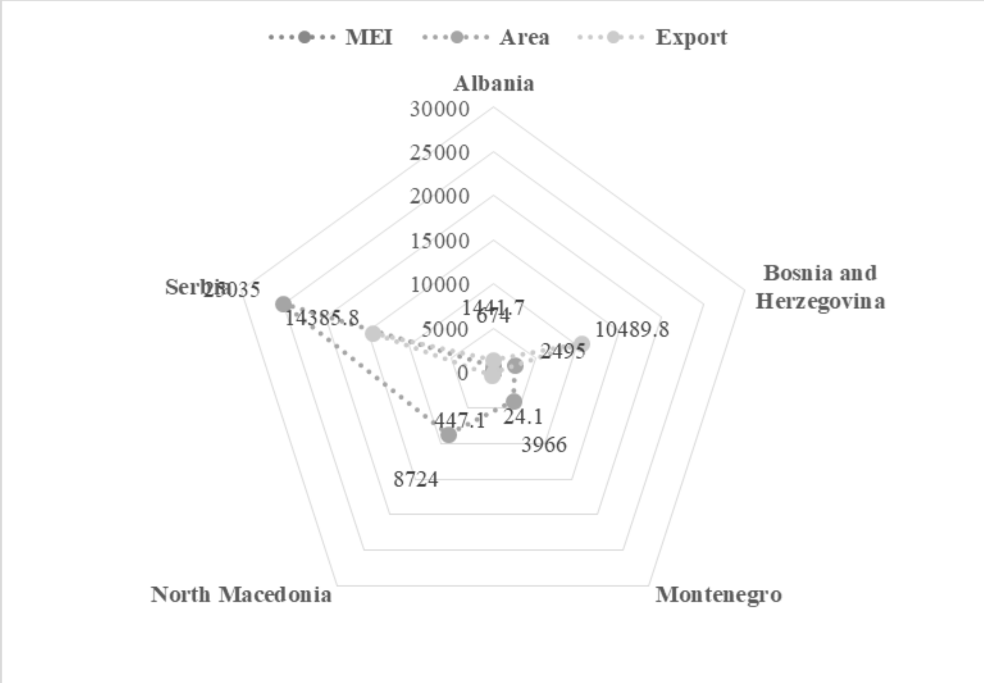

Figure 3 – Market Efficiency Index in selected countries (2022)
Source: Author 's figure

CONCLUSION

The analysis of organic agriculture in the Western Balkans and Croatia underscores the sector's uneven yet progressively evolving character across the region. Despite persistent environmental and infrastructural limitations in relation to the soil contamination and limited policy emphasis on sustainability - several countries demonstrate clear signs of growth in organic land area, export performance, and market integration.

The introduction of the Market Efficiency Index (MEI) offers a valuable metric for assessing the relationship between certified organic area and export output, enabling more nuanced comparisons between countries. Serbia emerges as a regional leader, exhibiting a strong export capacity and early adoption of advanced standards such as Demeter certification. This not only reflects its institutional and infrastructural readiness, but also highlights the latent potential of the entire region to transition toward more sustainable agricultural models.

Although the share of land under organic management remains modest in most countries, rising export volumes - particularly to the European Union - illustrate the sector's growing alignment with international markets. However, to fully harness this potential, targeted policy interventions are needed to support certification systems, farmer education, technical capacity building, and value chain development.

In this context, organic agriculture should not be viewed merely as a niche production system, but as a strategic pillar for rural development, environmental protection, and European integration. The foundation for more advanced organic systems - such as biodynamic farming - is already present in parts of the region, providing a promising basis for further expansion and innovation.

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Од 24 -25 априла 2025. године у Београду је одржана Међународна научна Конференција:

APPLICATION OF ARTIFICIAL INTELLIGENCE IN ENVIRONMENTAL PROTECTION AND AGRICULTURE (ПРИМЕНА ВЕШТАЧКЕ ИНТЕЛИГЕНЦИЈЕ У ЗАШТИТИ ЖИВОТНЕ СРЕДИНЕ И ПОЉОПРИВРЕДИ)

Конференција је одржана је под покровитељством Министарства науке, технолошког развоја и иновација Републике Србије

Организатор скупа:
Научно-стручно друштво за заштиту животне средине Србије "ECOLOGICA"

Суорганизатори:
АЛФА БК Универзитет, Београд
Савез инжењера и техничара Србије, Београд
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Bulgarian National Society of Agricultural Engineers, Bulgaria
Balkan Environmental Association (B.EN.A.)

Међународни научни скуп отворила је Председница Управног одбора Научно-стручног Друштва ECOLOGICA Емеритус проф. Др Лариса Јовановић.
Поздравне говоре одржали су:
Проф. Др Илија Ћосић, председник Инжењерске академије Србије;
Проф. Др Валентина Будинчић, проректор АЛФА БК Универзитета

Конференција је радила у оквиру Пленарног заседања и пет секција:

- New methods for analyzing soil and plant composition /
  Нове методе анализе састава земљишта и биљака
- Modelling of fitigeochemical profiles /
  Моделирање фитогеохемијских профила
- The role of artificial intelligence in environmental security /
  Улога вештачке интелигенције у еколошкој безбедности
- Application of AI in environmental protection/
  Примена вештачке интелигенције у заштити животне средине
- Application of artificial intelligence in the economic assessment of mineral reserves /
  Примена вештачке интелигенције у економској процени минералних резерви

У раду Међународне научне Конференције *„Примена вештачке интелигенције у заштити животне средине и пољопривреди“* учествовали су научници, привредници, инжењери, професори и други учесници скупа.

Конференција је имала за циљ да укаже на значај Вештачке интелигенције у заштити животне средине. Конференција је обухватала следеће тематске области: Примена иновативних метода анализе састава земљишта и биљака у циљу моделирања фитогеохемијских профила; Примена вештачке интелигенције у економској евалуацији минералних резерва; Значај вештачке интелигенције у економској модернизацији.

Članovi Naučnog odbora Međunarodne naučne konferencije "Application of artificial intelligence in environmental protection and agriculture"

Najavljivanje naučnih sekcija Međunarodne naučne konferencije, Beograd, 24-25 April, 2025. god.

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