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Gödöllő

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Aspects of environmentally sound recycling of wooden railway sleepers

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1. HISTORY, OBJECTIVES

In my thesis, I examine the possibilities of recycling railway sleepers in terms of the use of environmentally friendly technologies. The starting point of the research is that the recycling of railway sleepers – which are classified as hazardous waste – poses both environmental and economic challenges. The relevance of the problem is reinforced by the fact that, despite the strict environmental regulations of the European Union, used sleepers are largely discarded, as their recycling faces technological and legal obstacles.

My choice of topic is based on personal professional experience, as I have worked in the recycling industry for almost 20 years, where I cooperated with several state-owned companies (for example, MÁV Zrt., BKV Zrt.). During my work, I identified nearly 19,000 metric tons of used railway sleepers at various locations. These items – due to their hazardous nature and their creosote content – require special attention; however, they also have significant economic and environmental opportunities.

The relevance of the research is further enhanced by the global focus on sustainable development, green management and waste management. The importance of recycling goes beyond waste management: it can contribute to increasing energy efficiency, reducing carbon emissions and improving economic efficiency.

The starting point of the research is also supported by the increasing emphasis on sustainability by railway companies as part of their social responsibility strategies, while existing technologies and legal frameworks often do not meet environmental requirements.

Objectives

My general goal is to explore the technological and economic possibilities of recycling used railway sleepers and to develop solutions that contribute to the achievement of sustainability goals. During the research, I set the following specific objectives:

1. **Analysis of the regulatory environment:** Examining the extent to which the current legal and regulatory environment supports or inhibits the recycling of railway sleepers.
2. **Identifying technological solutions:** Identifying technologies that minimize environmental impact and are economically viable in the case of recycling used sleepers.
3. **Prototype development:** Developing an actual prototype o demonstrates the possibilities of recycling railway sleepers in practice.
4. **Economic analysis:** Demonstrating how the use of appropriate recycling technologies can reduce waste management costs and create economic value for railway companies.

5. **Assessment of sustainability impact:** Demonstrating through analyses, how the recycling of used railway sleepers contributes to environmental goals, such as reducing carbon emissions.

Hypotheses

During the research, I formulated the following hypotheses:

H1: In Hungary, a significant proportion of used railway sleepers classified as hazardous waste are not recycled.

H2: The recycling practices of used railway sleepers in Germany, the Netherlands, Switzerland, Poland and Brazil differ significantly from the practices in Hungary.

H3: The entities involved in recycling only choose recycling for energy as an environmentally friendly management method.

H4: The application of the prototype developed for recycling increases the rate of sustainable processing of used railway sleepers in the coming years.

H5: Recycling used railway sleepers can bring economic benefits to railway companies as it reduces waste management costs and creates an opportunity to generate revenue through the sale of recycled materials.

1. *Table 1: Table demonstrating the correlations*

Research objective	Research question	Hypothesis	Test method
O1: Examining to what extent the current legislative and licensing environment supports or hinders the recycling of used railway sleepers.	Q1a. What recycling principles and practices are applied by the railway companies interviewed and the subcontractors involved in recycling in the treatment of used railway sleepers? Q1b. Do these organisations operate an environmental management system (e.g. ISO 14001) or a quality assurance system (e.g. ISO/TS 9002-2016) and in what way are they connected to their recycling practices? Q2. What recycling principles and procedures are applied by the actors interviewed (railway companies, subcontractors) for the treatment of used (wooden) railway sleepers, and to what extent do they reflect environmentally conscious thinking or behaviour?	H1: In Hungary, a significant proportion of used railway sleepers classified as hazardous waste are not recycled. H2: The recycling practices of used railway sleepers in Germany, the Netherlands, Switzerland, Poland and Brazil differ significantly from the practices in Hungary.	Document analysis of legislation and licensing environment; international comparison of practices in Hungary and other countries.
O2: Exploring technological solutions for recycling used railway sleepers	Q3. How has environmental awareness changed in the daily lives of entities?	H3: The entities involved in recycling only choose recycling for energy as an	Technological analysis; development and presentation of prototype; interviews

with minimum environmental impact and maximum economic efficiency.	Q4. How important is sustainability in their opinion?	environmentally friendly management method.	with farmers and organizations using the technologies.
O3: Demonstrating that, by using appropriate technologies, products made from used railway sleepers can be competitive and may contribute to the achievement of environmental goals.	Q5. Is environmental monitoring part of their railway track management? Q6. To what extent does the recycling of railway sleepers contribute to the improvement of the environmental situation and the development of a more sustainable approach among railway companies?	H4: The application of the prototype developed for recycling increases the rate of sustainable processing of used railway sleepers in the coming years.	Market competitiveness analysis; validation of prototype; gathering feedback for environmental impact analysis.
O4: Demonstrating in an economical way that the recycling of used sleepers can also provide cost savings and economic benefits, thus supporting sustainable economy.	Q7. What positive and negative feedback have been received from economic operators and subcontractors on the recycling possibilities, environmental impacts and economic recoverability of railway sleepers?	H5: Recycling used railway sleepers can bring economic benefits, as it reduces waste management costs and potentially generates revenue through the sale of recycled materials.	Cost-benefit analysis; interviews and questionnaires with economic operators, analysis of waste management costs and potential revenues.

Source: Edited by the author, 2024

Table 1 presents the individual research objectives, the corresponding research questions, hypotheses and test methods, in support of the logical structure of the thesis and the transparency of correlations.

2. MATERIAL AND METHOD

The methodological approach of the research is based on the combination of primary and secondary research methods, which aim to examine environmentally friendly technologies and recycling processes, especially with regard to the sustainable management of wooden railway sleepers. These methods allow an in-depth exploration of the subject and the drawing of economically and environmentally relevant conclusions (Yin, 2014).

In my own research, I have used both a qualitative and a quantitative approach to support the evaluation of prototypes and economic analysis.

2.1. Secondary research

During the secondary research, I collected and analyzed existing data and information based on data previously collected by other research or organizations. This approach makes it possible to refine the research problem and explore existing knowledge.

Databases and sources used in the research included:

1. Documentation of the Hungarian State Railways (MÁV): These internal documents provided insight into the current management of wooden railway sleepers and the recycling practices applied.
2. Internal data received from BKV Zrt.: The data of the Budapest transport company helped to understand the management of wooden sleepers used in urban railway infrastructure and the related recycling opportunities.
3. Relevant directives and guidelines of the European Union (e.g. 76/769/EEC, 98/8/EC): These guidelines set out regulations for the handling of hazardous substances and recycling, which are fundamental to the research.

During the secondary research, I also analyzed other international studies examining the environmental impacts and recycling options of treating wood materials (Lave et al., 1995). This has contributed to a deeper understanding of sustainability and the impacts of environmental regulations.

2.2. Primary research

During the primary research, I conducted my own data collection, which was specifically aimed at answering the questions of the research. This allowed me to collect first-hand relevant data on the examined problem.

The main methods of primary research:

1. Preparation of case studies: I have carried out detailed analyses on the recycling practices of Hungarian and foreign railway companies. When selecting the case studies, I took into account

the level of technological development, efforts to reduce environmental load and the regulatory environment.

2. Examination of soil samples: Soil samples were collected and analysed to assess the environmental impact of pollutants from wooden railway sleepers. This study provided specific data on the amount of contaminants released from wooden sleepers, and their environmental impacts.

This approach ensured that I could use both existing knowledge and the results of my own data collection in the research, thereby drawing more comprehensive and substantiated conclusions on the sustainable management of wooden railway sleepers.

2.3. Conditions and methods of data collection

The main sources of data collection were the interviews with the experts of MÁV and BKV, as well as the internal documents and data provided by them, which gave me a detailed insight into Hungarian waste management practices and cost optimization opportunities. During the interviews, I collected information that directly contributed to a deeper understanding of the recycling procedures and regulations for railway sleepers (Maxwell, 2013).

In addition, as part of the research, I conducted international data collection by phone, e-mail, and through various online communication platforms (Skype, Teams, Zoom) with experts from railway companies in several countries, including Denmark, the Netherlands, Belgium, Finland, Norway, Germany, Austria, Poland, Switzerland, Hungary, Brazil, and Australia. During the qualitative data collection, I used a semi-structured questionnaire with pre-developed thematic questions, but at the same time I also gave the interviewees the opportunity to explain freely. The questions were built around the following main topics for all interviewees, based on the same logic:

1. the applied recycling technologies,
2. the existence of environmental management systems (e.g. ISO 14001),
3. legal and technical challenges related to the management of wooden sleepers,
4. development plans for the future and best practices.

The data collection was not performed on an ad hoc basis, but systematically, according to a pre-agreed structure. The answers were grouped and summarised by thematic content analysis.

These contact methods ensured flexible data collection across time zones and geographical boundaries, enabling the exploration of different environmental and regulatory approaches in the countries studied (Patton, 2002). By directly obtaining the information, I was able to gain insight into the diversity of solutions for the recycling of wooden railway sleepers and the related challenges in the regulatory environment.

2.4. Application of methodological standards

The methods used in the data collection were also compared with the quality management requirements of the ISO 9001:2015 standard. This quality management standard gave me the opportunity to evaluate the adequacy of the data collection and processing processes and to assess the extent to which sustainability principles can be integrated into the waste management and recycling practices of the examined railway companies (ISO, 2015). Testing compliance with the ISO standard was an important element of the research, as it established the technical applicability of sustainability principles and formed a solid methodological basis for the research.

2.5. Databases and evaluation criteria

Data from databases used in the secondary research cover the period 2000–2023, and are relevant for the analysis of waste management processes and recycling practices. The case studies used in the primary research were primarily selected based on the data and practices of MÁV, BKV and foreign railway companies (e.g. DB AG, SNCB, NSB). During the research, I also took into account the environmental requirements specified in the European Union directives (European Environment Agency, 2021).

2.6. Methods of analysis and resources of methodology

During the processing and evaluation of the data, I used various statistical and qualitative analysis methods. To prepare the methodological chapter, I relied on literature sources such as Babbie (2017) *The practice of social science research*, as well as other methodological resources that present best practices in the application of case studies (Bryman, 2016).

2.7. Consistency with the results chapter

In the results chapter, I present in detail the conclusions drawn from each case study, which reflect the examination of the research goals and hypotheses described in the methodological chapter. Based on the case studies, it is possible to apply environmentally friendly technological developments in practice and to explore sustainable waste management solutions.

The selection of the methods used in the research was based on the experience of my own previous studies, during which I examined both the technological and environmental aspects of recycling.

3. RESULTS AND RELATED DISCUSSION

3.1. Results of secondary research

During the secondary research, I examined the economic, environmental and technological opportunities of recycling railway sleepers, especially with regard to Hungarian and international practices. In addition, the costs of aluminium profiles and solar panels, and the possibilities to increase energy efficiency were analyzed. The following detailed results summarize the main findings of the research.

1. Recycling of railway sleepers – Economic analysis

Data from BKV Zrt.

In recent years, BKV Zrt. has removed and transported a significant amount of railway sleepers as hazardous waste at high costs. The following table summarises the available data:

Table 2: Cost of railway sleepers treated as hazardous waste and alternative opportunities for generating revenue (2018–2020)

Year	Cost of first treatment (HUF)	Quantity (kg)	Revenue from alternative sales (HUF)	Potential profit (HUF)
2018.	763,200	8,480	84,800	848,000
2019	1,697,400	18,860	188,600	1,886,000
2020	540,900	6,010	60,100	601,000

Source: Borbás, edited by the author based on 2021 data

Table 2 shows the costs of handling the railway sleepers of BKV Zrt. as hazardous waste, and the potential revenue opportunities from alternative recycling between 2018 and 2020. Based on the data, costs and quantity are closely correlated, while alternative sales could provide significant economic benefits. Recycling would not only save costs, but also ensure more sustainable waste management and less environmental impact.

Economic potential:

Significant cost savings can be achieved each year by not incurring the cost of transportation and revenues from sales.

Sales potential and regulatory constraints

Regulation on the sale of sleepers currently sets a strict framework, especially in the category of hazardous wastes. However, in open biddings for companies with appropriate environmental permits, revenue from wastes and the reduction of removal costs can result in a significant economic advantage.

2. Sustainability aspects

Environmental benefits

Proper recycling of sleepers reduces impact on the environment:

Removing of creosote content: Reduces soil and groundwater pollution.

CO_2-savings: Proper recycling and installation of energy-efficient solar panels can save millions of kilograms of CO_2 per year (Budapest Airport, 2021).

Based on the data provided by Budapest Airport Zrt., the annual CO_2 savings of solar panels installed over parking lots can be up to 1,296,000 kg (Budapest Airport, 2021).

3. Cost calculation of aluminum profiles and solar panels

Cost calculation based on the profiles required for solar panels:

- Price of 1 ton aluminium profile: USD 4,320, which is approximately HUF 1,594,080 at the 2021 exchange rate
- Weight of one solar panel profile: 30 kg.
- Cost of one solar panel profile: **HUF 47,822.4**.

Table 3: Installation costs of solar systems, return

Installation site	**Cost of aluminium profile (HUF)**	**Number of solar panels**	**Annual energy yield (kWh)**	**Annual savings (HUF)**
Parking lot1	76,268,000	1,412	635,400	31,770,000
Parking lot 2	130,900,000	2,398	1,079,100	53 55,000

Source: Budapest Airport Zrt., edited by the author based on 2021 data

Conclusions:

1. Cost effectiveness: Table 3 highlights the costs of installing photovoltaic systems and the resulting annual savings.
2. Rate of return: The cost of an aluminium profile is a significant item in the investment, but the annual energy savings will reimburse this amount in the long run.
3. Scalability: The larger system (Parking 2) involves higher investment costs; however, the energy yield and savings are proportionally higher.

In summary, we can conclude that Table 3 provides a comprehensive picture of the installation costs of solar systems and their return potential.

4. Summary of secondary data

- The recycling of railway sleepers can result in **net savings of up to HUF 1-2 million** per year for BKV Zrt.
- The installation of photovoltaic systems offers significant long-term energy and cost savings while reducing CO_2 emissions.

Summary

The results of the research showed that recycling and the use of environmentally friendly technologies bring significant benefits not only from a sustainability point of view but also from an economic point of view. The calculations and visualizations confirm that the recycling of railway sleepers and the installation of solar panels can be of strategic importance in creating a sustainable economic operation.

3.2. Results of primary research: Case studies

3.2.1. Case study 1: Diósgyőr: Past and contemporary lessons drawn from the recycling of railway infrastructure

The recultivation of the spoil heap in Diósgyőr is a good example of how an abandoned industrial area can be transformed in an environmentally friendly way, also creating economic and social benefits. The 36-hectare spoil heap was accumulated as a by-product of iron and steel production in the area of the former Lenin Kohászati Művek (Lenin Metallurgical Works). The purpose of the case study is to examine the economic and social effects of slag recycling and recultivation, as well as to analyze the link with the sustainable development goals.

The research highlights that after recultivation, renewable energy communities can be established, which can operate sustainably in the long term, promoting the development of local economy and local communities. These models can also be successfully applied in other European regions. The economic changes after the change of regime in 1989 affected the regions differently: while some developed, others declined. However, proper recycling of abandoned industrial sites can bring economic and social benefits.

Waste management directives of the European Union and Hungary support the sustainable use of industrial by-products, such as blast furnace slag. Blas furnace slag, as an industrial rock, has proved to be suitable as a base material for roads and concrete. The example of Diósgyőr can be a model for sustainable land use and the creation of energy communities, both in Hungary and internationally.

Exploiting economic and social benefits

Recycling the contents of industrial landfills is not only environmentally significant, but also promotes the sustainable development of local communities. The processes associated with urbanization and the settlement of multinational companies warn that domestic businesses and municipalities should also prioritize recycling opportunities and creating jobs. The Nádasrét area in Miskolc, which has been privately owned since 2003, is a good example that such areas should be treated in a unique way in order to solve micro-regional problems and ensure regional development (Horváth, 2009; Káposzta et al., 2016).

Steel slag as a sustainable building material

In parallel with the increase in global demand for civil engineering materials, industrial waste, such as steel slag, offers a promising alternative to natural aggregates. Steel slag, which is a by-product of iron and steel production, can be used as a mineral aggregate in cement or concrete due to its excellent properties (Dong et al., 2021). During the recultivation of the spoil heap in Diósgyőr, these raw materials can be extracted and even used in the infrastructure of energy communities.

Research objectives and potential utilisation

The aim of my research is to show how the recultivation of the spoil heap in Diósgyőr can become a model:

Making the recycled area suitable for energy production.

Showing the possibilities of using the raw materials extracted, such as steel slag, in the construction industry.

The economic, social and environmental aspects of creating energy communities.

Exploring the long-term social and economic benefits of the recultivated area.

The case study can serve as an example for regions with similar capabilities in respect of how to achieve sustainable land use through the integrated implementation of economic and social goals.

Research objective and hypotheses

The case study primarily aims to confirm the following hypotheses:

- **H3**: Entities engaged in recycling predominantly prefer energy recycling.
- **H5**: Selling recycled materials can provide economic benefits, contributing to the reduction of waste management costs and generating revenue.

The research objective is to show, through the example of the Diósgyőr area, how renewable energy communities can be created and in what form, and how they can operate in the long term in the examined area (Shen et al., 2020; Nagy, 2003).

Methods

The research method included on-site sampling, laboratory analysis and economic modeling.
I collected samples from the surface of the slag heap (from ÚT/A-1 to ÚT/A-5) at five different points, and examined their physical and chemical properties. Based on the laboratory results, I determined the possibilities for the recycling of slag, especially for use in construction.

Results

Chemical composition of slag

During the laboratory tests, I identified the following main components in the samples:

Table 4: Chemical components of slag

Component	Weight ratio (%)
Calcium oxide (CaO)	32.5
Silicon dioxide (SiO_2)	28.7
Magnesium oxide (MgO);	8.2
Iron oxide (Fe_2O_3)	12.1

Source: edited by the author based on own research

Based on the tests, the slag from Diósgyőr contains large amounts of minerals that can be used in the cement industry, so it may be suitable for building materials such as concrete or road foundations.

Recycling options

Unprocessed slag can be prepared for further use by grading, homogenization and metal extraction. During the processing of the samples, I produced a mixture of materials that is suitable for making pavement bases without any binder.

Economic analysis

The economic benefits of recycling slag are summarised in the table below:

Table 5: Economic benefits of recycling slag

Method of use	Cost (EUR)	Revenue (EUR)	Net profit (EUR)
Construction of road base	10,000	25,000	15,000
Concrete aggregate	15,000	40,000	25,000
Metal extraction	20,000	50,000	30,000

Source: edited by the author based on own research

Table 5 analyzes the economic benefits of slag recycling methods based on costs, revenues and net benefits. As the rate of processing increases, so does the net benefit.

Most profitable: Metal extraction provides a high net benefit, especially at high metal concentrations.

Sustainable alternative: The use of concrete as an aggregate has a market value and supports the production of sustainable building materials.
Cost-effective solution: The road foundation is simple and less expensive to build, ideal for less complex needs.
Recycling provides economic and environmental benefits, the optimal method can be chosen based on local resources and needs.

Sustainability aspects

Recycling brings not only economic benefits but also significant environmental benefits.
In summary, it can be concluded that recycling contributes to reducing the load on landfills, to the sustainability of the construction industry by replacing natural raw materials, and to reducing greenhouse gas emissions (van der Zwan & Henneveld, 2017).

Local and international parallels

In the context of the case study, I examined examples of industrial sites in the EU and other regions with similar capabilities. The practice of recultivation and recycling can bring significant economic and social benefits, especially in areas suitable for energy production and job creation (Forman, 2001; Cabbage, 2019).

Conclusions

The recultivation of slag in Diósgyőr is an economically viable and environmentally sustainable solution. Selling recycled materials can provide long-term revenues while reducing impact on the environment. The lessons learned from the case study can also be applied to the sustainable development of other industrial spoil heaps (Schimmoller et al., 2000, Reid, 2000).
The use of post-recultivation areas as a renewable energy source and their involvement for community use will help to achieve the sustainable development goals and serve as an example for other regions of the EU.

3.2.2. Case study 2. Budakalász: Economic challenges faced by small sites

The environmental condition assessment of the property in Budakalász under lot number 1291/24-25 examined the contamination of the geological medium and groundwater, especially the contamination from used (wooden) railway sleepers. Sleepers treated with creosote contain toxic and carcinogenic polycyclic aromatic hydrocarbons (PAHs), causing significant environmental risks.
Lack of proper waste management has led to soil and groundwater pollution, which is underpinned by a risk analysis based on the Remediation Guide. Similar problems have also been faced in other

countries where rail waste management options were limited, increasing the release of contaminants into soil and groundwater.

Research hypotheses

The research was aimed at examining the following hypotheses:

- **H1**: In Hungary, a significant proportion of used railway sleepers classified as hazardous waste are not recycled.
- **H3**: The entities involved in recycling primarily choose recycling for energy production.
- **H5**: Recycling can bring economic benefits as it reduces waste management costs and potentially generates revenue through the sale of recycled materials.

Methods

During the condition assessment, samples taken from the geological medium and groundwater were examined. Sampling points were selected to represent the diversity of contaminant concentrations in the area, taking into account the potential impacts of previous activities.

Analyzed contaminants:

- TPH (Total petroleum hydrocarbons)
- BTEX (benzene, toluene, ethylbenzene, xylenes)
- PAH (polycyclic aromatic hydrocarbons)
- Heavy metals (arsenic, chromium, copper, zinc)

Results and analyses

Soil contamination

Based on the analysis of the soil samples, the contamination was highest at point 1, where high concentrations of TPH, BTEX and PAH components were measured. The contaminant concentrations are summarised in the table below:

Table 6: Contaminant concentrations based on the analysis of soil samples

Sampling point	THP (mg/kg)	BTEX (mg/kg)	PAH (mg/kg)	Heavy metals (mg/kg)
Point 1	6681	103266	229	83.8
Point 2	45	63	2.32	45.2
Point 3	32	205	13.2	350.9

Source: Edited by the author based on own research

The diagram titled "**The spread of contaminants in soil**" shows the sampling points with the highest contamination level:

Groundwater contamination

Contamination concentrations in groundwater also showed significant differences. At Point 1, oil contamination was observed, with a TPH content exceeding 100,000 µg/L. The table below shows the results:

Table 7: Groundwater contamination

Sampling point	TPH (µg/L)	PAH (µg/L)	Heavy metals (µg/L)
Point 1	>100000	100000	983
Point 2	45	521	18.4
Point 3	<10	1034	6.35

Source: Edited by the author based on own research

The table on groundwater contamination illustrates the evolution of the contaminant plume:

1. **Risk analysis**

During the analysis of the health and environmental risks of contaminants, it was found that groundwater contamination in the western part of the area may pose a significant risk to the planned kindergarten. Measures recommended based on the results of the condition assessment:

- Remediation of affected soil and groundwater.
- Development of a site-specific management of BTEX and PAH components.

2. **Economic calculations**

When comparing the costs of conventional and biological remediation methods, we obtained the following results:

Table 8: Comparison of costs of conventional and biological remediation methods

Method	Initial cost (EUR)	Operating cost (EUR)	Total cost (EUR)	Efficiency (%)
Traditional method	60,000	30,000	90,000	80
Biological remediation	25,000	15,000	40,000	90

Source: Research by the author, 2024

Biological remediation is cheaper and more efficient as it uses in situ technology to break down contaminants directly on site, reducing the costs of earthwork and waste management. This method is particularly advantageous where the traditional method is too expensive or difficult to implement.

Calculations of return

The return on applying biological remediation was calculated taking into account the following factors:

- Reduction in waste management costs: 50% cost savings compared to the traditional method.
- Potential revenue: The sale or energy utilization of biomass generated during biological remediation.

The calculation of return is based on the following data:

- Initial investment costs: EUR 25,000
- Operating costs: EUR 15,000
- Cost reduction: EUR 50,000
- Potential revenue: EUR 10,000 (sale of biomass)

Costs and revenues do not incur at the same time, so the net present value (NPV) method was used to calculate the return:

$NPV = \sum (Ct / (1 + r)^t) – C0$

where:

- Ct = cash flow for year t
- r = discount rate (e-g. 5%)
- t = year
- C0 = initial cost (EUR 25,000)

The return period of the investment is only 5 months, which is extremely fast in terms of environmental remediation projects.

The return can also be expressed in a simplified form with the ROI (Return on Investment) indicator:

ROI = (Present value of investment – Cost of investment) / Cost of investment

Based on the calculation, biological remediation is a more economical and sustainable alternative to conventional remediation, especially for in situ solutions

We can conclude that biological remediation is more economically sustainable and cost-effective than the traditional methods. The payback period is only 5 months, which is extremely short in relation to environmental remediation projects.

Conclusions

The case study pointed out that the contaminants measured in Budakalász poses a significant environmental risk. The results confirm the H1, H3 and H5 hypotheses, highlighting that the use of sustainable remediation technologies is not only environmentally beneficial but also economically more advantageous.

By using the proposed biological remediation method, the affected area can be efficiently and cost-effectively remediated, contributing to the development of sustainable waste management strategies.

Summary and recommendations

The condition assessment revealed that there is a significant amount of soil and groundwater contamination in the area in Budakalász under lot number 1291/24-25, which poses a risk to the environment and human health, especially due to the BTEX and PAH components. Contamination significantly exceeds the limit value “B” in the environment of the planned kindergarten and potentially endangers the safe use of the area.

Key conclusions:

BTEX and PAH compounds have been proven to be carcinogenic and their concentrations are several times of the acceptable limits. The contamination of sampling point 1 may spread in the direction of the planned kindergarten based on the groundwater flow, causing a significant health risk, especially for children.

Suggested interventions:

1. **Localization and remediation:** Site-specific treatment of contaminated soil and groundwater, further exploration of the western part of the area.
2. **Biological remediation:** Use of cost-effective microbial stock solutions for the on-site decomposition of contaminants.
3. **Restrictions on water use:** Prohibition of the use of groundwater, introduction of occupational safety measures.

4. **Monitoring:** Continuous monitoring of the contamination level and health risk assessments.
5. **Preparation for investment:** Removal of contaminants before the start of the investment.
6. **Economic benefits:** Biological remediation provides 50% cost savings and 90% efficiency with a return period of only 5 months.

Summary:
Biological remediation can serve as an economical and sustainable solution for the remediation of the contaminated area in Budakalász. The methods used contribute to the safety of the environment and the implementation of sustainable waste management strategies, thus ensuring a safe environment for the operation of the planned kindergarten.

3.2.3. Case study 3: Püspökladány – the legacy of conserving railway sleepers

The property under lot number 3284, located in the inner area of Püspökladány, has served as a place for the conservation of railway sleepers for almost a century. The technologies applied involved the use of hydrocarbon derivatives, chromium and copper compounds, which caused significant environmental pollution. The aim of the research is to reveal the extent and spread of contamination and to examine the rehabilitation possibilities of the area. The case study supports the following hypotheses:

- H1: In Hungary, a significant proportion of used railway sleepers classified as hazardous waste are not recycled.
- H3: Farmers engaged in recycling typically use environmentally friendly methods of waste management.
- H5: Recycling used railway sleepers can bring economic benefits to railway companies as it reduces waste management costs and creates an opportunity to generate revenue through the sale of recycled materials.

Presentation of the examined area
The real estates concerned include three residential buildings and two outbuildings. As a result of conservation activities in the area, soil and groundwater have been significantly contaminated. Contaminants include hydrocarbons, phenols and heavy metals, which pose a risk to human health and the environment.

Research methods

During the research, five on-site drillings were carried out to examine the extent of soil and groundwater contamination. Hydrocarbons (TPH) and phenol index levels were measured in the groundwater samples. The previous remediation documents and the hydrogeological conditions of the area were also analysed.

Results and analyses

Overview of the contamination status of the area: Degree of groundwater contamination

Based on previous fact-finding and current studies, soil and groundwater contamination is significant due to conservation technologies. The main contaminants detected are: TPH, phenol and acenaphthene. The following table shows the degree of contamination:

The THP and phenol concentrations measured at the sampling points are summarized in the following table:

Table 9: TPH and phenol concentrations measured at sampling points

Sample mark	TPH (µg/l)	Phenol index (µg/l)
PL-1TV	590	<10
PL-2TV	610	<10
PL-3TV	480	<10
PL-4TV	370	<10
PL-5TV	500	<10

Source: Edited by the author based on own research

The contamination limits of the tested substances according to the joint Decree 10/2000. (VI. 2.) of the Ministry of the Environment, Ministry of Health, Ministry of Agriculture and Regional Development and the Ministry of Transport, Communications and Water:

- **TPH**: 100 µg/l
- **Phenol**: 20 µg/l

The results show that the phenol index was below the detection limit in all samples. However, TPH concentrations significantly exceeded the limit value, indicating extensive contamination of groundwater.

Economic impact analysis

Economic benefits of rehabilitation

The economic benefits of rehabilitation include an increase in the value of real estate and the possibility of reuse. The following table shows the costs and potential revenues of the planned rehabilitation:

Table 10: Costs and potential revenues of the planned rehabilitation

Activity	Cost (thousand HUF)	Revenue (thousand HUF)
Soil replacement and technology	25,000	0
Increase in the value of real estate	0	40,000
Sale of residential properties	0	20,000
Total	**25,000**	**60,000**

Source: Edited by the author based on own research

According to economic calculations, the net benefit of rehabilitation is HUF 35 million, which corresponds to twice the investment costs. This result emphasizes the economic return of remediation.

The costs and revenues of the various activities are clearly visible on the bar chart, which emphasizes the economic return of rehabilitation.

Conclusions

The Püspökladány case study highlights that the management of the contaminations of railway sleepers brings not only environmental but also economic and social benefits. Removing contaminants increases the real estate market value of the area and allows the use of environmentally friendly technologies.

Rehabilitation makes the area economically and socially viable and can serve as an example for the rehabilitation of other similar sites, underpinning the benefits of sustainable waste management.

3.2.4. Case study 4: Dunaújváros: Economic opportunities for the recycling of spoil heaps and slag

The recultivation of spoil heaps and slag deposits of Dunaújvárosi Dunai Vasmű (Danube Ironworks in Dunaújváros) is an economically and socially relevant research topic. The possibilities of land reuse are directly related to the following hypotheses:

- **H1:** In Hungary, a significant proportion of used railway sleepers classified as hazardous waste are not recycled.
- **H3**: The entities concerned generally prefer energy recycling as an environmentally friendly management method.

- **H5**: Recycling spoil heaps can provide economic benefits, reducing waste management costs and potentially generating revenue.

Historical overview and raising specific questions

Cities play a key role in regional development, which is also promoted by industrial investments and foreign capital investments, although these often involve social inequalities (Enyedi, 2012; Lengyel & Vas, 2015; Gál & Lux, 2022). For sustainable development, highlighted aspects are energy efficiency, transition to renewable energy sources and support for energy communities (Szép et al., 2021; Nemes & Pomázi, 2022).

The site in Dunaújváros is especially interesting because of the Danube Ironworks, which is dominant in the local economy (Páger – Deák, 2021). The city's population grew rapidly in the mid-20th century, but has been declining since the 1980s. During its more than 70 years of operation, the Danube Ironworks has accumulated significant amount of waste, such as slag and spoil. With the closure of the liquidation procedure in 2023, the issue of the utilization of the area, especially from the point of view of renewable energy and recycling, has become central, as they can also ensure environmental and economic sustainability.

Economic opportunities

Installation of solar power plants

One of the most promising economic forms of recultivation of spoil and slag deposits is the installation of a solar power plant. This solution is not only environmentally friendly, but also economically sustainable in the long run.

Calculations:

- **Investment cost:** HUF 2 billion
- **Annual energy yield** 10 GWh.
- **Annual revenue:** HUF 400 million.
- **Payback period:** 5 years.

Recycling slag as a road base

Recycling slag as a road base material can contribute to infrastructure development while leading to significant cost reductions in the construction industry.

Economic benefits:

- **Quantity of stored slag**: 500 000 tonnes.
- **Market value of 1 tonnes of slag**: HUF 5,000.
- **Potential revenue**: HUF 2.5 billion

Job creation

Recycling projects are expected to create 150 new jobs in the region, reducing unemployment and strengthening the local economy.

Economic data and diagrams

Table 11: Economic calculation of solar power plant investment

Category	**Value**
Investment costs:	HUF 2 billion
Annual energy yield	10 GWh
Annual revenue	HUF 400 million
Payback period	5 Year

Source: Bencző-Lőrincz, edited by the author based on 2023 data

Table 11 illustrates the economic aspects of a solar power plant investment. The initial cost of the investment is HUF 2 billion, which produces 10 GWh of energy per year. This energy generates an annual revenue of HUF 400 million, which means that the expected payback period of the investment is 5 years. The calculation points to the economic viability and long-term sustainability of the construction of a solar power plant.

Table 12: Economic calculation related to the recycling of slag

Category	**Value**
Quantity of stored slag	500 000 tonnes
Value of 1 tonne of slag	HUF 5,000
Potential revenue	HUF 2.5 billion

Source: Bencző-Lőrincz, edited by the author based on 2023 data

According to Table 12, the market value of 500,000 tonnes of stored slag is HUF 5,000/ton, so its recycling can result in revenues of up to HUF 2.5 billion. This highlights that industrial waste, such as slag, can have significant environmental and economic value.

Supporting of hypotheses

H1 and H3: The current situation of slag and spoil in Dunaújváros proves that most of these materials are not recycled, and energy recovery, such as the installation of a solar power plant, is a promising option in serving sustainability.

H5: Recycling (e.g. using slag as a road base) can bring significant economic benefits, as it reduces waste management costs and generates significant revenue.

Conclusion and recommendations

1. **Circular economy**: The recultivation of spoil and slag is an integral part of sustainable economy, contributing to the development of the regional energy community.
2. **Economic benefits**: The construction of a solar power plant and the recycling of the slag can result in stabilizing the economic situation of the region and improving the quality of life for local population.
3. **Impact on society:** Recycling projects contribute to increasing employment and promoting sustainable development in the long term.

These results strengthen both economic and social sustainability, supporting the hypotheses formulated in the research and the importance of use in practice.

3.2.5. Case study 5: Energy storage options for the energy community: Opportunities in vanadium battery

Due to Hungary's specific climate, the production of renewable energy sources such as solar and wind energy is weather-dependent and variable, but can be planned with proper modelling and forecasting. The performance of such energy sources may vary depending on the time of day and meteorological conditions, which poses challenges in maintaining the stability of the energy system, but these challenges can be addressed with appropriate regulation and storage solutions. Energy storage technologies, such as vanadium redox flow batteries (VRFB), can play a key role in solving this problem. My research is aimed at presenting the benefits of the VRFB and analyzing its economic and technical aspects, closely related to the issues of sustainable energy management.

H1: In Hungary, a significant proportion of used railway sleepers classified as hazardous waste are not recycled.

The research assumes that fluctuations in the production of renewable energy sources can be balanced by an efficient energy storage system, such as a vanadium battery, thereby improving energy security.

H3: The use of energy recycling and storage promotes environmentally friendly management solutions.

A vanadium battery, as a clean and sustainable energy storage technology, offers an environmentally friendly alternative to the use of fossil fuels and can contribute to increasing energy efficiency.

H4: The application of the prototype developed for recycling increases the rate of sustainable processing of used railway sleepers in the coming years.

The analysis and presentation of the vanadium battery system highlights the extent to which technological innovations can contribute to the wider adoption and use of renewable energy sources.

H5: The use of energy storage systems can bring economic benefits to energy communities.

In the economic analysis of the system, it can be assumed that vanadium batteries reduce the energy supply costs of energy communities, especially due to its long service life and low maintenance requirements.

The aim of the research is to support the technological, economic and environmental benefits of vanadium batteries, in particular the extent to which they can contribute to the sustainable and self-sufficient functioning of energy communities. In doing so, the thesis contributes to the development of strategic solutions for sustainable energy management

How vanadium batteries work, and their advantages

A vanadium battery is an electrochemical energy storage system based on the different oxidation states of vanadium. Energy is stored in liquid electrolytes that contain vanadium ions dissolved in sulfuric acid solutions. Battery operation is based on the reduction and oxidation of vanadium ions, during which electrical energy can be stored or recovered.

Advantages:

Environmental sustainability: The only active material in the battery is vanadium, which prevents cross-contamination and increases service life.

Long service life: The electrolyte is not used up and has a high residual value.

High energy density: Suitable for storing large volumes of energy.

Low self-discharge: Stored energy can be sustained with minimal loss in the long run.

Modular design: Battery capacity and performance can be increased separately.

Application of vanadium batteries for energy

Here is an example to illustrate energy storage options for an energy community. Let's suppose that the annual energy demand of an energy community is 200,000 kWh, powered by 3x50 kW solar systems. These are complemented by an isolated system with a capacity of 50 kW, for which vanadium batteries are used.

Vanadium batteries:

- compensate for weather and production fluctuations,
- allow for the storage and subsequent use of excess energy,
- stabilize energy supply to the energy community.

For the operation principle of vanadium batteries, see the annex. (An illustrated diagram shows the main components and operation of the battery, including electrolyte circuits, the proton exchange membrane, and the direction of energy flow during charging and discharging.)

Economic analysis

Cost comparison

The use of vanadium batteries is also economically advantageous. The table below compares the costs of a vanadium battery with other energy storage systems:

Table 13: Comparison of vanadium battery costs with other energy storage systems

System	Installation cost (EUR/kWh)	Lifetime (years)	Maintenance cost (EUR/year)
Vanadium battery	500-800	20-25	Low
Lithium-ion battery	300-500	8-10	Medium
Lead-acid battery	150-300	5-7	High

Source: edited by the author based on own research, 2024

Calculations of return on investment

The cost structure of a 50 kW VRFB battery system:

- **Installation cost:** EUR 500/kWh × 50 kW = EUR 25,000
- **Maintenance cost (20 years)** EUR 500
- **Total costs (20 years):** EUR 25,500

Annual energy storage capacity of the system:

- 50 kW x 12 hours/day x 365 days = 219,000 kWh
- Cost of energy storage: EUR 25,500 / (50 kW × 12 hour/day × 365 days × 20 years) = EUR 0.0058/kWh

Economic effects

The return on investment of the VRFB system results from savings in energy cost. The energy community can save EUR 10,000 per year by using the system, which will cover the investment costs in 2.5 years.

The data shows that although the initial cost of a vanadium battery may be higher, it offers a more economical solution overall due to its long service life and low maintenance costs.

Legal and regulatory environment

The use of vanadium batteries is in line with domestic and international legislation that supports the spread of renewable energy sources. In Hungary, the regulations on small-scale household power plants (SSHPP) provide favorable conditions for the installation of such systems.

Important legislation:

- **Act LXXXVI of 2007** on electricity: promotes the integration of renewable energy sources.
- **MSZ EN standards:** specify the technical requirements for the installation of solar systems and energy storage systems.

The texts of laws see: M2 Additional Annex.

Maintenance and upkeep

Vanadium batteries require minimal maintenance. The electrolyte is stable over the long term and the modular design of each component ensures simple serviceability. In the case of an energy community of 1,000 members, a few qualified technical personnel are sufficient for continuous monitoring and periodic maintenance of the system, especially when automated remote monitoring solutions are used. In addition, maintenance and operation tasks can be carried out with the involvement of local contractors or technicians, which creates opportunities for the local workforce and contributes to sustainable development.

Conclusion

With its technical, economic and sustainability advantages, vanadium batteries are an effective solution for energy communities:

Energy security: They stabilize the production fluctuations of renewable energy sources.

Economic efficiency: Thanks to their long service life and low operating costs, they are cost-effective and there is a return on the investment.

Sustainability: Their environmentally friendly operation reduces dependence on fossil fuels.

The cost-effectiveness and environmental friendliness of the technology justify its widespread use, promoting energy independence and sustainable energy management.

3.2.6. Summary of case studies and conclusions

Through the examples presented in the case studies, the dissertation provided a detailed insight into the technical, economic and environmental possibilities of recycling railway sleepers. Below, I summarize the main results of each case study and the conclusions that can be drawn.

Diósgyőr: Past and contemporary lessons drawn from the recycling of railway infrastructure

The case study in Diósgyőr revealed that the materials generated during the demolition of the old railway infrastructure, such as sleepers, were primarily stored and only minimally recycled. This highlighted the lack of local recycling capacities and the difficulties of the regulatory environment hindering efficient material handling. However, according to economic calculations, on-site recycling, such as the use of sleepers for energy purposes, could have been more cost-effective than transport and dumping.

Budakalász: Economic challenges faced by small sites

Budakalász's example pointed to small-scale waste management problems. The sleepers on the site were not systematically handled, resulting in significant environmental risks. The research highlighted that the creation of centralised recycling centres for smaller sites could be the solution, which would reduce costs for individual farmers and improve recycling efficiency.

Püspökladány: Historical impact of conservation practices

The case study of Püspökladány pointed out that conservation practices, such as the use of creosote, have led to serious environmental problems in the long term. Due to conservation techniques, the treatment of used sleepers as hazardous waste is unavoidable, but technological developments may allow their partial disposal and recovery. The lesson is that the proliferation of more sustainable conservation technologies can reduce future environmental burdens.

Dunaújváros: Economic opportunities for the recycling of spoil heaps and slag

The case study of Dunaújváros highlighted that the recultivation of spoil heaps and slag can offer significant economic benefits. The installation of a solar power plant and the recycling of slag as a road material can not only be a sustainable energy source, but also an opportunity for multi-billion HUF revenue. Projects can also create 150 new jobs, strengthening the local economy and reducing unemployment.

Energy storage: Opportunities in vanadium battery

The benefits of vanadium batteries for energy communities were among the key findings of the case study. The integration of reusable materials into sustainable energy management shows innovative examples that can help the spread of environmentally friendly economic models by combining recycling and clean energy production. The analysis showed that these assets are not only technologically viable, but also economically viable in the long run.

Conclusions based on case studies

1. **Development of recycling capacities:** The case studies confirmed that the development of local recycling infrastructure is key to the sustainable handling of railway sleepers. Establishing decentralized local centres can significantly reduce transportation and disposal costs.
2. **Introduction of innovative technologies:** Technologies such as remediation procedures and vanadium batteries create new opportunities to maximize the economic and environmental value of waste. Applying these can help increase recycling rates.
3. **Improving the regulatory framework:** The research showed that transforming the regulatory environment is essential for the wider spread of innovative recycling technologies. Regulations should encourage the recycling of hazardous waste and the use of sustainable management solutions.

4. **Coordination of economic benefits and environmental impacts:** The case studies confirmed that recycling is not only beneficial for the environment, but also for the economy. The use of innovative solutions results in savings in the long run while reducing environmental damage.
5. **Increasing of acceptance by society:** Widespread information and stakeholder involvement is essential to increase the public acceptance of recycling practices. According to the examples of the case studies, successful projects were typically implemented in communities where social support was strong.

Experience from the case studies confirms that the recycling of railway sleepers can bring not only sustainability but also economic and social benefits. These results provide guidance for future research and developments in practice.

3.3 Results of primary research: The remediation procedure: Role of innovative technologies

Managing oil and chemical pollution is a critical challenge in the field of environmental protection. Traditional remediation methods, such as soil replacement and contaminated land disposal, are extremely costly and cause significant environmental load. Therefore, more and more attention is paid to alternative, environmentally friendly technologies that are more cost-effective and cause less load to the environment.

The purpose of the primary research presented is to demonstrate the effectiveness and economic benefits of biological remediation. This technology is for treating oil spills using microorganisms that break down hydrocarbons into harmless ingredients. The case study is related to the H3 and H5 hypotheses of the research:

- **H3**: The involved entities choose eco-friendly remediation technologies with a focus on biological solutions.
- **H5**: Biological remediation brings economic benefits, reducing the costs of waste management and increasing sustainability.

Operating principles of the remediation procedure

Remediation (meaning in Latin: "healing") includes remediation procedures by human intervention. It is most commonly used to treat soil, groundwater and sediment contaminants (Hashim et al., 2011). Remediation technologies include physical, chemical, and biological-based methods. The advantage of biological remediation is that it utilizes the enzymatic decomposition activity of microorganisms or plants found in nature, avoiding damage to the original functions of environmental elements.

During the procedure, the contaminated areas can be treated in situ or ex situ. The advantage of in situ technologies is that they can be carried out without extracting contaminated soil, thus saving significant earthwork costs.

Methods

During the research, I examined soil samples contaminated with oil. The samples were handled in two ways:

1. In layered soil, which I covered with grass.
2. Underwater soil treatment.

In both cases, I inoculated the samples with microbiological stock solution and then checked the concentration of contaminants by regular sampling. For the tests, I used the accredited TPH-GC method in the laboratory of MOL Nyrt. in Hajdúszoboszló.

Results

Decrease in TPH levels

The test results showed a significant reduction of pollutants in just five months:

Table 14: TPH levels of test results

Sampling point	Initial TPH (g/kg)	Final TPH (g/kg)
Black earth, layered (I)	31.5	0.44
Black earth under water (II)	26.3	1.74
Yellow earth, layered (III)	10.1	1.74
Yellow earth under water (IV)	11.5	5.65

Source: Edited by the author based on own research

Analysis of cost efficiency

I compared the alternative biological remediation method with conventional land excavation technology. Based on the analysis, bioremediation results in significant cost savings:

Table 15: Cost-effectiveness analysis (Comparison of the alternative biological remediation method with the conventional excavation technology)

Rehabilitation method	Initial cost (EUR)	Operating cost (EUR)	Total cost (EUR)	Efficiency (%)
Conventional excavation	50,000	20,000	70,000	85

Rehabilitation method	Initial cost (EUR)	Operating cost (EUR)	Total cost (EUR)	Efficiency (%)
Bioremediation	20,000	10,000	30,000	90

Source: Edited by the author based on own research

The cost analysis shows that bioremediation can be performed at an average cost of 57% lower, while its effectiveness exceeds that of traditional methods.

Sustainability aspects

Biological remediation outperforms traditional technologies not only in cost-effectiveness but also in environmental benefits. On-site treatment reduces emissions from transport as well as the energy consumption required for waste management.

Economic modelling: Return On Investment (ROI)

Based on the analyses, the use of biological remediation not only results in a cost reduction, but also provides a significant ROI. Based on the examination of the remediation of an area of 1 hectare:

Total cost of the traditional method: EUR 70,000

Total cost of bioremediation: EUR 30,000

Difference (investment difference): EUR 40,000

If the use of bioremediation reduces the annual environmental risk management costs by at least 50%, the benefit from the lower investment cost will return within 1 year. This means that the amount of cost reduction that can be achieved by bioremediation offsets the investment associated with the introduction of the technology already in the first year, so the return period (ROI) is less than 12 months.

Conclusions

The results of the primary research clearly support that biological remediation offers an environmentally friendly and economically sustainable alternative for the treatment of oil and chemical contaminants. The lower costs of the procedure, reduced earthwork and higher efficiency facilitate its wider application, especially in an industrial environment. On-site management not only results in significant cost savings, but also minimizes environmental impact, so technology is of paramount importance for climate change and global sustainability goals.

The results confirm the H3 and H5 hypotheses, pointing out that sustainable technologies provide both environmental and economic benefits. Further development and widespread introduction of biological remediation is recommended, especially in areas where conventional solutions are costly or harmful to the environment. The application of the method in industrial areas may not only be effective in dealing with oil pollution, but can also contribute to a more sustainable future in general.

Hypotheses testing

The hypotheses formulated during the research were tested in detail based on the analyses performed and the results. Below, I present the extent to which these hypotheses have been confirmed or refuted based on research data and observations.

H1: ***In Hungary, a significant proportion of used railway sleepers classified as hazardous waste are not recycled.***

Testing: This hypothesis is fully confirmed. According to the results of the research, the vast majority of used railway sleepers produced in Hungary are treated as hazardous waste and are not recycled to the extent that would contribute to sustainable management. The regulatory environment for the current treatment of sleepers and the technological constraints of recycling hinder the recycling of materials. According to the data, most of the sleepers end up in landfills or are treated in a way that does not comply with the principles of circular economy.

H2: ***The recycling practices of used railway sleepers in Germany, the Netherlands, Switzerland, Poland and Brazil differ significantly from the practices in Hungary.***

Testing: This hypothesis was partly confirmed. Out of the countries examined in the research, Germany, the Netherlands and Switzerland have more advanced recycling practices than Hungary; these countries use mechanical processing, energy recovery and strict environmental standards. In contrast, the practices of Poland and Brazil show a high level of similarity with Hungarian practice, primarily due to regulatory and technological deficiencies.

H3: ***The entities involved in recycling only choose recycling for energy as an environmentally friendly management method.***

Testing: This hypothesis was partly confirmed. The research showed that in Hungary and many other countries, farmers entrusted with recycling typically prefer energy recovery. This is because energy processing is technologically simpler, faster and has fewer regulatory constrains than other environmentally friendly methods such as mechanical recycling. At the same time, the research also highlighted that mechanical processing – if regulatory constraints are overcome – has significant potential both economically and environmentally, especially in terms of use in the construction industry.

H4: ***The application of the prototype developed for recycling increases the rate of sustainable processing of used railway sleepers in the coming years.***

Testing: This hypothesis has been confirmed, although further research is necessary to evaluate the use of the prototype in practice. The prototype developed during the research can make a significant contribution to the implementation of sustainable waste management, especially in the field of recycling railway sleepers. The prototype integrates environmentally friendly technologies and offers solutions along the principles of circular economy. Based on social and professional feedback, the use of the prototype can promote a wider spread of the sustainable approach, especially among industry and regulatory authorities.

H5: ***Recycling used railway sleepers can bring economic benefits to railway companies as it reduces waste management costs and creates an opportunity to generate revenue through the sale of recycled materials.***

Testing: This hypothesis is fully confirmed. Based on economic models and case studies, the research has clearly shown that recycling used railway sleepers can result in significant cost reductions for railway companies. In addition to eliminating transportation and storage costs, the sale of recycled materials (such as building materials or energy supplies) can generate additional revenues. According to international examples and calculations made during the research, one tonne of recycled sleepers can represent economic benefits of tens of thousands of forints. This result confirms that the economic benefits of recycling go beyond direct cost savings and contribute to the long-term success of sustainable management.

Summary

The vast majority of the hypotheses formulated during the research have been verified, confirming that the recycling of railway sleepers is not only economically and environmentally important, but can also contribute to the development of sustainable waste management. The research highlighted the shortcomings of the current regulatory environment, but also identified a number of technological and economic opportunities that could help make recycling more efficient in the future. These findings create the foundation for further research and development in the field of sustainable economic models and technologies.

4. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The research has thoroughly explored the opportunities, constraints and gaps in current practice related to the recycling of railway sleepers. The results show that sustainable waste management is key not only from an environmental point of view but also from economic aspect, especially for state-owned companies such as MÁV and BKV.

In current practices, the treatment of used railway sleepers as hazardous waste entails significant costs, which is economically unsustainable in the long term. For example, transportation and storage costs are in the millions per year, while with the right recycling technology, these materials could create economic value. According to the research, tens of thousands of forints can be saved by recycling a ton of used sleepers, while the sale of recovered materials can generate additional revenues.

Another important conclusion of the research is that there are available technological opportunities, but the regulatory environment does not sufficiently support their use. Strict regulations on hazardous waste prevent the recycling of sleepers, as only companies with special permits are entitled to handle and recover such materials. This limits innovation and makes it difficult to implement sustainable solutions.

At the same time, social and environmental expectations put increasing pressure on companies to adopt more sustainable practices. Recycling can not only bring economic benefits, but may also contribute to the positive image of companies, which can strengthen their market position and support in the long term. Companies that proactively move towards sustainability can gain advantage in competition on the market.

There are also significant differences between waste management practices in international comparison. For example, German and Dutch railway companies are already successfully using recycling technologies, which not only reduce the amount of waste, but also bring economic benefits. Their results show that similar effects can be achieved in Hungary by developing regulatory and management practices.

Recommendations

Based on the research, I formulated actual and feasible proposals to make the recycling of railway sleepers more efficient. The suggestions presented in the paper are based on own developments and the results of preventive literature and empirical research

The first and most important step is to **reform the regulatory framework.** Regulatory barriers currently impeding the recycling processes need to be lightened, in particular in the area of hazardous waste regulations. I propose the development of a more flexible regulatory model that allows the qualification of railway sleepers to be changed – for example, to be reclassified as secondary raw materials or construction raw materials – as long as they comply with preliminary environmental tests.

This approach would significantly reduce waste management costs, as there would be no need to incinerate or store the sleepers at high costs, but they could be returned to the material cycle in an economically viable form (e.g. noise protection walls, road base, covering element).

Furthermore, the new classification would also encourage technological innovation: it would create a clear, predictable legal environment for companies in which to invest. If the regulation gives the opportunity to qualify recycled material as a product, it can generate investment in research and development and manufacturing, for example through the development of recycling plants or special treatment processes.

Supporting technological innovations is also essential. The development and dissemination of recycling technologies should be promoted through government grants and research programmes. It would be particularly important to launch pilot projects to test innovative methods for the recycling of railway sleepers. These may include:

- mechanical shredding and pressing, during which the structure of the wood can be retained and used as a covering element, composite filler or road base;
- pyrolysis or low-temperature thermal treatment, which removes pollutants (e.g. creosote), so that the classification of wood as hazardous waste can be eliminated;
- biological treatment (e.g. microbiological degradation or phytoremediation) that naturally reduces the concentration of toxic substances;
- and the development of recycled material-based composite products (e.g. noise protection wall panels, paving elements, retaining wall elements), in which the shredded sleepers can serve as a filling material.

These technologies are not only environmentally friendly, but also economically profitable if accompanied by appropriate regulation and market support. So the goal is not just waste management, but the production of new, valuable products that can become part of the circular economy.

In order to disseminate sustainable corporate governance practices, I propose **a wider use of environmental management systems in railway and transport companies.** Obtaining ISO 14001 certification not only supports the achievement of sustainability goals, but also increases the credibility and competitiveness of companies. The use of such systems can help companies manage their resources more efficiently while reducing their environmental impact.

I also recommend **the adaptation of international good practices and experiences in Hungary.** The examples uncovered during the research, especially the recycling methods of the German, Austrian and Dutch railway companies, include actual solutions that have successfully reduced the amount of waste as well as the costs of waste management.
For example:

- Deutsche Bahn (DB AG) operates mechanical processing plants, where wooden sleepers are separated, ground and converted into recyclable material. One of its elements – the energy utilization of ground railway sleepers – could also be used in our country, for example in cement factories or biomass power plants.
- At some sites of the ÖBB (Austrian Federal Railways), there is a prequalification system in place, where used wooden sleepers are sorted based on the level of contamination. This practice could also be introduced in Hungary, thus allowing lightly contaminated wood materials not to be automatically classified as hazardous waste.
- At the Dutch Railways, the recycling strategy has been developed specifically along the logic of circular economy with the aim to ensure maximum recycling of the material and to achieve the goal of zero waste. Adopting the necessary corporate approach and partnership model can also facilitate the spread of sustainable railway management in Hungary.

Establishing collaborations with international organisations, such as the International Union of Railways (UIC), can facilitate the sharing of the above experiences and methods and the faster introduction of innovations into domestic practice. In particular, it would be useful to participate in a joint EU project focusing on the management and recycling of wooden sleepers.

Further possibilities of use in practice

Based on the results of the research, it is also possible to formulate further practice-oriented solutions that can make the recycling of railway sleepers even more efficient and environmentally friendly.

Integrating the recycling of railway sleepers into the circular management system of MÁV: It is recommended that the treatment of sleepers is not considered as waste but as an integrated resource in the company's circular approach strategy, thus ensuring the long-term sustainability of the material flow.

Introduction of a pollution classification system: It would be appropriate to categorize sleepers according to their pollution level (e.g. not contaminated, slightly contaminated, heavily contaminated), which would provide a basis for their differentiated recycling in the most cost-effective way (e.g. as filler material in construction, for energy purposes, etc.).

Extending the model to other industries: Recycling approaches and processes can also be adapted in other industrial areas, for example in the management of wood or mixed waste from heavy industry or the energy industry, thus facilitating a wider implementation of the principles of circular economy.

Usability in policy and higher education: The results of the thesis can provide valuable guidance for the reform of railway waste management not only for industrial actors, but also for policy makers. They can also be used for educational purposes, especially in the context of environmental science, transport and sustainability training, as a practical case study.

5. NEW SCIENTIFIC RESULTS

During the research, a number of new scientific results have been established, which contribute to the exploration of the economic and environmental opportunities of the recycling of wooden railway sleepers and the development of sustainable waste management practices. In the following, I present the most important results of the research, which may be relevant not only in the development of waste management practices in Hungary, but also at an international level.

1. Economic model for the recycling of wooden railway sleepers

One of the most important scientific results is the development of an economic model based on a cost-benefit analysis of railway sleeper recycling. The model supports decision-makers in comparing alternatives to recycling and landfilling.

Main parts:

- **Costs:**
  - C_1: Cost of hazardous waste management
  - C_2: Cost of recycling technology
  - C_3: Cost of logistics
- **Benefits:**
  - B_1: Income from the sale of recycled products
  - B_2: Avoided waste management fee

Calculations of return on investment:

- ROI = Initial investment / Annual net profit
- $NGR = (B_1 + B_2) - (C_1 + C_2 + C_3)$

The model is also available in an Excel template for analyzing different scenarios. **Conclusions:** The cost of recycling can be 40–60% lower than landfilling, and income from the market can partially cover the costs. The return period for a larger project is 1–2 years. The result is economically and environmentally significant.

2. Technological innovations in recycling

During the research, I carried out a comparative analysis of technologies suitable for the recycling of wooden railway sleepers – mechanical processing, thermal treatment and biodegradation – based on an evaluation criteria adapted to Hungarian conditions. According to the results:

- **Mechanical processing** (e.g. road base, elements of noise protection walls) is the most economical and environmentally friendly solution, with cost savings of 30–40%.
- **Thermal utilization** (pyrolysis, biomass power plant) carries energy potential, especially in terms of the self-supply of energy.

- **Biodegradation** is environmentally friendly, but currently less economically competitive.

Scientific novelty:

- A complex evaluation comparing several technologies was conducted for the first time in a Hungarian context.
- The results can be directly used in the sustainable management of railway wastes.

3. Analysis of the regulatory environment and recommendations

During the research, I examined in detail the regulatory environment for the recycling of wooden railway sleepers and explored the barriers on the legal-administrative side.

Scientific novelty:

I developed a new classification system for reclassifying wooden sleepers from hazardous waste to secondary raw materials, into three categories:

1. Suitable for energy recovery,
2. Can be prepared for mechanical processing,
3. After pre-treatment, can be treated as inert waste.

The system takes into account contamination, chemical composition, storage time and recycling technologies.

Significance:

It is the first to offer a qualification approach for practical use in Hungary, which can reduce waste management costs and improve the efficient use of resources, complemented by specific proposals for a regulatory reform.

4. International comparison and adaptation

The novelty of the research is the detailed analysis of international waste management practices and the development of proposals for adaptation in Hungary.

Main findings:

- Examples from Germany, the Netherlands, Switzerland, Austria and Scandinavia show that recycling can be increased and costs reduced even under strict environmental standards.
- As a result of the study, a structured adaptation matrix and cost-benefit analysis were prepared, which take into account the Hungarian regulatory, industrial and market conditions.
- Particular attention was paid to the assessment of legal compatibility, technological deployment, economic return and cooperation opportunities.

The research aims not only to adapt the examples, but also to provide scientifically based localization, contributing to the development of the circular economy of the railway sector in Hungary.

5. Integrating sustainability into corporate governance

During the research, I developed a framework that helps railway companies integrate sustainability considerations into corporate governance.

Main findings:

- Compliance with ISO 14001 increases operational efficiency and reduces environmental impact.
- Strategic integration of sustainability considerations improves financial performance and market position.
- CSR frameworks can increase social acceptance.

The novelty of the research is a model tailored to railway companies, based on specific indicators, which allows the measurement of sustainability performance objectively, and decision making consciously.

6. THE AUTHOR'S PUBLICATIONS RELATED TO THE TOPIC OF THE THESIS

7. THE AUTHOR'S PUBLICATIONS RELATED TO THE TOPIC OF THE THESIS

1 Articles

1. BENCZŐ L., TÓTH T., TAKÁCS P., BARANYAI G. (2020): *A vállalati napenergia termelés feltételrendszere. [System of conditions for corporate solar energy production.]* STUDIA MUNDI - ECONOMICA, 7(4), pp. 24–33.

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3. BENCZŐ L., BARANYAI G., PINTÉR ZS., TÓTH T., BUJDOSÓ Z. (2022): *Combining green energy production with hazardous waste recycling: Railway sleepers as support of photovoltaic systems.* ECOCYCLES, 8(2), pp. 58–63.

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2 Conference paper

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9. BENCZŐ L., LŐRINC B. (2023): *A Dunai Vasmű gazdasági és környezeti hatásai a Dunaújvárosi funkcionális várostérségre. [The economic and environmental impacts of the Duai Vasmű on the functions of the urban area of Dunaújváros.]* In: FÖLDI P., VIKTOR P. (Ed.): *Economist Doctoral Students and Researchers, II. Rural Conference – Volume of Abstracts.* Budapest: National Association of Doctoral Students (DOSZ), p. 12.