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ELECTRONIC PEER-REVIEWED AND OPEN-ACCESS JOURNAL ON ALL TOPICS OF INDUSTRIAL AND MUNICIPAL ECOLOGY

RECENZOVANÝ ČASOPIS PRO VÝSLEDKY VÝZKUMU A VÝVOJE Z OBLASTI PRŮMYSLOVÉ A KOMUNÁLNÍ EKOLOGIE

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symposium pro výsledky výzkumu a vývoje pro průmyslovou a komunální ekologii

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Vážení čtenáři,

máte před sebou letošní třetí číslo toho časopisu se sedmi příspěvky. Každý rok jsem rád, když mám toto číslo hotové, protože kvůli prázdninám a dovoleným bývá zajištění recenzí i následné činnosti komplikovanější, než u ostatních čísel. Nicméně konec dobrý, všechno dobré.

Patronem tohoto čísla je opět symposium ODPADOVÉ FORUM 2025, které má letos tři hlavní témata: ODPADY ZE A PRO STAVEBNICTVÍ, ODPADNÍ TEXTIL a OEEZ A ELEKTROPRŮMYSL. Na konci čísla je uveden jeho program, pro případ, že by se chtěl někdo dodatečně přihlásit. Oficiální termín byl sice 15. 9. 2025, ale je možné se přihlásit i po tomto datu, jen vám již nebudeme moci garantovat požadované ubytování, neb rezervace celé kapacity hotelů k tomuto datu končí.

Rovnou si zde dovolím všechny pozvat na další ročník symposia ODPADOVÉ FORUM 2026, který se bude konat již 24. až 26. 3. 2026 a opět v Hustopečích. Chceme se vrátit k původnímu a osvědčenému jarnímu termínu, který jsme kvůli covidu před časem opustili. Zvýrazněnými tématy budou: **AKTUÁLNÍ PROJEKTY: ODPADY – VODA – OVDUŠÍ; VEDLEJŠÍ PRODUKTY Z POTRAVINÁŘSTVÍ; ODPADY Z RECYKLACE A VÝROBY AUTOMOBILŮ a RADIOAKTIVNÍ A PROBLÉMOVÉ ODPADY. Podrobnější informace k připravovanému ročníku již brzy najdete na www.tvip.cz.**

Ondřej Procházka

Editorial

Dear readers,

The patron of this issue is the Czech-Slovak symposium WASTE FORUM 2025, which this year has three main topics: WASTE FROM AND FOR CONSTRUCTION, WASTE TEXTILE and WEEE AND ELECTRICAL INDUSTRY. Its program is listed at the end of the issue.

The next year of the symposium WASTE FORUM 2026 will be held from 24 to 26 March 2026 and again in Hustopeče near Brno. The highlighted topics will be: CURRENT PROJECTS: WASTE – WATER – AIR; BY-PRODUCTS FROM THE FOOD INDUSTRY; WASTE FROM RECYCLING AND AUTOMOTIVE PRODUCTION and RADIOACTIVE AND PROBLEM WASTE. More detailed information about the upcoming year will soon be available at www.tvip.cz.

The main language of the symposium is Czech and Slovak, but participants from abroad are welcome. Lectures or posters in English are possible, but the organizers do not provide simultaneous translation or interpretation.

Regards

Ondřej Procházka

Pro autory

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Vydávání časopisu není nikým dotované. Proto, abychom příjmově pokryli náklady spojené s vydáváním časopisu, vybíráme publikační poplatek ve výši 1000 Kč za každou stránku (bez DPH). V případě nepublikování příspěvku v důsledku negativního výsledku recenzního řízení je tato částka poloviční.

Uzávěrka nejbližšího čísla časopisu WASTE FORUM je 8. října 2025, další pak 8. ledna 2026.

For authors

WASTE FORUM is an open access electronic peer-reviewed journal that primarily publishes original scientific papers from scientific fields focusing on all forms of solid, liquid and gas waste. Topics include waste prevention, waste management and utilization and waste disposal. Other topics of interest are the ecological remediation of old contaminated sites and topics of industrial and municipal ecology.

WASTE FORUM publishes papers in English, Czech or Slovak. Papers submitted for publication must be the author's own work and may not have been previously published elsewhere or sent to another publisher at the same time. For more, see Publication Ethics.

Manuscripts for publication in the journal WASTE FORUM should be sent only in **electronic form** to the e-mail address prochazka@cemc.cz. Manuscripts must be fully formatted (i.e. printer-ready) in MS WORD. The file should have a name that begins with the surname of the first author or the surname of the corresponding author.

All articles submitted for publication in WASTE FORUM undergo assessment by two independent reviewers. The reviews are dispatched to authors anonymously, i.e. the names of the reviewers are not disclosed to the authors. **The paper, if it is of good quality and passes the review, is published no later than 10 weeks after the editorial deadline.**

All papers that was not subjected to a peer-review are labeled in a header of each page by the text ***Not peer-reviewed and commercial papers.***

Publication of the journal is not subsidized by anyone. Therefore, in order to cover the costs associated with publishing the magazine, we charge a publication fee of CZK 1,000 or 50 USD per page (excluding VAT). If the contribution is not published due to a negative result of the review process, this amount is halved.

The deadline of the next issue is on October 8, 2025, more on January 8, 2026.

Waste hierarchy as an obstacle for transition to circular economy

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Summary

This paper examines the legislative challenges of implementing principles of the circular economy within the legal boundaries set by the European Union´s Waste Directive, with a specific focus on its transposition into Slovak national law. The current waste hierarchy, as outlined by the EU, prioritizes waste management strategies that do not fully integrate the comprehensive "R strategy" elements such as reusing, repairing, refurbishing, remanufacturing, and repurposing. This oversight perpetuates a linear economy model, inadvertently encouraging waste generation rather than promoting circular models that extend the life span of products and materials. Through a detailed analysis of Slovak legislative measures and their alignment with the European Union´s Waste directive, this paper highlights the gaps and inconsistencies that hinder the transition to a circular economy. The findings suggest that a re-evaluation of the definitions used in waste hierarchy characteristics is essential to incorporate comprehensive R strategies elements effectively, thereby fostering a more sustainable and circular economic model. Recommendations for policy adjustments are proposed to better support the circular economy principles and reduce waste generation at its source.

Keywords: *Circular economy, Waste hierarchy, European Green Deal.*

Introduction

Since environmental protection is one of the most harmonized fields within the secondary legislation of the EU, the EU institutions are the key players in formulating the legal instruments regulating both conservation and industrial production. The transition from linear to circular economic models is crucial for sustainable development, as it minimizes waste, maximizes resource efficiency, reduce greenhouse gas emissions, and promotes long-term environmental and economic resilience. Circular economy is a key element in many recent strategic documents adopted by the EU, namely the first circular economy action plan titled Closing the Loop: An EU Action Plan for the Circular Economy[1] (hereinafter referred to as "CEAP 1") adopted in 2015, the European Green Deal[2] (hereinafter referred to as "EGD") first presented in 2019 and then finalized in 2020, A New Circular Economy Action Plan for a cleaner and more competitive Europe[3], which was adopted in 2020, and the Clean Industrial Deal[4] (hereinafter referred to as "CID"), which was introduced in 2025.

These policy documents, mainly CEAP 1, in 2018 transpired into legislative changes, six EU waste directives were amended in a manner proposed in 2015, namely:

a) Directive 94/62/EC on packaging and packaging waste,
b) Directive 1999/31/EC on the landfill of waste,
c) Directive 2000/53/EC on end-of-life vehicles,
d) Directive 2006/66/EC on batteries and accumulators and waste batteries and accumulators,
e) Directive 2008/98/EC on waste (hereinafter referred to as "the Waste Directive"),
f) Directive 2012/19/EU on waste electrical and electronic equipment[5].

Moreover, the EGD has introduced a comprehensive set of new or significantly revised legislative measures aimed at strengthening environmental protection while enabling an effective green and digital transformation of industry in response to the growing threats of Climate change. Considering the EGD as a growth strategy that aims to transform the EU into a fair and prosperous society with a modern, resource-efficient, and competitive economy; and achieve zero greenhouse gas emissions by 2050[6], the EGD emphasizes the importance of designing products that are durable, repairable, and recyclable. The EGD represents a transformative framework that supports both carbon neutrality and the development of a sustainable circular economy. This approach seeks to extend product life cycles, reduce waste, and minimize resource consumption by promoting processes that retain materials within the EU economy for as long as possible. To achieve these goals, the EGD calls for a fundamental rethinking of production and consumption patterns, aiming to establish closed-loop circular systems. These systems not only reduce the carbon footprint of products and services but also contribute to overall environmental sustainability. Empowering consumers and public buyers with the tools and information necessary to make sustainable choices is a central component of the EGD, as it helps stimulate demand for environmentally responsible products and services. The EGD prioritizes sectors with significant environmental impacts, including electronics, batteries, packaging, plastics, textiles, construction, and food. By focusing on these areas, the EU aims to achieve substantial reductions in resource use and waste generation. Through the establishment of high standards and the promotion of sustainable practices, the EGD positions the EU as a global leader in the transition to a circular economy. These efforts are integral to achieving broader EU objectives, such as climate neutrality, halting biodiversity loss, and increasing circularity. Ultimately, the EGD embodies a holistic approach to sustainability, which is expected to be reflected in future legal instruments.

Regarding EGD, in order to promote circular economy and sustainable industry, several legislations were adopted, namely:

a) Regulation 2020/852/EU on the establishment of a framework to facilitate sustainable investment, and amending Regulation 2019/2088/EU (known as the EU Taxonomy),
b) Directive 2022/2464/EU amending Regulation (EU) No 537/2014, Directive 2004/109/EC, Directive 2006/43/EC and Directive 2013/34/EU, as regards corporate sustainability reporting (known as the CSRD),
c) Regulation 2023/1542/EU concerning batteries and waste batteries (hereinafter referred to as “the Battery Regulation”),
d) Regulation 2024/573/EU on fluorinated greenhouse gases, amending Directive (EU) 2019/1937 and repealing Regulation (EU) 517/2014 (hereinafter referred to as “the F-gas Regulation”),
e) Directive 2024/1785/EU on industrial emissions (integrated pollution prevention and control) and Council Directive 1999/31/EC on the landfill of waste (known as the IED 2.0),
f) Regulation 2025/40/EU on packaging and packaging waste, amending Regulation 2019/904, and repealing Directive 94/62/EC (known as the PPWR).

The regulatory landscape has become increasingly complex, particularly due to the broad range of legal instruments introduced under the REACH framework (Registration, Evaluation, Authorisation and Restriction of Chemicals). In general, the principles—or even explicit requirements—of circularity are now embedded in nearly every new regulation or directive adopted within the framework of the EGD.

Particular attention to the promotion of circular economy objectives has been given through CID. Although CID is a relatively recent EU initiative and has not yet resulted in major legislative changes, it is expected to play a pivotal role in advancing circular economy principles. One of its key aims is to support secure access to critical raw materials, reduce industrial emissions, and ultimately lead to the adoption of a comprehensive Circular Economy Act by 2026. This legislative milestone is intended to strengthen the competitiveness of the European economy while reinforcing its sustainability and climate goals.

Nevertheless, recent strategic and legislative changes on the EU level that intensively emphasize circular economy may be relatively new, the idea of circular economy and its principles has been around much longer and during that time it kept constantly evolving closely following technological development and even overtaking legal instruments securing efficient waste management. So-called waste management “R-strategies” were invented and are well known by the general public since the late 20th

century[7]. Starting with the basic "3-R strategy" representing the **reduce-reuse-recycle idea**, this strategy sets grounds for circularity by cutting back the amount of waste, finding new use for unwanted things and eventually turning something useless into something useful. This strategy was later extended to "5-R strategy" by adding refuse at the very beginning and reform as the second to last option in waste management establishing a space for not creating any waste at all and later in the life cycle of a product acknowledging its other opportunities to still be useful, generally known as **refuse-reduce-reuse-reform-recycle idea**. However latest "10-R strategy"[8] represents, as far as industrial production is concerned, a highly appreciated approach, which distinguishes short, medium and long loops in circular economy implementing **refusing, rethinking and reducing** within the early "design" phase of products that focus on the beginning of the life cycle of products. Medium loops involve **reusing, repairing, refurbishing, remanufacturing, and repurposing** products that do not necessarily have to be considered a waste within their mid-life cycle. Long loops focus on **recycling and recovering** materials from products that finally may be considered being at their end-of-life phase thus becoming waste. Schematic explanation of the "10-R strategy" is depicted in Figure 1.

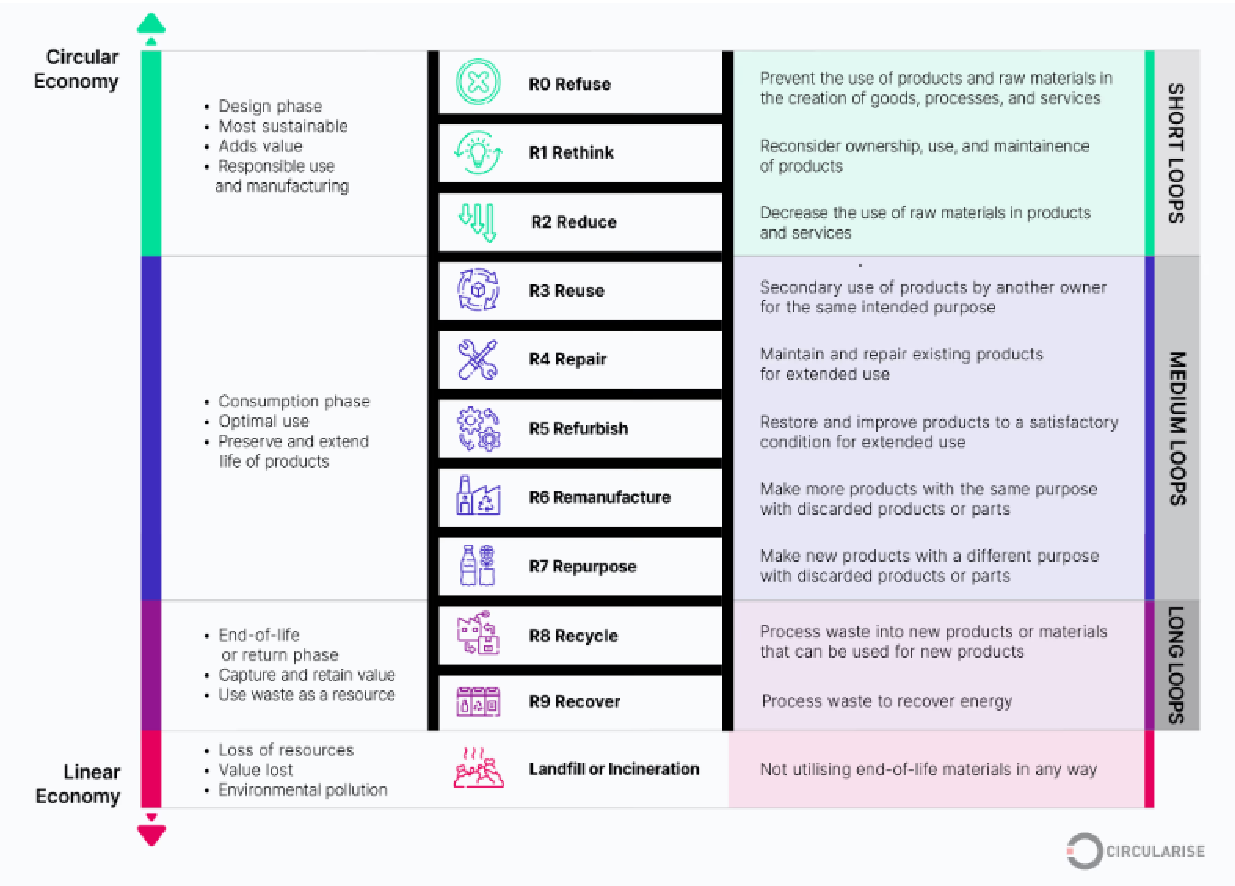

Figure 1: Schematic depiction of the "10-R strategy"[8].

There are many sources regarding waste management legislation, however, the lack of relevant legal literature on the circular economy must be underscored[9]. This article draws from the most recent papers on the circular economy published in legal journals, internet resources, non-legislative documents of the EU and existing legislation adopted on European and national level mentioned in the references part. Using doctrinal research methods and legal comparison, the authors articulate their perspective on an existing research gap regarding legal definitions used within the waste hierarchy.

Results and discussion

Waste by its legal definition is any substance or object which the holder discards or intends or is required to discard by this or any other act[10]. Paragraph 1 of Article 4 of the Waste directive defines the waste hierarchy as a set of priorities, that shall be applied in waste management and policy as follows:

a) prevention,
b) preparing for re-use,
c) recycling,
d) other recovery, and
e) disposal.

For the purposes of this article, it must be explained, that the waste hierarchy sets up a prioritized order of activities that shall be applied to ensure as long life cycle of a product as possible in order to prevent its transformation into a waste or eventually secure its as useful as possible application. The waste hierarchy based upon the Waste directive is transposed into Slovak national legislation through subsection 1 of section 4 of the act no. 79/2015 Coll. on Waste and on Amendments of Certain Laws, as amended (hereinafter referred to as „the Act on Waste“). **Prevention**, placed on the top of the waste hierarchy as the most important step, is defined as measures taken before a substance, material or product has become waste, that reduce:

a) the quantity of waste, including through the re-use of products or the extension of the life span of products;
b) the adverse impacts of the generated waste on the environment and human health; or
c) the content of harmful substances in materials and products[11].

Preparing for re-use means checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be reused without any other pre-processing[11].

Recycling means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes, if the other provisions of the Act on Waste do not stipulate otherwise; recycling includes the reprocessing of organic material. Recycling does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations[11].

Other recovery means any operation the principal result of which is waste serving a useful purpose by replacing other materials in production activities or in the wider economy, or ensuring the readiness of waste to fulfill this function; the list of waste recovery activities is given in Annex no. 1 to the Act on Waste[11].

Disposal means any operation which is not recovery even where the operation has as a secondary consequence the reclamation of substances or energy. Annex no. 2 of the Act on Waste sets out a non-exhaustive list of disposal operations[11].

All of the abovementioned definitions streamline the waste hierarchy into five levels, of which only the first one is about a “non-waste” meaning the phase before a substance, material or product has become waste, whereas all the following levels are regarding the “waste” phase. Such a hierarchy and strict legal definitions only hardly allow the recognition of the short and medium loops of the 10-R strategy to be applied, because these loops are focusing on the early and middle life cycle before a substance, material or product becomes a waste. Such a comparison between waste hierarchy and the use of non-waste and waste within its levels is depicted in Figure 2.

The transition towards the circular economy necessitates the recognition of medium circularity loops in the treatment and processing of products which did not reach their end-of-life i.e. waste phase, particularly in the context of commercial relationships and compliance with cross-border transport regulations[15, 16]. Addressing these systematic and legal challenges is essential for establishing a fully operational circular economy aligned with the principles of sustainable resource management.

Figure 2: Waste hierarchy compared with non-waste and waste applications[12].

Recently adopted regulations present circularity in a broader and more nuanced framework, particularly the F-gas Regulation and the Battery Regulation. These legal instruments not only emphasize measures to prevent the generation of waste but also detail specific processes and actions for achieving this objective. As regulations, they are directly applicable and legally binding across all EU Member States, introducing uniformity in their enforcement. However, these new legislative requirements are at bad odds with the provisions currently outlined in the Waste Directive and subsequently in the Act on Waste. This divergence highlights critical discrepancies that need reconciliation.

Furthermore, the innovative approaches embodied in these two regulations represent a pivotal evolution in the interpretation of circularity principles, establishing concrete steps for the systemic transformation of processes. Consequently, they serve as a benchmark and inspiration for revising other waste management legislative acts to align with the enhanced understanding of circular economy objectives and practices. Addressing these inconsistencies and adopting best practices from these regulations is crucial for fostering coherent and effective frameworks that support sustainability across Europe.

The Battery Regulation sets mandatory recycled content targets for materials like cobalt, lead, lithium, and nickel. This aims to promote the recovery of these materials from waste, supporting the circular economy. Furthermore the regulation addresses the entire lifecycle of batteries, including end-of-life management, to support recycling markets and the use of secondary raw materials and also introduces whole new spectrum of activities for handling with used batteries, not necessarily those that shall be considered waste, such as preparation for repurposing, repurposing and remanufacturing[17] which once again broadly oversteps common definitions of waste management hierarchy.

F-Gas Regulation emphasizes the recovery, recycling, and reclamation of fluorinated greenhouse gases as a key application of circular economy principles. This includes provisions for the recovery of substances from products and equipment to prevent emissions and maximize the reduction of emissions[18]. Particularly paragraph 12 of article 3 of the F-gas regulation with its definition of recycling as re-use of a recovered fluorinated greenhouse gas following a basic cleaning process, including filtering and drying[18] oversteps first three priorities of the waste management hierarchy meaning that recycling of fluorinated greenhouse gas, based on the actual methods of recycling put in use, may be considered not only just as a prevention but as well as preparation for re-use and recycling according to the definitions used in the Waste Directive and subsequently in the Act on Waste.

Conclusion

Considering the fundamental requirements of the EGD for material circularity, it brings new opportunities to the EU economy through the circular use of resources. It is essential to note that the use of such materials is expected to significantly reduce greenhouse gas emissions, contributing to carbon neutrality. Concurrently, EU legislation motivates manufacturers to utilize materials from circular cycles instead of raw natural resources. Therefore, it is crucial to support the implementation of practical procedures and legal instruments to achieve the overall concept of circular economy realistically.

If there is a demand for circular materials and the gradual implementation of new technologies allows for greater variability of input materials in production processes, these potentials within the EU should not be wasted due to the lack of a sufficient legislative framework that acknowledges the value of circularity and promotes sustainable thinking.

Waste undoubtedly represents a significant risk to the environment. Strict rules had to be applied to prevent the pollution and threats caused by improper handling of waste. This approach is clearly depicted in waste management legislation such as the Waste Directive and its national transposing laws, which in Slovakia is the Act on Waste. However, the legal instruments of waste management can by their rigidity prevent an effective implementation of circular economy principles into relevant legal systems, because circular economy by its definition seeks further use for products after their original purpose is fulfilled and does not see them as a waste, which is in contrary to the waste hierarchy. The waste hierarchy in its second most preferable priority “preparing for re-use” does not allow any checking, cleaning or repairing of a substance, material or product that is not a waste, thus pushing the whole industrial production system into creating waste even though its original form may still be an object of reusing, repairing, refurbishing, remanufacturing or repurposing.

The waste prevention, as a top priority of the waste hierarchy defines as one its measures the extension of the life span of products. This follows both from the Waste Directive and the Slovak Act on Waste. However, the term “extension of product life span” is not defined in either the directive or the national law, and for this reason as one of the key conceptual changes supporting the transition towards the circular economy shall be the legal definition of the extension of a product’s life span. The definition shall encompass activities related to the inspection, cleaning, repair, renovation, refurbishment, or repurposing of a used product or part of an unused product that has not become waste, and whose result is that the product or its unused part is used for the same purpose or has the same or a similar application as originally intended. The definitional features shall be designed to non-discriminatorily include relevant activities, while also setting the objective of such activities: to achieve the same intended use or function as the original new product, thereby preventing the generation of waste.

Small steps towards recognition of circularity of products before their end-of-life i.e. waste phase may be visible in the Battery Regulation which recognizes repurposing and remanufacturing as operations that do not necessarily must concern waste batteries and may be understood as a mere re-use. The F-gas Regulation also introduces new approach which offers rather wide interpretation overstepping commonly known definitions of the waste management hierarchy priorities. The existence of such a definition would narrow the legislative gap between the first priority and the second priority of waste management hierarchy and would significantly contribute to reducing waste generation, which is currently a key requirement for industrial operations. At the same time, it would harmonize the various possible interpretations of the Waste Directive with the Battery Regulation and the Regulation on Fluorinated Gases, thereby bringing a higher degree of legal certainty to the business environment.

Additionally, and specifically for the automotive industry, which is a key industrial sector not only within the EU but especially in the context of Slovakia, the proposed changes appear to be a suitable starting point for meeting the requirements arising from the BAT conclusions for surface treatment using organic solvents[19]. For example, BAT 24 sets an indicative level for the quantity of waste generated per coated vehicle sent off the site. At the same time, BAT 22, which defines techniques for reducing the quantity of waste sent for disposal, establishes the use of a waste management plan as a mandatory technique. This plan should include among the other things the optimization of re-use, regeneration and/or recycling of waste. One of the optional techniques listed in BAT 22 is the recovery and/or recycling of solvents from liquid waste by filtration or distillation, either on site or off site.

In cases where the operator aims to reduce the amount of waste by reusing the solvent, due to the high quality standards required in vehicle manufacturing, this is not possible without at least inspecting and cleaning the used solvent. Under the current legislative setup, the used solvent must necessarily be classified as waste in order to undergo preparing for re-use. However, if operators could rely on a clear definition of extension of product life span, and thus subject the used solvent to inspection and cleaning without the need to classify it as waste, this would significantly contribute to meeting the requirements of BAT 24 and reduce waste generation and contribute towards the application of circular economy principles.

Even though it is clear that harmonized EU legislation which is a base for national laws is recognizing the importance of a circular economy, the revision of definitions of the waste hierarchy priorities, as we know them, is required and has not happened yet even though it is now needed more than ever.

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Hierarchia odpadového hospodárstva ako prekážka prechodu na obehové hospodárstvo

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Súhrn

Tento príspevok sa zaoberá legislatívnymi výzvami implementácie princípov obehového hospodárstva v právnom rámci stanovenom smernicou Európskej únie o odpade s osobitným zameraním na jej transpozíciu do slovenského národného práva. Súčasná hierarchia odpadového hospodárstva, ako ju upravuje legislatíva EÚ, uprednostňuje stratégie odpadového hospodárstva, ktoré plne nezahŕňajú komplexné prvky „R stratégií", ako je opätovné použitie, oprava, renovácia, repasovanie a zmena účelu (z angl. reusing, repairing, refurbishing, remanufacturing, and repurposing). Takéto nazeranie zachováva model lineárnej ekonomiky, ktorý neúmyselne podporuje tvorbu odpadu namiesto podpory obehových modelov, ktoré predlžujú životný cyklus produktov a materiálov. Prostredníctvom podrobnej analýzy slovenských legislatívnych opatrení a ich zosúladenia so smernicou o odpadoch tento príspevok poukazuje na medzery a nezrovnalosti, ktoré bránia prechodu na obehové hospodárstvo. Zistenia naznačujú, že prehodnotenie definícií používaných v popise hierarchie odpadového hospodárstva je nevyhnutné na účinné začlenenie prvkov komplexných R stratégií, čím sa podporí udržateľnejší a obehový ekonomický model. Navrhujú sa odporúčania na úpravy politiky s cieľom lepšie podporiť princípy obehového hospodárstva a znížiť tvorbu odpadu pri jeho zdroji.

Kľúčové slová: *Obehové hospodárstvo, Hierarchia odpadového hospodárstva, Európska zelená dohoda.*

Comparison of Linear and Circular Economy and Their Impact on the Product Life Cycle

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Abstract

This article analyzes the differences between the linear and circular economy, focusing on their impact on the product life cycle. It explores how each of these economic models influences the environmental and economic aspects of the product cycle, emphasizing the stages of production, use, and disposal. The linear economy, based on the traditional "take-make-dispose" model, often leads to resource depletion and environmental harm, with limited opportunities for material reuse and recycling. In contrast, the circular economy prioritizes resource efficiency, waste reduction, and the reuse of materials, aiming to close material loops and promote sustainability throughout the product life cycle. The article compares the advantages and disadvantages of both models, assessing their implications for environmental conservation and economic sustainability. Through a SWOT analysis, the study identifies the strengths of the circular economy, such as its potential for reducing waste, creating new job opportunities in recycling and repair, and fostering long-term cost savings. However, challenges such as higher initial investments and the need for stronger regulatory support are also discussed. The linear model's weaknesses, including its reliance on finite resources and its contribution to pollution and environmental degradation, further highlight the need for its transformation. This article concludes that transitioning from a linear to a circular economy is crucial for achieving sustainability. By adopting circular principles, businesses can not only minimize their ecological footprints but also enhance economic growth, improve competitiveness, and align with the growing consumer demand for environmentally responsible practices.

Keywords: *linear economy; circular economy; product life cycle; sustainability; environmental impact*

Content

Introduction

Currently, the world faces serious environmental and economic problems that are a consequence of the traditional linear economic model. This model, also known as the "take-make-dispose" approach, focuses on maximizing production and consumption while ignoring the negative impacts on natural resources and the environment (Ellen MacArthur Foundation, 2013)[1]. With the growing number of inhabitants and consumers worldwide, it is evident that such an approach is no longer sustainable (Murray et al., 2017)[2]. On the other hand, the circular economy offers an alternative model that emphasizes closing material loops, efficient resource use, and waste reduction (Geissdoerfer et al., 2017)[3]. In order to better understand the advantages and limitations of these two models, a SWOT analysis was conducted to assess their respective strengths, weaknesses, opportunities, and threats (Hill et al., 2014)[4]. The aim of this article is to compare linear and circular economies, with a particular focus on their impacts on the product life cycle. The article will discuss the individual stages of the product life cycle in both economic models and their environmental and economic consequences (Bocken et al., 2014)[5].

Materials and methods

The analysis of the impact of linear and circular economies on the product life cycle employed a literature review and comparative analysis method. Sources were obtained from scholarly articles, reports, books, and research studies that address sustainability issues, environmental impacts, and innovations in recycling and waste valorization. Specific criteria included publications from the last ten years to ensure the currency and relevance of the information.

In addition to the literature review, a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis was conducted for both the linear and circular economy models (Gürel & Tat, 2017)[6]. This analysis aimed to assess the internal and external factors that influence the performance and sustainability of both models. The SWOT analysis was based on key performance indicators such as resource efficiency, environmental impact, and economic viability. Quantitative data on waste, emissions, and resource efficiency in both models were utilized for the analysis, as well as the qualitative aspects derived from the literature.

To support the SWOT evaluation, a weighted scoring approach was used to compare individual factors within each model. Each factor was assigned a performance score (ranging from 1 to 5) based on its impact as described in the literature, and a relative weight (0 to 1) indicating its significance. These scores were derived from repeated findings in peer-reviewed research and informed author judgment. While the values are not based on primary empirical research or expert surveys, they reflect synthesized trends and common conclusions found in the literature (e.g., Geissdoerfer et al., 2017; Haas et al., 2019; Bocken et al., 2016)[3, 5, 7]. This semi-quantitative method was chosen to create a clear and structured comparison framework. However, the approach carries a degree of subjectivity, and future studies may improve its robustness by applying empirical validation or expert-based methods.

A comparative analysis was also applied to systematically evaluate both models across selected sustainability and economic indicators. This comparison involved the structured examination of qualitative and semi-quantitative aspects, including life cycle phases, environmental impacts, and strategic potential. The aim was to clarify the differences and identify the areas where circular approaches offer improvements over linear ones.

The aim of this analysis is to identify the main differences between linear and circular economies and to understand how each model affects the various stages of the product life cycle. Quantitative data on waste, emissions, and resource efficiency in both models were also utilized for the analysis.

Product life cycle in linear and circular economy

The product life cycle (PLC) is a critical concept in understanding the environmental and economic impacts of product manufacturing and consumption. Traditionally, the linear economy has dominated, where products follow a “take-make-dispose” approach, resulting in high resource consumption, waste, and environmental degradation. In contrast, the circular economy presents a sustainable alternative by emphasizing the reuse, repair, and recycling of materials, creating a closed-loop system that minimizes waste and optimizes resource use. This section will explore the differences between these two models, focusing on their respective impacts throughout the various stages of the product life cycle, and evaluate how each model contributes to or mitigates environmental and economic challenges (Geissdoerfer et al., 2017)[3].

Linear Economy

In a linear economy, a product has a limited life cycle characterized by a "take-make-dispose" model. This model progresses through four fundamental phases: raw material extraction, production, consumption, and disposal (Bocken et al., 2016)[5]. Following the phases of production, distribution, and consumption, the product is disposed of, often through landfilling or incineration. This approach results in excessive resource waste and high environmental costs, as it generates significant amounts of waste that can be challenging to recycle. This linear progression is illustrated in Figure 1.

During the raw material extraction phase, resources are extracted with minimal regard for environmental consequences, contributing to land degradation and resource depletion (Lehner et al., 2019)[8]. According to a report by the European Environment Agency (2020)[9], over 2 billion tons of waste are generated globally each year, with the majority stemming from linear economic practices. In the production phase, raw materials are transformed into finished products; however, this process often overlooks the principles of resource efficiency. For example, in the automotive industry, it is estimated that the production of a single vehicle generates an average of 20 tons of waste (Geissdoerfer et al., 2017)[3].

Consumption focuses on short-term needs and a preference for disposable products, which leads to significant waste and pollution problems (Murray et al., 2017)[2]. The linear model promotes a culture of consumption that emphasizes quantity over quality, ultimately resulting in unsustainable practices that not only deplete natural resources but also exacerbate environmental issues. The lack of incentives for recycling and reusing materials further entrenches this wasteful cycle, highlighting the urgent need for a transition to more sustainable economic models that prioritize the circular economy.

Figure 1: The phases of the product life cycle in a linear economy

This model's reliance on finite resources and its consequent environmental impact underscore the necessity for a systemic shift toward sustainable practices that prioritize resource conservation, waste reduction, and long-term ecological balance.

Circular Economy

In contrast, the circular economy aims to transform traditional linear processes into a closed-loop system. This model focuses on the design of products that are durable, repairable, and recyclable (Bocken et al., 2016)[5]. The life cycle phases in a circular economy encompass design for longevity, recycling, repair, and the reuse of materials (Wright et al., 2016)[10]. This approach has the potential to reduce environmental burdens as fewer resources are depleted and less waste is produced. Moel of circular economy is illustrated in Figure 2.

The circular economy emphasizes the efficient use of existing resources through strategies such as reuse and recycling. Many companies are striving to harness renewable energy sources and innovative technologies that minimize waste production (Haas et al., 2019)[7]. By integrating sustainability into their operations, businesses can not only comply with regulatory demands but also cater to the growing consumer preference for eco-friendly products.

Figure 2: Phases of the product life cycle in a circular economy

In the final phase, recovery and recycling, the circular economy focuses on collecting and processing materials to regenerate resources. This contributes to reducing ecological footprints and fosters innovation and sustainability through the creation of new business models (Korhonen et al., 2018)[11]. For instance, companies can implement take-back programs that encourage consumers to return used products, which can then be refurbished or recycled into new items. This practice not only helps conserve natural resources but also promotes a circular economy mindset among consumers.

Moreover, the circular economy fosters collaboration among various stakeholders, including manufacturers, consumers, and policymakers. By working together, these groups can create a supportive environment for sustainable practices, encouraging investment in circular solutions and reducing regulatory barriers.

In summary, the circular economy represents a paradigm shift that not only addresses the limitations of the linear model but also presents opportunities for sustainable growth and innovation. By prioritizing resource efficiency and waste reduction, the circular economy paves the way for a more sustainable future that benefits both the environment and the economy.

Environmental and economic aspects

In analyzing the impacts of linear and circular economic models, it is crucial to consider both environmental and economic factors. The environmental consequences of production and consumption practices are significant, with both models contributing to and mitigating ecological degradation in different ways. Similarly, the economic implications extend beyond short-term profit and immediate costs, influencing long-term sustainability, resource efficiency, and innovation. This section will explore both the environmental and economic aspects of each model, highlighting the benefits and challenges of transitioning to more sustainable practices (Tukker, 2015)[12].

Environmental Aspects

The environmental impact of economic models is perhaps the most urgent issue facing societies today. Linear economies often contribute to resource depletion, pollution, and ecosystem degradation, whereas circular economies offer solutions that focus on sustainability, waste reduction, and efficient resource use. This section will explore the significant environmental challenges posed by linear models and the potential for circular economies to alleviate these pressures (Bocken et al., 2016)[5].

Linear Economy and Environmental Impact

The linear model of production and consumption has a significant negative impact on the environment. The continuous extraction of raw materials leads to deforestation, loss of biodiversity, and greenhouse gas emissions (Lehner et al., 2019)[8]. For instance, mining activities can devastate ecosystems, while industrial agriculture contributes to soil degradation and water scarcity. Additionally, the production of waste, particularly non-recyclable materials, contributes to pollution of soil, water, and air (Ellen MacArthur Foundation, 2013)[1]. Landfills emit methane, a potent greenhouse gas, and contaminated water runoff from these sites can severely affect surrounding communities and wildlife. This model's focus on short-term gains and high consumption rates disregards the long-term sustainability of the planet's resources.

Circular Economy and Its Environmental Benefits

Transitioning to a circular economy can significantly reduce environmental burdens. Recycling materials, extending product lifespans, and effectively utilizing resources lead to reductions in emissions and energy consumption (Haas et al., 2019)[7]. For example, recycling aluminum saves up to 95% of the energy required to produce new aluminum from raw materials. This approach also alleviates pressure on natural ecosystems by minimizing the need for the extraction of new resources. Moreover, initiatives like urban mining, where materials from old products are recovered, can contribute to sustainability goals while reducing dependence on virgin resources. The circular economy not only promotes environmental sustainability but also fosters a culture of responsibility and stewardship towards natural resources.

Economic Aspects

Economically, both the linear and circular economy models present distinct advantages and challenges. The linear economy, with its emphasis on efficiency and cost-cutting in the short term, contrasts with the long-term financial benefits that can be realized by embracing circular practices. This section will examine the economic implications of both systems, including their impact on resource efficiency, innovation, and job creation (Geissdoerfer et al., 2017)[3].

Economic Efficiency of the Linear Economy

In the short term, the linear model may be more advantageous for certain sectors as it minimizes costs associated with research and development for new solutions aimed at reusing materials (Bocken et al., 2016)[5]. This model allows businesses to operate at lower immediate costs, potentially increasing profit margins. However, this approach does not account for external costs in the long term, such as environmental damages that can become significant financial burdens for society (Murray et al., 2017)[2]. These hidden costs may manifest in the form of increased healthcare expenses due to pollution-related illnesses, loss of ecosystem services, and government expenditures on waste management.

Economic Benefits of the Circular Economy

The circular economy can provide long-term economic advantages. It reduces costs associated with raw materials, supports innovation, and creates new jobs in recycling and repair industries (Wright et al., 2016)[10]. For instance, businesses that implement circular principles often find opportunities to develop new markets for refurbished goods. Despite higher initial investments required for developing sustainable products and processes, long-term savings and environmental benefits can contribute to economic stability and competitiveness (Haas et al., 2019)[7]. Furthermore, the circular economy can enhance brand reputation, attracting consumers who are increasingly concerned about sustainability, thus driving sales and fostering loyalty.

Comparison of the Impacts of Both Economic Models

When comparing the impacts of linear and circular economies, it is evident that the circular model offers a more sustainable approach to production and consumption. The linear economy, while historically prevalent, fails to facilitate the efficient use of resources and contributes to ecological issues that are becoming increasingly urgent. This traditional model, often characterized by a "take-make-dispose" mentality, promotes overconsumption and waste generation, leading to significant environmental degradation.

For instance, the extraction of raw materials in the linear model often results in habitat destruction and increased carbon emissions. Furthermore, the lack of emphasis on recycling and resource recovery means that valuable materials are frequently discarded, contributing to the depletion of natural resources and escalating landfill problems (Ellen MacArthur Foundation, 2013)[1]. This cycle of consumption and disposal not only harms the environment but also poses long-term economic risks, as resource scarcity can drive up costs and destabilize markets (Murray et al., 2017)[2].

In contrast, the circular economy represents an innovative paradigm that takes into account the entire life cycle of products. It emphasizes reducing waste and conserving resources by promoting practices such as recycling, reusing, and refurbishing materials. This approach fosters a closed-loop system where products are designed for durability and end-of-life disassembly, allowing for materials to be reclaimed and reintegrated into the production process (Bocken et al., 2016)[5]. As a result, the circular economy not only mitigates environmental impacts but also enhances resource efficiency and economic resilience.

Moreover, transitioning to a circular economy can lead to new economic opportunities. By adopting circular principles, companies can innovate their business models, reduce dependency on finite resources, and engage consumers in sustainable practices. This shift not only benefits the environment but can also enhance brand loyalty and attract a growing market segment that prioritizes sustainability (Wright et al., 2016)[10].

Ultimately, the comparative analysis highlights that while the linear economy may provide short-term economic gains, it is the circular economy that offers a viable pathway towards long-term sustainability, environmental protection, and economic stability. Adopting circular practices is crucial in addressing the pressing challenges of resource depletion and environmental degradation that our society faces today.

SWOT Analysis of Linear and Circular Economies

To further illustrate the differences between the linear and circular economic models, a SWOT analysis (Strengths, Weaknesses, Opportunities, Threats) has been conducted. This analysis provides a structured overview of the internal and external factors influencing each model, highlighting their respective advantages, limitations, potential opportunities, and challenges (Kotler & Keller, 2016)[13].

SWOT Analysis of the Linear Economy

The linear economy, characterized by the "take-make-dispose" approach, has been the dominant model for decades. Its strengths include straightforward implementation and low initial costs, but it faces significant challenges related to sustainability.

The SWOT analysis of the linear economy (Table 1) highlights its foundational characteristics, practical strengths, and substantial challenges. The linear model, based on the "take-make-dispose" paradigm, has long been the dominant economic framework across numerous industries due to its simplicity, low initial investments, and clearly defined processes. It benefits from established supply chains, fast time-to-market, and short-term profitability, making it attractive especially in traditional production systems.

Table 1: SWOT analysis of the linear economy

Strengths	**Weakness**
Simple and well-established processes.	High dependence on non-renewable resources.
Low initial investments in infrastructure.	Excessive waste generation and environmental pollution.
Existing supply chain and market mechanisms.	External costs of environmental degradation.
Fast time-to-market and adaptability in production.	Short product lifecycles with minimal reuse or recycling.
Clear cost structures and pricing models.	Limited incentives for innovation in sustainability.
Opportunities	**Threats**
Implementation of policies to reduce environmental impacts.	Rising raw material costs due to resource depletion.
Technological advancements for resource efficiency.	Consumer pressure for sustainable alternatives.
Collaboration on waste reduction initiatives.	Environmental risks leading to economic instability.
Potential to integrate partial circular strategies (e.g. reuse).	Stricter environmental regulations and carbon pricing.
Shift in investor interest towards sustainable transformation.	Competitive disadvantage compared to circular-oriented businesses.

However, the model's long-term viability is increasingly under scrutiny due to its unsustainable use of finite resources, extensive waste generation, and associated environmental degradation. Despite some opportunities for improvement through policy support and technological innovation, the model is exposed to growing threats such as resource scarcity, regulatory pressure, and consumer demand for sustainability. The following analysis outlines five key strengths, weaknesses, opportunities, and threats that characterize the linear economy and affect its future potential.

The linear economy’s strengths lie in its straightforward and widely established processes. It does not require complex systems for material recovery or waste management, making it cost-effective in the short term. Companies operating within this model benefit from mature and efficient supply chains, as well as low initial investments in infrastructure. Moreover, the model enables fast time-to-market, supporting quick adaptation to market demands and maintaining competitive agility. Clear cost structures and predictable pricing models further enhance its attractiveness, particularly for industries focused on short-term profitability and operational simplicity. These strengths explain the long-standing dominance of the linear economy in traditional industrial sectors. (Sariatli, 2017)[14].

The weaknesses of the linear economy are primarily rooted in its unsustainable use of resources. It relies heavily on non-renewable natural resources, which contributes to their depletion and environmental degradation. The "take-make-dispose" approach generates excessive waste and pollution, overlooking opportunities for material reuse or recycling. As a result, the model not only causes environmental harm but also externalizes these costs, often leading to long-term economic burdens such as escalating waste management expenses and the loss of biodiversity. Additionally, the linear economy’s short product lifecycles and lack of innovation in sustainable practices hinder progress toward resource efficiency. The absence of incentives for integrating circular principles or reducing environmental impact further compounds the model's inherent inefficiencies (Sharma et al., 2021)[15].

Despite its challenges, the linear economy presents several opportunities for reform and adaptation. Governments and industries have the potential to implement policies aimed at mitigating environmental impacts, such as enhancing waste management systems, adopting stricter regulations on resource extraction, and promoting sustainable practices across sectors. Emerging technologies, particularly in the fields of resource efficiency and waste reduction, offer the chance to improve the sustainability of the linear model. Innovations such as resource-efficient production processes and cleaner technologies could help reduce material consumption and pollution. Additionally, there are opportunities for collaboration within industries to reduce waste and improve recycling efforts, even within the confines of existing linear systems. As consumer demand for more sustainable products rises, industries can explore new ways to integrate eco-friendly strategies, creating a path for gradual transformation (Marino et al., 2016)[16].

The linear economy faces substantial threats, particularly as global awareness of environmental issues continues to grow. Resource scarcity, driven by the continued depletion of natural resources, is leading to increased raw material costs, which can destabilize supply chains and cause economic uncertainty. Additionally, consumer demand is shifting rapidly toward more sustainable products and practices, putting pressure on businesses to adapt to these evolving expectations. Legislative and regulatory changes, such as the introduction of carbon taxes, waste reduction mandates, and stricter environmental regulations, are creating additional challenges for industries still reliant on the linear model.

Furthermore, the linear economy is increasingly vulnerable to economic instability caused by environmental crises, such as climate change, biodiversity loss, and the negative effects of pollution. These threats highlight the urgent need for industries to embrace more sustainable practices or face the risk of obsolescence (Sillanpää & Ncibi, 2019)[17].

The SWOT analysis of the linear economy underscores its reliance on simplicity and short-term profitability, which have contributed to its dominance over time. However, it also reveals significant limitations, particularly in terms of sustainability and resource efficiency. Although there are opportunities for incremental improvements—such as policy reforms, technological advancements, and industry collaborations—the model's dependence on finite resources, environmental impacts, and growing pressures from consumers and regulations make it vulnerable. The threats posed by resource scarcity, environmental degradation, and shifting market demands emphasize the need for a transition to more sustainable models. Transitioning to the circular economy is increasingly seen as critical for mitigating these risks and ensuring long-term economic and environmental stability.

SWOT Analysis of the Circular Economy

The circular economy represents a paradigm shift, offering solutions to many of the linear economy's challenges. While it holds promise for long-term sustainability, its implementation requires overcoming several hurdles.

Table 2: SWOT analysis of the circular economy

Strengths	**Weakness**
Reduction in waste and environmental impact.	Higher initial costs for transition.
Efficient use of resources and extended product lifecycles.	Complexity of implementation across industries.
Encourages innovation and new business models.	Dependence on the availability of recyclable materials.
Reduced dependence on finite resources.	Consumer reluctance to change behaviors.
Creation of new job opportunities.	Insufficient data and tracking mechanisms.
Opportunities	**Threats**
Development of innovative technologies, e.g., urban mining.	Resistance to change from traditional industries.
Increased consumer demand for sustainable products.	Inadequate recycling infrastructure.
Emergence of new markets for refurbished and recycled goods.	Lack of international coordination.
Government incentives and regulations promoting sustainability.	Market volatility and economic instability.
Expansion of collaboration across sectors.	Competition from linear economy models.

The SWOT analysis of the circular economy highlights its innovative framework, environmental benefits, and implementation challenges. Unlike the traditional linear model, the circular economy is based on resource efficiency, reuse, and waste minimization. It aims to create closed-loop systems that reduce environmental impact while stimulating sustainable economic growth. Although the circular model offers considerable advantages in terms of sustainability and innovation, its adoption is often limited by systemic complexity, infrastructure limitations, and the need for coordinated policy support.

The circular economy is based on resource efficiency, waste reduction, and sustainability, offering several key strengths. One of the primary advantages is the reduction of waste and environmental impact, as products are designed for reuse, recycling, and refurbishment. This model contributes to a more sustainable use of resources. The circular economy also promotes the efficient use of materials, extending product lifecycles and reducing the need for raw material extraction. Moreover, the circular economy fosters innovation, creating new business opportunities and driving the development of innovative technologies such as closed-loop recycling and urban mining. It encourages the creation of new business models that can help build a more resilient and sustainable economy. Additionally, the circular economy aligns well with increasing consumer demand for sustainable products, enhancing market growth and improving brand reputation for companies that embrace circular practices. The model also supports a sustainable economic framework that reduces reliance on finite resources and minimizes external environmental costs. By preserving natural capital and creating closed-loop systems, it helps industries become more economically resilient (Kirchherr et al., 2017)[18].

The transition to a circular economy requires significant initial investment, which can be a financial barrier. Implementation is complex and demands coordination across various sectors, requiring adaptation of existing processes. The circular model also depends on the availability of recyclable materials, which can limit its effectiveness in some industries. Furthermore, the lack of standardization in circular practices hinders widespread adoption, and limited consumer awareness and reluctance to embrace circular products can further restrict market growth (Corvellec et al., 2022)[19].

Despite the challenges, the circular economy offers substantial opportunities for innovation and growth. Governments and industries have the potential to implement policies that promote sustainability, such as incentivizing businesses to adopt circular models, improving waste management systems, and fostering cross-sector collaboration. Technological advancements, especially in urban mining and closed-loop recycling, present opportunities to recover valuable materials from waste, reducing dependence on virgin resources. Innovations in product design, repairability, and recyclability can also contribute to longer product lifecycles and more efficient resource use. Additionally, the growing consumer demand for sustainable products creates a market incentive for businesses to adopt circular practices. As environmental awareness increases, industries have an opportunity to tap into new markets for refurbished, recycled, and upcycled goods. Collaboration between governments, industries, and consumers can drive the development of new business models such as product-as-a-service or take-back schemes, further promoting sustainability and waste reduction (Sariatli, 2017)[14].

The transition to a circular economy faces several threats. Resistance from industries entrenched in linear production models is a major challenge, as companies may be hesitant to invest in new technologies or modify existing processes. Inadequate recycling infrastructure remains a significant barrier, with many regions lacking proper facilities to effectively process and recycle materials. Furthermore, the lack of international coordination and harmonized regulations can complicate the global adoption of circular economy principles. Differences in policies, standards, and practices across regions create obstacles for businesses seeking to implement circular models worldwide. Market fragmentation could also disrupt alignment between sectors, leading to inefficiencies and slow progress. Lastly, insufficient political and financial support from governments could delay the transition to a circular economy. Without robust policies, incentives, and investments to support circular initiatives, the model may struggle to gain the necessary traction for widespread adoption (Geisendorf & Pietrulla, 2018)[20].

The SWOT analysis demonstrates that the circular economy has strong potential to reduce environmental impacts and promote sustainable growth. While there are challenges such as high initial costs, systemic complexity, and infrastructure gaps, the model offers a promising alternative to the linear economy. As technology advances and consumer demand for sustainability grows, the circular economy is poised to play a critical role in addressing global environmental and economic challenges.

Comparative Evaluation of Strengths in Linear and Circular Economic Models

Understanding the strengths of both linear and circular economic models is essential for assessing their practical relevance and potential for sustainable development. While the linear economy is characterized by simplicity and established infrastructure, the circular economy emphasizes resource efficiency and long-term sustainability. This section provides a comparative overview of the key strengths of each model, including their performance and significance, evaluated through a weighted scoring system.

Table 3: Strengths of the Linear Economy

Strengths	Performance (1 – 5)	Weight (0 – 1)	Calculated Value	Max Value
Simple and well-established processes	5	0.25	1.25	1.25
Low initial investments in infrastructure	4	0.20	0.80	1.00
Existing supply chain and market mechanisms	4	0.20	0.80	1.00
Fast time-to-market and adaptability in production	4	0.20	0.80	1.00
Clear cost structures and pricing models	3	0.15	0.45	0.75
Total		**1.00**	**4.10**	**5.00**

The strengths of the linear economy, as shown in Table 3, highlight its operational efficiency, particularly in terms of simplicity, established infrastructure, and quick adaptability. These factors contribute to the model's high performance in a variety of industries where rapid production and low initial investment are crucial. However, the linear economy lacks a sustainability orientation, which limits its capacity to address long-term environmental challenges. The total calculated value of 4.10 out of 5.00 reflects these strengths but also underscores the inherent trade-off between operational efficiency and environmental sustainability.

Table 4: Strengths of the Circular Economy

Strengths	Performance (1 – 5)	Weight (0 – 1)	Calculated Value	Max Value
Reduction in waste and environmental impact	5	0.25	1.25	1.25
Efficient use of resources and extended product lifecycles	5	0.25	1.25	1.25
Encourages innovation and new business models	4	0.20	0.80	1.00
Reduced dependence on finite resources	4	0.15	0.60	0.75
Creation of new job opportunities	3	0.15	0.45	0.75
Total		**1.00**	**4.35**	**5.00**

In contrast, the circular economy's strengths, outlined in Table 4, emphasize sustainability through waste reduction, resource efficiency, and long product lifecycles. The model's ability to innovate and foster new business models like product-as-a-service is also a critical advantage, driving new market opportunities. With a total calculated value of 4.35, the circular economy demonstrates a strong potential to address environmental and economic challenges that are becoming increasingly important in today's global context. Although the creation of new job opportunities in circular industries is a notable benefit, the model's performance in this area is slightly less significant compared to its environmental and resource-focused strengths.

While both economic models offer valuable strengths, the linear economy excels in operational efficiency, established supply chains, and low upfront costs, making it suitable for rapid production cycles. However, the circular economy presents a more sustainable alternative, with higher potential for environmental impact reduction, resource efficiency, and long-term resilience. As industries and governments increasingly prioritize sustainability, the circular model's strengths are likely to gain more importance in shaping future economic strategies.

Weaknesses of the Linear and Circular Economies

The linear and circular economic models each have their own set of weaknesses that must be considered when evaluating their long-term viability and potential for sustainable development.

Table 5: Weaknesses of the Linear Economy

Weakness	Performance (1 – 5)	Weight (0 – 1)	Calculated Value	Max Value
High dependence on non-renewable resources	5	0.25	1.25	1.25
Excessive waste generation and environmental pollution	5	0.25	1.25	1.25
External costs of environmental degradation	4	0.20	0.80	1.00
Short product lifecycles with minimal reuse or recycling	4	0.15	0.60	0.75
Limited incentives for innovation in sustainability	3	0.15	0.45	0.75
Total		**1.00**	**4.15**	**5.00**

Table 5 evaluates the weaknesses of the linear economy, highlighting significant issues such as high dependence on non-renewable resources and excessive waste generation, both scoring the highest performance rating of 5. These factors contribute to environmental degradation. The external costs of environmental harm, short product lifecycles, and limited incentives for sustainability innovation further underscore the limitations of the linear model. With a total calculated value of 4.15, these weaknesses reveal the need for more sustainable practices, which the circular economy model aims to address.

Table 6: Weaknesses of the Cirkular Economy

Weakness	Performance (1 – 5)	Weight (0 – 1)	Calculated Value	Max Value
Higher initial costs for transition	4	0.25	1.00	1.25
Complexity of implementation across industries	4	0.20	0.80	1.00
Dependence on the availability of recyclable materials	3	0.20	0.60	1.00
Consumer reluctance to change behaviors	4	0.15	0.60	0.75
Insufficient data and tracking mechanisms	3	0.20	0.60	1.00
Total		**1.00**	**3.60**	**5.00**

The table above outlines the weaknesses of the circular economy (Table 6), highlighting key challenges such as higher initial costs, complexity of implementation, and reliance on recyclable materials. The highest-scoring weaknesses are the initial transition costs and implementation complexity, both rated 4, reflecting their significant impact. Consumer reluctance and insufficient data tracking mechanisms also pose barriers, scoring 4 and 3, respectively. The total calculated value of 3.60 out of a maximum of 5.00 indicates that while the circular economy offers strong potential, these challenges must be addressed for broader adoption.

In summary, both the linear and circular economies present weaknesses that impact their effectiveness in achieving sustainability goals. The linear economy's weaknesses are primarily environmental, resulting from resource depletion and waste generation. Meanwhile, the circular economy faces challenges related to implementation complexity, initial costs, and consumer adoption. Addressing these weaknesses is crucial for transitioning toward a more sustainable, circular model while mitigating the negative effects of the linear approach.

Opportunities of the Linear and Circular Economies

The opportunities associated with both the linear and circular economy models are essential for shaping future sustainability efforts. While the linear economy remains grounded in traditional business models, it still presents significant areas where transformation can occur, particularly through policy changes, technological advancements, and evolving market dynamics. In contrast, the circular economy offers a more profound, systemic shift that prioritizes sustainability, innovation, and resource efficiency, promoting long-term environmental and economic benefits.

It's important to note that in the tables provided, the probability of success for each opportunity does not necessarily need to sum to 1. Each opportunity is assessed independently, reflecting its individual likelihood of success without the constraint of a total probability. This approach allows for a more nuanced evaluation of each opportunity, considering factors that may vary across different contexts and scenarios.

Table 7: Opportunities of the Linear Economy

Opportunities	**Appeal (1 – 5)**	**Probability of Success (0 – 1)**	**Calculated Value**	**Max Value**
Implementation of policies to reduce environmental impacts	5	0.60	3.00	5
Technological advancements for resource efficiency	5	0.50	2.50	5
Collaboration on waste reduction initiatives	4	0.30	1.20	4
Potential to integrate partial circular strategies (e.g. reuse)	4	0.40	1.60	4
Shift in investor interest towards sustainable transformation	3	0.70	2.10	3
Total			**10,4**	**21**

Table 7 summarizes the key opportunities within the linear economy model. Notable opportunities include the implementation of environmental policies and technological advancements, both demonstrating high appeal and a strong probability of success. Investor interest in sustainable transformation stands out, with a high probability (0.70), suggesting increasing external pressure for change. The potential to integrate circular principles, like reuse, implies that hybrid strategies may improve the sustainability of linear systems. With a total calculated value of 10.4 out of 21, these opportunities show that, despite its constraints, the linear economy can still foster positive change when bolstered by innovation and policy.

Table 8: Opportunities of the Circular Economy

Opportunities	**Appeal (1 – 5)**	**Probability of Success (0 – 1)**	**Calculated Value**	**Max Value**
Development of innovative technologies, e.g., urban mining	5	0.70	3.50	5
Increased consumer demand for sustainable products	4	0.60	2.40	4
Emergence of new markets for refurbished and recycled goods	4	0.50	2.00	4
Government incentives and regulations promoting sustainability	5	0.60	3.00	5
Expansion of collaboration across sectors	4	0.40	1.60	4
Total			**12.50**	**22**

Table 8 highlights key opportunities associated with the circular economy model. Significant prospects include the development of innovative technologies such as urban mining and strong government support through incentives and regulations, both of which have high appeal (5) and considerable probabilities of success. The growing consumer interest in sustainable products and the rise of new markets for refurbished and recycled goods emphasize the circular economy's potential. With a total calculated value of 12.50 out of a maximum 22, this model shows considerable promise, particularly in technology, policy, and shifting market demands.

The comparison of opportunities in the linear and circular economies reveals that both models offer potential for positive transformation, albeit in different ways. The linear economy's opportunities primarily focus on incremental improvements and hybrid strategies, while the circular economy offers a more transformative, sustainability-driven approach. Despite the foundational differences, both models highlight the importance of innovation, policy, and market dynamics in creating a sustainable future. While the circular economy shows greater potential for systemic change, the linear economy still holds opportunities for improvement and positive impact.

Threats of the Linear and Circular Economies

This table (Table 9) outlines the key threats associated with the linear economy model. The most significant risks include rising raw material costs, driven by resource depletion, and consumer pressure for sustainable alternatives, both of which are considered highly probable and impactful. Environmental risks, such as those leading to economic instability, also pose substantial challenges, as do stricter environmental regulations and carbon pricing, which increase operational costs for linear businesses.

Table 9: Threats of the Linear Economy

Threat	**Appeal (1 – 5)**	**Probability of Success (0 – 1)**	**Calculated Value**	**Max Value**
Rising raw material costs due to resource depletion	4	0.70	2.80	4
Consumer pressure for sustainable alternatives	5	0.80	4.00	5
Environmental risks leading to economic instability	4	0.60	2.40	4
Stricter environmental regulations and carbon pricing	5	0.75	3.75	5
Competitive disadvantage compared to circular-oriented businesses	4	0.65	2.60	4
Total			**15.55**	**24**

Additionally, the competitive disadvantage of linear-oriented businesses, compared to circular models, is another critical concern that could hinder long-term success. With a total calculated value of 15.55 out of 24, this highlights the considerable threats facing the linear economy, with a particular emphasis on sustainability challenges and market pressures driving a shift towards more circular and sustainable business models. These risks call for strategic adaptation and innovation to mitigate negative impacts and transition toward more resilient and sustainable practices.

Table 10: Threats of the Circular Economy

Threats	**Appeal (1 – 5)**	**Probability of Success (0 – 1)**	**Calculated Value**	**Max Value**
Resistance to change from traditional industries	4	0.40	1.60	4
Inadequate recycling infrastructure	3	0.30	0.90	3
Lack of international coordination	3	0.20	0.60	3
Market volatility and economic instability	4	0.50	2.00	4
Competition from linear economy models	2	0.30	0.60	2
Total			**5.70**	**16**

Table 10 highlights the key threats associated with the circular economy model. Resistance to change from traditional industries is considered a notable threat, with a relatively high probability of occurrence, as industries may be hesitant to adopt circular principles due to established business practices. The inadequate recycling infrastructure poses another challenge, reducing the potential for effective material recovery and reuse. Similarly, a lack of international coordination can hinder the widespread adoption of circular strategies, particularly in global supply chains. Market volatility and economic instability also represent significant risks, as fluctuations in the market can undermine investment in sustainable practices. Lastly, competition from linear economy models remains a concern, particularly in sectors that have yet to embrace circular models fully. With a total calculated value of 5.70 out of 16, this illustrates that while there are significant threats to the circular economy, the overall calculated value remains lower than that of the linear economy. This suggests that despite the challenges, the circular economy model still holds substantial potential for long-term sustainability, but overcoming these threats will require coordinated efforts, infrastructure development, and systemic changes in industry practices.

Final SWOT Matrix of the Linear Economy

The results of the SWOT analysis of the linear economy indicate that weaknesses slightly outweigh strengths (∑S – ∑W = 4.10 – 4.15 = –0.05), suggesting challenges in its current form, particularly in terms of environmental impact and sustainability. Externally, threats significantly outweigh opportunities (∑O – ∑T = 10.4 – 15.55 = –5.15), highlighting the growing pressure from regulatory changes, resource depletion, and the market's shift toward more sustainable practices (Figure 3). The need for internal transformation toward sustainability and adaptation to external pressures is evident.

$$\sum S - \sum W = 4.10 - 4.15 = -0.05 \rightarrow$$ Weaknesses outweigh strengths slightly

$$\sum O - \sum T = 10.4 - 15.55 = -5.15 \rightarrow$$ Threats slightly outweigh opportunities

Figure 3: SWOT Score Calculation for the Linear Economy

Based on the quantitatively evaluated SWOT analysis, the calculated coordinate for the linear economy is (−0.05, −5.15), which we have illustrated in the strategic SWOT matrix (Figure 4). This coordinate falls within the fourth quadrant, specifically in the area of the retreat strategy.The retreat strategy indicates that weaknesses (W) and threats (T) significantly outweigh strengths (S) and opportunities (O). In the case of the linear economic model, this suggests that the approach is environmentally and economically unsustainable in the long term. Dominant negative factors, such as high waste generation, excessive use of natural resources, and environmental burden, outweigh potential benefits such as implementation simplicity or low initial costs. From a strategic decision-making perspective, this points to the need for a gradual abandonment or radical transformation of the linear model toward more sustainable forms of economic activity, such as the circular economy. Implementing a circular economy model could help reduce environmental impacts while creating new economic opportunities.

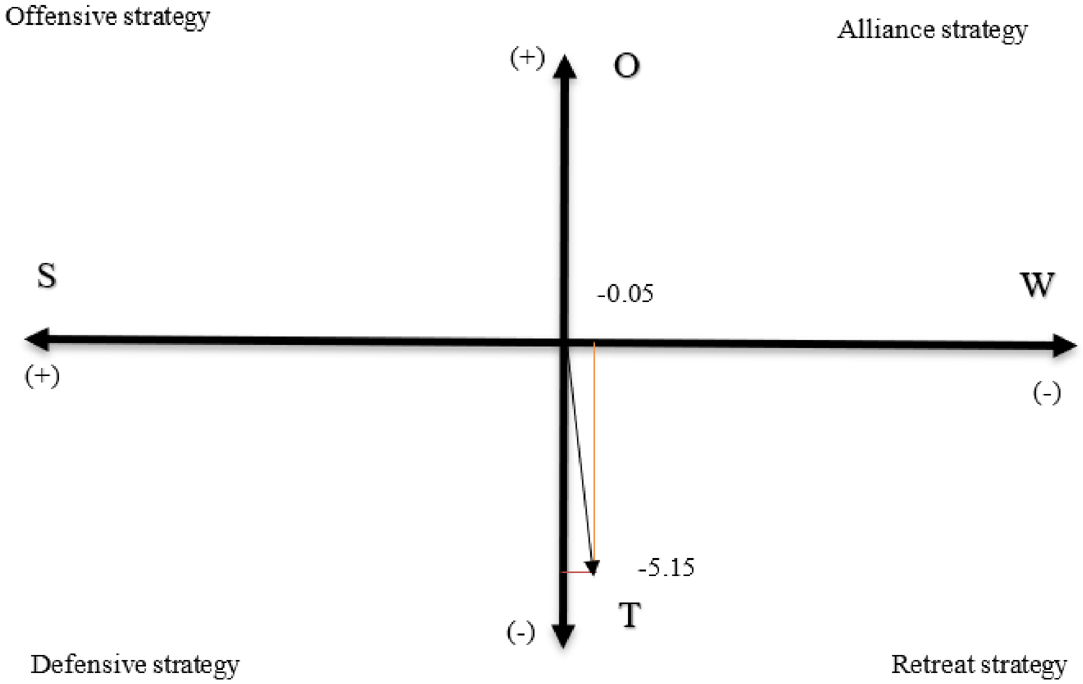

Figure 4: SWOT Score Calculation for the Linear Economy

The results of the SWOT analysis of the circular economy (Figure 5) show that strengths outweigh weaknesses (∑S – ∑W = 4.35 – 3.60 = +0.75), indicating that the circular economy offers significant advantages in resource efficiency, innovation, and long-term sustainability. Externally, opportunities significantly outweigh threats (∑O – ∑T = 12.50 – 5.70 = +6.80), suggesting a favorable environment for the growth of circular economy models, driven by increasing consumer demand for sustainable products, government incentives, and technological developments. This shift presents a promising future for industries embracing the circular economy.

$$\sum S - \sum W = 4.35 - 3.60 = +0.75$$ ⟶ Strengths outweigh weaknesses

$$\sum O - \sum T = 12.50 - 5.70 = +6.80$$ ⟶ Opportunities significantly outweigh threats

Figure 5: SWOT Score Calculation for the Circular Economy

Based on the quantitatively evaluated SWOT analysis, the calculated coordinate for the circular economy model is (+0.75, +6.80), which we have graphically represented in the strategic SWOT matrix (Figure 6). The position of the point in the first quadrant clearly indicates the area of the offensive strategy. An offensive strategy suggests that, in the case of the circular economy, strengths (S) and opportunities (O) significantly outweigh weaknesses and threats. This result confirms the potential of this economic model as a sustainable alternative to the traditional linear economy (Figure 6). Key strengths include more efficient resource use, reduced waste generation, support for innovation, and a positive impact on the environment. At the same time, the circular economy is supported by legislation and environmental trends, creating favorable opportunities for its development.

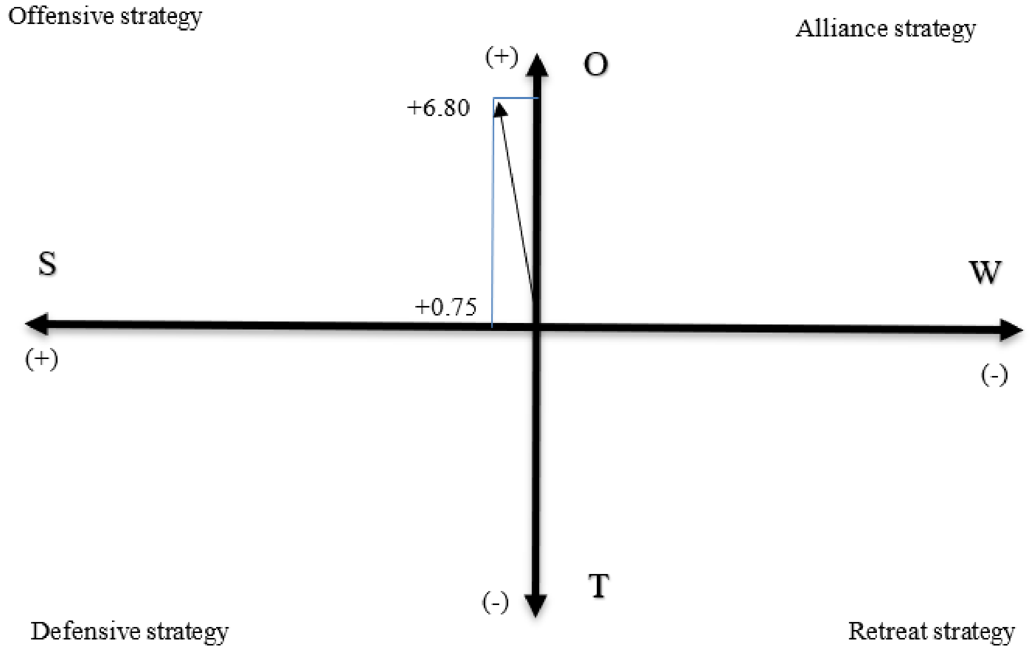

Figure 6: Graphical representation of the strategy for the Circular Economy

The analysis result suggests that organizations and companies implementing the principles of the circular economy should actively develop this strategy and support its wider adoption, thereby gaining a competitive advantage and positively contributing to sustainable development.

Conclusions

The transition from a linear to a circular economy is essential for achieving sustainability and protecting the environment. Based on the results of our analysis, including a detailed SWOT evaluation, it is clear that the linear model, with its inherent focus on resource depletion, waste generation, and inefficiency, is no longer a viable path for long-term economic and environmental health. The circular economy provides a comprehensive framework to address critical environmental issues, such as resource depletion, waste generation, and the exhaustion of natural ecosystems. By prioritizing the reuse and recycling of materials, this model seeks to minimize ecological footprints and foster a more sustainable relationship between economic growth and environmental stewardship.

Our SWOT analysis revealed key strengths of the circular economy, such as its potential for reducing waste, lowering costs in the long run, and creating new job opportunities in the recycling and repair sectors. However, challenges include the higher initial investment required and the need for stronger legislative support and business commitment. Conversely, the linear economy's weaknesses—resource depletion, pollution, and lack of long-term sustainability—highlight the necessity for its transformation. Notably, the linear model's short-term economic benefits often obscure its long-term environmental and economic costs.

Investment in innovation and legislative support are crucial for the successful implementation of the circular model. This includes funding for research and development of sustainable technologies, as well as policies that encourage businesses to adopt circular practices. Specific recommendations for transitioning toward a circular economy include:

Encouraging government subsidies and incentives for companies that embrace circular principles, particularly in industries with high material consumption, such as manufacturing and construction.

Promoting consumer awareness campaigns to increase demand for circular products and services.

Fostering collaboration between industries, governments, and academia to drive forward-thinking solutions to the challenges posed by waste and resource inefficiency.

Without such transformation, we face serious ecological, economic, and social challenges that demand collective efforts from all stakeholders involved, including governments, businesses, and consumers.

The circular economy not only reduces environmental impacts but also promotes economic growth and enhances the competitiveness of businesses. By implementing circular principles, companies can reduce costs associated with raw material procurement, minimize waste, and create new revenue streams through recycling and reuse. Additionally, this shift towards sustainable practices can enhance brand loyalty among consumers who are increasingly prioritizing environmental responsibility in their purchasing decisions.

Based on our SWOT analysis and the identified strengths, weaknesses, opportunities, and threats for both the linear and circular economic models, it is imperative that governments, businesses, and individuals commit to adopting more sustainable practices and models. Such a commitment will ensure a better future for our planet and future generations. By embracing the principles of the circular economy, we can work towards a resilient economic system that aligns with the ecological limits of our planet, fostering a harmonious coexistence between humanity and nature.

Acknowledgements

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Porovnání lineární a cirkulární ekonomiky a jejich vlivu na životní cyklus produktu

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Souhrn

Tento článek analyzuje rozdíly mezi lineární a cirkulární ekonomikou a zaměřuje se na jejich dopad na životní cyklus produktu. Zkoumá, jak každý z těchto ekonomických modelů ovlivňuje environmentální a ekonomické aspekty cyklu produktu, s důrazem na fáze výroby, použití a likvidace. Lineární ekonomika, založená na tradičním modelu „vezmi-vyrob-znič", často vede k vyčerpání zdrojů a poškozování životního prostředí s omezenými možnostmi opětovného využití a recyklace materiálů. Naproti tomu cirkulární ekonomika upřednostňuje efektivní využívání zdrojů, snižování odpadu a opětovné použití materiálů s cílem uzavřít materiálové cyklus a podporovat udržitelnost v celém životním cyklu produktu. Článek porovnává výhody a nevýhody obou modelů a hodnotí jejich dopady na ochranu životního prostředí a ekonomickou udržitelnost. Prostřednictvím SWOT analýzy studie identifikuje silné stránky cirkulární ekonomiky, jako je její potenciál pro snižování odpadu, vytváření nových pracovních příležitostí v oblasti recyklace a oprav a podporu dlouhodobých úspor nákladů. Diskutuje se však také o výzvách, jako jsou vyšší počáteční investice a potřeba silnější regulační podpory. Slabé stránky lineárního modelu, včetně jeho závislosti na omezených zdrojích a jeho příspěvku ke znečištění a degradaci životního prostředí, dále zdůrazňují potřebu jeho transformace. Tento článek dochází k závěru, že přechod z lineární na cirkulární ekonomiku je klíčový pro dosažení udržitelnosti. Přijetím cirkulárních principů mohou podniky nejen minimalizovat svou ekologickou stopu, ale také podpořit hospodářský růst, zlepšit konkurenceschopnost a přizpůsobit se rostoucí poptávce spotřebitelů po environmentálně odpovědných postupech.

Klíčová slova: *lineární ekonomika; cirkulární ekonomika; životní cyklus produktu; udržitelnost; dopad na životní prostředí*

Time series analysis of the climate change impacts of conventional agricultural practices

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Abstract

Agricultural activities have a considerable impact on the environment. In Hungary, crop production covers nearly half of the country's land, approximately 5.1 million hectares as of 2022. Sustainable agricultural competitiveness hinges on two key pillars: maintaining environmental balance and mitigating the damages from climate change anomalies. Our research focuses on a time series analysis of the climate change impacts of conventional agricultural practices in the Lajta Project study area, using the Environmental Life Cycle Assessment (LCA) method. The investigation spans two decades, calculating the annual average percentage contribution of each crop per hectare to the overall environmental impact, the environmental ranking is as follows (in ascending order): rapeseed (1.0%) – silage maize (4.9%) – grain maize (7.1%) – winter barley (43.1%) – winter wheat (44.0%). The results obtained enhance the ability to assess environmental impacts, climate risks, and the effects of climate change related to arable crop production technologies. This, in turn, aids in selecting the most suitable technologies that are adapted to environmental sensitivities.

Keywords: *agricultural land use; carbon footprint; ranking; comparison; life cycle analysis*

Introduction

The fundamental change in the nature of the functioning of the economy (as a productive sector) since the industrial revolution has been a major cause of environmental problems. However, this sector (including agriculture) is also the easiest to regulate. Among the many regulatory principles already developed, voluntary regulation (including life cycle analysis, ISO 14040-44:2006) can provide an effective, proactive approach to addressing problems[1].

Monoculture agriculture plays a critical role in global food production, occupying nearly 50% of habitable land and contributing significantly to climate change—food systems alone are responsible for approximately 26% of global greenhouse gas emissions[2]. Within agricultural emissions, crop production accounts for around a quarter of food-related emissions, while livestock contributes roughly 31%[3].

Extensive machinery usage and high input levels, including synthetic fertilizers and pesticides, dominate emissions. Studies show that expanding farm size increases carbon emissions per hectare when evaluated with LCA[4]. Conventional tillage and nitrogen application not only produce CO_2 and N_2O but also degrade soil organic carbon[2].

Monocultures over large areas disrupt habitat continuity, leading to biodiversity decline. For example, insect populations—including critical pollinators—are significantly reduced in landscapes dominated by monoculture cropping systems with high pesticide use. Moreover, the simplification of agroecosystems reduces resilience to climate shocks, such as droughts and pest outbreaks[5].

In Hungary, crop yields from arable farming show greater fluctuations than necessary, partly due to weather conditions, soil quality, technological factors, and low irrigation capacity. The yields of major agricultural crops remain close to the levels of two or three decades ago[6].

Several researchers, however, emphasize that the production of biomass on arable land is only justified if technologies are applied that meet both environmental and sustainability criteria. Dinya[7] highlights the importance of decision-making that prioritizes professional considerations, fits into a broader system, and focuses on long-term thinking and value chains, both at local and national levels.

Footprints can be used individually or collectively to characterise steps towards sustainability and are a good tool for benchmarking environmental performance[8]. The carbon footprint shows the total - direct and indirect - greenhouse gas (GHG) emissions of an activity, person, organisation, event or product, expressed in carbon dioxide equivalents. The larger the carbon footprint of an activity or individual, community or society, the greater its impact on global warming[8].

To examine the environmental impacts of crop production, we need to understand the resources required for production. These resources include the soil, moisture (water), heat, light, CO2 (air), and living organisms[9]. In addition to these, we must consider the landscape, which can be significantly altered by agricultural activities. Besides the needs of the plants, we must also account for technological processes and machinery, as they are significant influencing factors.

According to Kreybig[10], there is an extensive, interactive relationship between agriculture and the environment. Environmental factors fundamentally determine the nature, effectiveness, and even the existence of agricultural activities, while the reverse is also true, as agriculture exerts a direct and significant impact on the environment. Agriculture is one of the most important and fundamental human activities, which, by utilizing elements of the natural environment, also brings about significant changes in their condition. Agricultural activity has always been associated with some form of environmental change, but the intensity and scope of these changes have been, and continue to be, highly variable in time and space[11].

Negative changes in the state of environmental elements can be significant, especially because of inappropriate cultivation and resource use, so the right choice of technologies and use of materials is crucial[9].

In our work, we set the goal of conducting a time-series analysis of the conventional arable farming operations associated with key crops (silage maize, grain maize, rapeseed, winter barley, winter wheat) cultivated in significant quantities in the Lajta Project study area, focusing on their impacts on climate change (technological carbon footprints), using the comparative environmental Life Cycle Assessment (LCA) method, which also allows for ranking.

Materials and methods

The examined Lajta Project research area (3065 ha) is in the northwestern corner of Hungary, in Győr-Moson-Sopron County. The area is typically farmed in an intensive conventional way, almost completely lacking a meadow-pasture environment. It has become an important area for the cultivation of wheat, winter barley, maize, sugar beet, lucerne and red clover.

The Lajta Project dates to the early 1980s, when the goal was to study the bustard (*Otis tarda*) population in the Moson Plain and the Hanság region. Even at that time, more complex, multifaceted research was being conducted, which laid the foundation for the ecological protection of the bustard population in Hungary. During this period, several comprehensive ecological studies were launched across the country, aimed solely at assessing conventional agricultural activities and investigating their impacts. One of the areas studied was the Lajta-Hanság State Farm. It was already established then that the bustard's habitat shift was not only caused by the loss of previous habitats but was also a natural response to environmental factors. Furthermore, the complex nature of the research highlighted the importance of other species coexisting with the bustard, although these were only secondary focuses at the time. Towards the late 1980s, another bird species, the Hungarian partridge (*Perdix perdix*), became a focus of the research, due to its declining population. Various efforts were made to increase the partridge populations, but with little success, as the causes of the decline were not identified, and the proposed solutions were inadequate. As part of this process, the Department of Wildlife Management at the Forestry and Wood Industry University launched a survey and study of wildlife species living in field habitats and their environments in the Mosonszolnok II area of the Lajta-Hanság State Farm. During this period, the Hungarian Partridge Protection Program, supported by the Ministry of Agriculture, was also established, with the partridge as its indicator species. This enabled the simultaneous implementation of scientific research and practical work, which helped record both biological and ecological baseline information that could be applied in wildlife management practices[12].

As part of the complex research of the Lajta Project regarding the ecological protection of the bustard population in Hungary, we conducted a life cycle assessment to identify the environmental impacts of conventional agricultural cultivation, with special emphasis on the development of the carbon footprint. The methodology applied for conducting the LCA complies with the requirements of the ISO 14040:2006[13] and ISO 14044:2006[14] standards. The analysis was carried out using the Sphera GaBi thinkstep Professional software[15]. The required steps of the LCA were as follows: 1. defining the goal, scope and system boundaries, 2. inventory analysis, 3. impact assessment, 4. interpretation of results.

The selection of the crops included in the analysis was justified by the significant cultivation area they occupy in the study region. We conducted a life cycle assessment of cultivation data for five crops: rapeseed, winter barley, winter wheat, silage maize, and grain maize, based on data from agricultural field records. Our functional unit was 1 hectare of cultivated land. The study covers nearly two decades (1991-2011).

There are several impact assessment methods available to calculate the carbon footprint, in our study we chose one of the most widely used in Europe, the CML2001 (January 2016 version) impact assessment method and used the global warming potential (GWP 100 y). Global Warming Potential is a relative measure of how much heat a greenhouse gas retains in the atmosphere. Global Warming Potential is calculated in carbon dioxide equivalents, which means that the greenhouse effect of an emission is given relative to CO2. Since the atmospheric residence time of gases is included in the calculation, the assessment period is set at 100 years.

To assess the overall environmental impact (expressing the impacts in a dimensionless number), we used the 'CML2001, Experts IKP (Central Europe)' method in the LCA software. This method allowed us to present the increasing environmental ranking of the annual average environmental burden per hectare for each crop.

Results and discussion

We present the global warming potential (GWP 100 y) values from the CML2001 mid-point, problem-oriented impact assessment method, which shows the carbon footprint of the cultivation technologies of the examined crops (which primarily represents the mechanized operations, fertilization, and chemical crop protection carried out on the cultivated area). The values for silage maize per hectare are illustrated in the following diagram *(Figure 1)*.

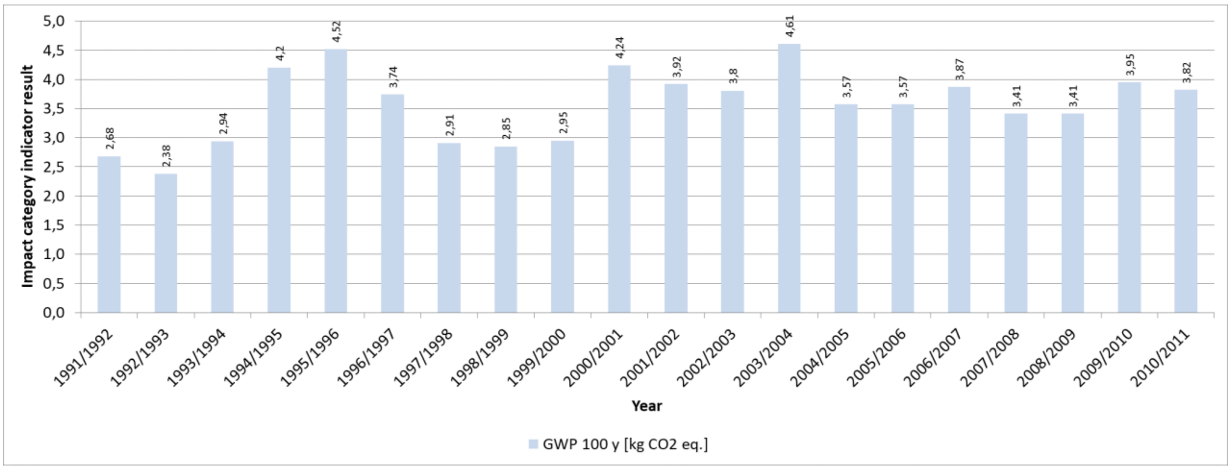

Figure 1: Time-series values of the technological carbon footprint using the CML2001-Jan. 2016 method in the case of silage maize per hectare

As the time series progresses, there is initially a slight increase in the impact category, followed by a more balanced pattern. There are also some standout years and periods that contributed significantly to the "GWP 100 y" value (as these years were characterized by more intensive mechanized operations and chemical crop protection on the cultivated area), namely the years from 1994/1995 till 1996/1997, 2000/2001, and 2003/2004.

The values for grain maize per hectare can be seen in *Figure 2*.

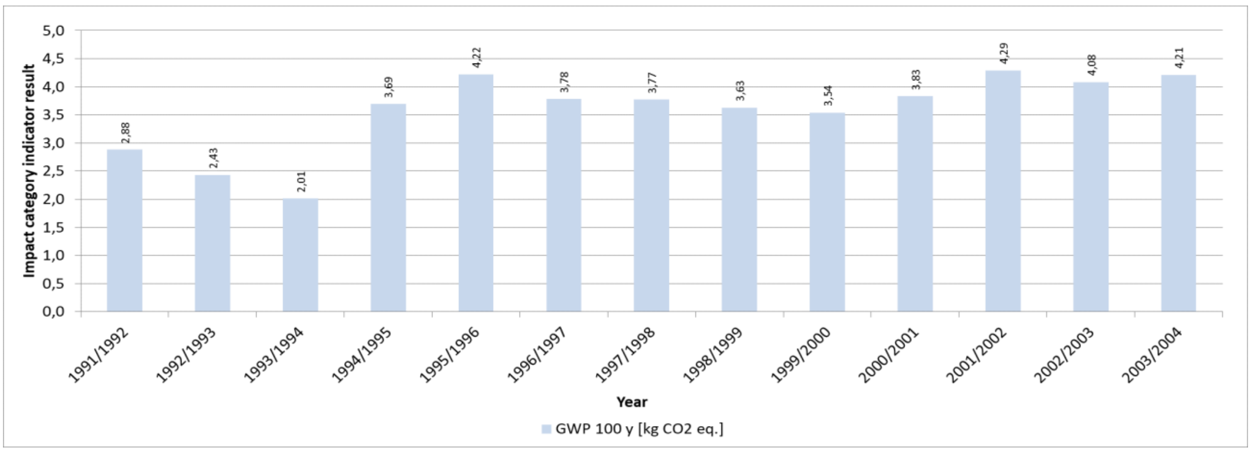

Figure 2: Time-series values of the technological carbon footprint using the CML2001-Jan. 2016 method in the case of grain maize per hectare

For grain maize, the impact was lower up until the 1993/1994 year. However, after that, the values increased in the global warming potential (GWP 100 y) impact category.

For rapeseed, the global warming potential (GWP 100 y) values per hectare are as follows *(Figure 3).* While the values are generally balanced, the years 1993/1994 and 2003/2004 experienced lower impacts.

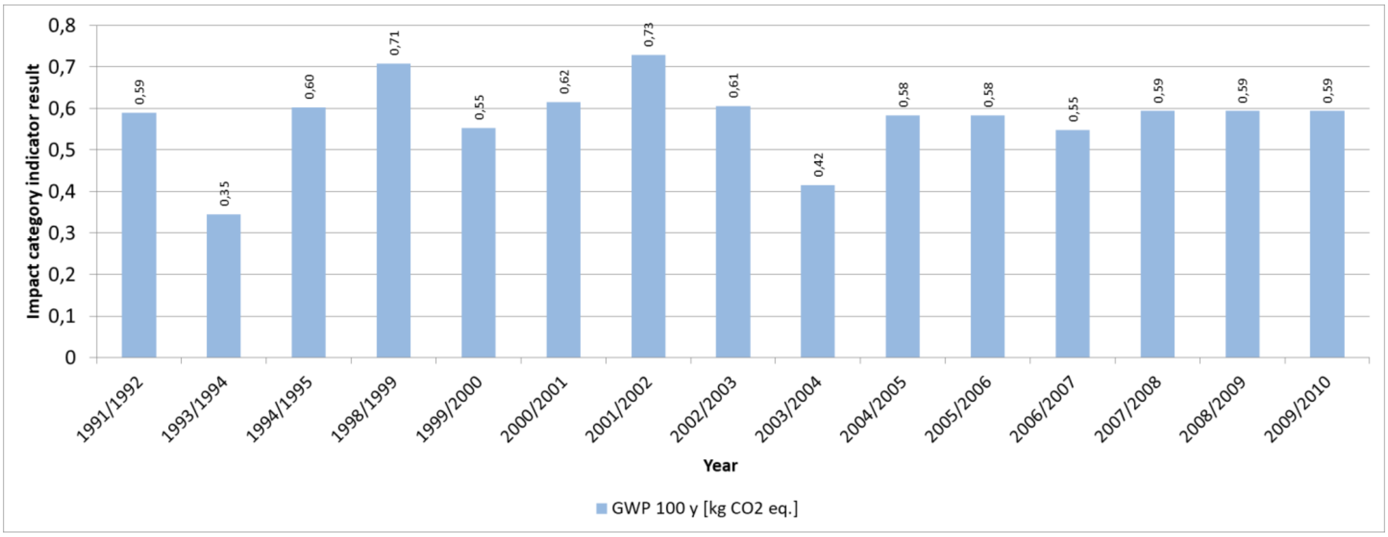

Figure 3: Time-series values of the technological carbon footprint using the CML2001-Jan. 2016 method in the case of rapeseed per hectare

The GWP 100 years indicator values for winter barley per hectare are as follows *(Figure 4)*. There are no standout values; only the year 2003/2004 experienced slightly higher values than the average.

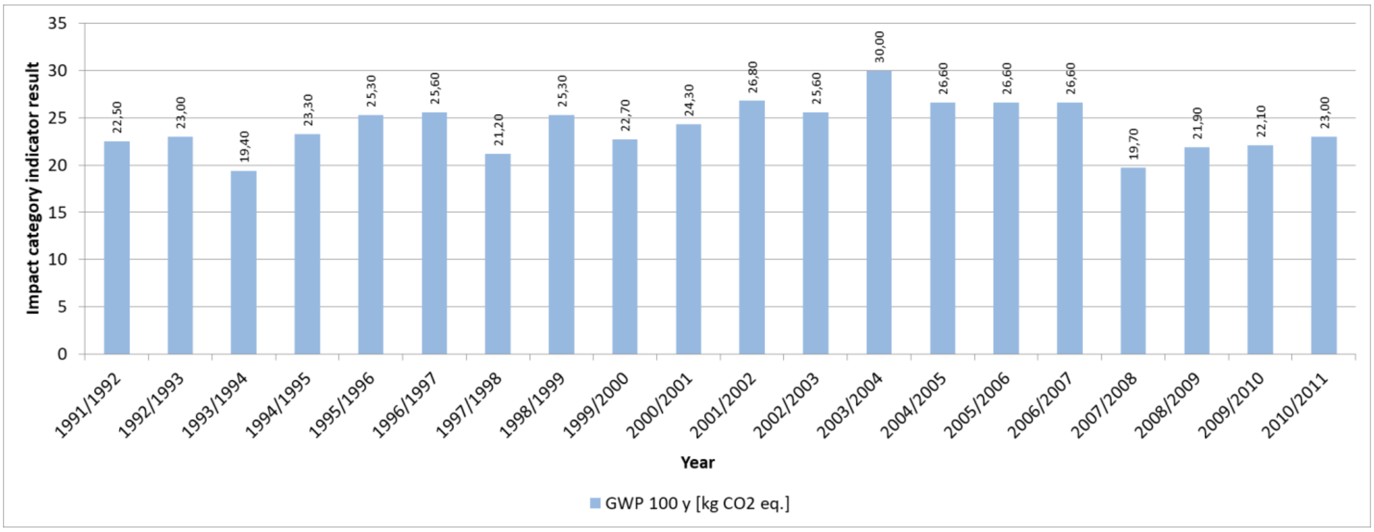

Figure 4: Time-series values of the technological carbon footprint using the CML2001-Jan. 2016 method in the case of winter barley per hectare

The indicator values for winter wheat per hectare are depicted in the following diagram *(Figure 5).*

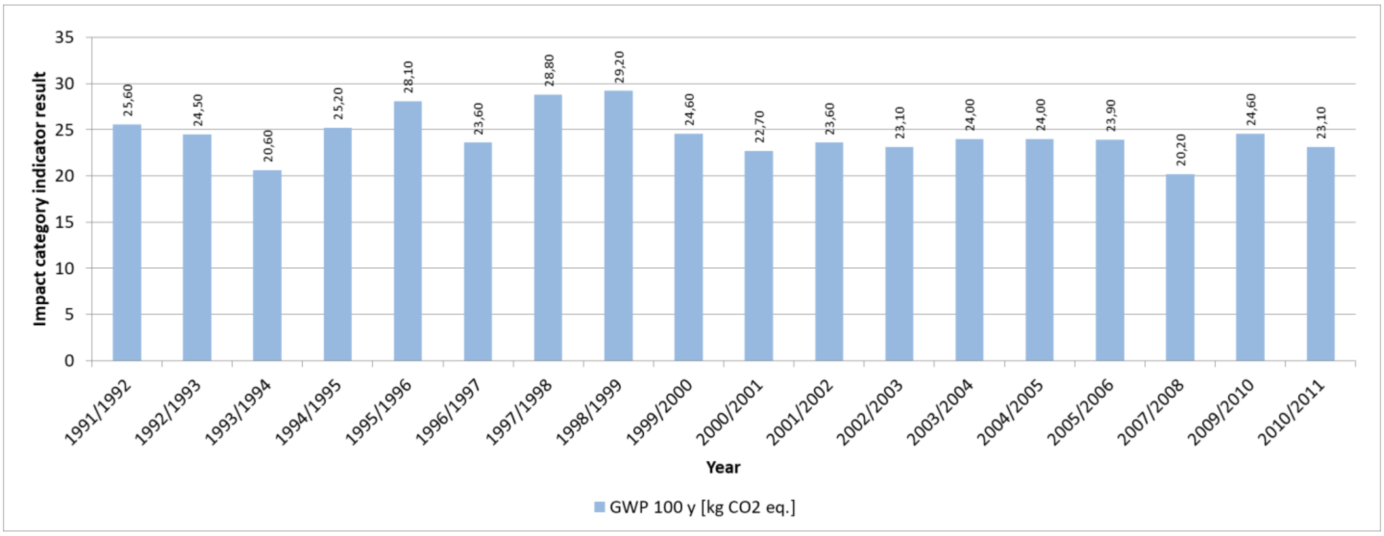

Figure 5: Time-series values of the technological carbon footprint using the CML2001-Jan. 2016 method in the case of winter wheat per hectare

The indicator values for the impact categories fluctuate in the first nine years. The following nine years show slightly lower, more uniform impacts. The exception is 2007/2008, which is characterised by lower values than the average for the period.

When calculating the environmental overall impact, the results for all CML 2001 impact categories can be viewed side by side in a dimensionless metric for each crop.

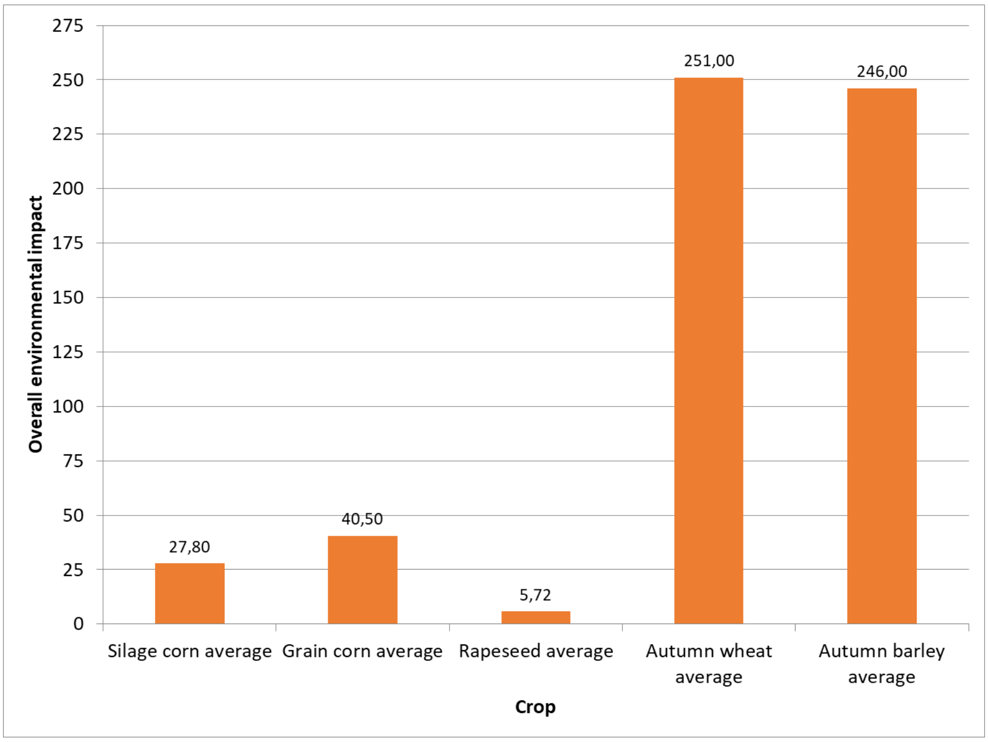

Figure 6: CML2001, IKP Experts (Central Europe) values per crop based on annual average inventory data

In the LCA, the values obtained from the mandatory impact assessment step, normalized for Central Europe (using the CML2001, IKP Experts (Central Europe) method)[16] *(Figure 6)*, show the following environmental ranking based on the percentage contribution of each crop (increasing order): rapeseed (1.0%) – silage maize (4.9%) – grain maize (7.1%) – winter barley (43.1%) – winter wheat (44.0%). The difference in the overall environmental impact between root and cereal crops is an order of magnitude, with cereal crops having values six to ten times higher.

Conclusion

In our research, we analyzed time series data related to the major field crop operations (silage maize, grain maize, rapeseed, winter barley, winter wheat) associated with the Lajta Project study area, focusing particularly on their impact on climate change (technological carbon footprints). This was achieved using a comparative Life Cycle Assessment (LCA) method, which also allows for ranking. The area is typically an intensive agricultural environment, with almost no presence of meadow-pasture environments.

The methodology used for the LCA complies with the requirements of ISO 14040:2006 and ISO 14044:2006 standards. We conducted a life cycle assessment of the cultivation data for five crops: rapeseed, winter barley, winter wheat, silage maize, and grain maize. Our functional unit was 1 hectare of cultivated land.

The time series carbon footprint analyses allowed for the presentation of the environmental impacts per functional unit for each crop across different years. This facilitated the understanding of the intensity of cultivation technologies, which in turn enabled further conclusions to be drawn from the time series evaluation of changes in the local plant and animal life.

When calculating the overall environmental impact of cultivation steps, the environmental ranking based on the percentage contribution for each crop is as follows (in increasing order): rapeseed (1.0%) – silage maize (4.9%) – grain maize (7.1%) – winter barley (43.1%) – winter wheat (44.0%).

Understanding these results will help to better identify the environmental impacts, climate risks, and roles of climate change in field crop cultivation technologies. It can also help in selecting appropriate cultivation technologies that align with the sensitivity of the environment.

Acknowledgment

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Analýza časových řad dopadů změny klimatu velkoplošných zemědělských praktik

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Souhrn

Zemědělské činnosti mají značný dopad na životní prostředí. V Maďarsku pokrývá rostlinná výroba téměř polovinu rozlohy země, přibližně 5,1 milionu hektarů k roku 2022. Udržitelná konkurenceschopnost zemědělství závisí na dvou klíčových pilířích: udržování environmentální rovnováhy a zmírňování škod způsobených klimatickými anomáliemi. Naše výzkumná práce se zaměřuje na analýzu časových řad dopadů změny klimatu na velkoplošné zemědělské praktiky ve studijní oblasti projektu Lajta, a to pomocí metody posuzování životního cyklu (LCA). Šetření pokrývá období dvou desetiletí a vypočítává průměrný roční procentuální podíl každé plodiny na hektar na celkovém dopadu na životní prostředí. Environmentální žebříček je následující (vzestupně): řepka (1,0 %) – silážní kukuřice (4,9 %) – zrnová kukuřice (7,1 %) – ozimý ječmen (43,1 %) – ozimá pšenice (44,0 %). Získané výsledky zlepšují schopnost hodnotit environmentální dopady, klimatická rizika a účinky změny klimatu související s technologiemi produkce orné půdy. To následně pomáhá při výběru nejvhodnějších technologií, které jsou přizpůsobeny environmentálním citlivostem.

***Klíčová slova**: využití zemědělské půdy; uhlíková stopa; hodnocení; srovnání; analýza životního cyklu*

Exploring Earth Air Heat Exchanger as an Innovative and Sustainable Application for Cooling and Heating: Excerpts from Literature

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Abstract

Energy needs and alarming CO_2 emissions across the globe have brought considerable attention to the development and implementation of renewable energy and energy-saving systems. An important aspect of the earth's thermodynamics is that its temperature remains low and constant throughout the year. This is in comparison to outdoor air temperatures.The ground temperature is used in Earth Air Heat Exchanger (EAHE) systems to pre-condition air before it enters a building. It effectively reduces the energy consumption of traditional Heating, Ventilation, and Air Conditioning (HVAC) systems. This paper provides a concise review of EAHE technology application in space heating and cooling. The write-up also emphasized on the iinfluence of air velocity, diameter,depth, material type and length of a buried pipe on the thermal behavior of the EAHE system. EAHE performance is not greatly affected by the material of the pipe, in contrast to the length and diameter of the pipe. The findings suggest that the most efficient cooling and heating effect is provided by pipes with smaller diameters. Additionally, it is indicative that longer pipes improve the cooling/heating output in the EAHE system. Overall, fund available for the construction determines the type of pipe material and length to use for an efficient EAHE system. Lower air velocities provide higher thermal performance than higher flow rates. Furthermore, the integration of the EAHE with other HVAC systems may increase the energy saving. Typically, these systems may contribute to reduction of energy consumption for heating by approximately 25 – 40%. This percentage range could yield to an EAHE efficiency almost 0.9.

Keywords: *Soil temperature; Earth Air Heat Exchanger system; sustainable energy; thermal comfort; heating and cooling systems; Renewable or green energy.*

Table of contents

Introduction

Globally, energy consumption in buildings has become a significant issue due to the increasing demand for energy and the consequent increase in greenhouse gas emissions. Heating and cooling systems are responsible for a large proportion of energy consumption in buildings. Air conditioning systems (ACs) are used to maintain interior thermal comfort, using around 15% of all energy consumed. By 2050, ACs number is predicted to rise from 1.6 billion to 5.6 billion, increasing the power consumption for ACs by thrice[1].The COVID-19 pandemic condition posed serious issues about regulating the interior environment to reduce virus transmission[2–4].

Therefore, new guidelines have been released to control the spread of COVID-19 in Heating, Ventilation, Air Conditioning (HVAC) systems. These guidelines recommend that fresh air should be increased up to 100% in enclosed spaces. Also, recirculated air should be avoided. These results in increased cooling/heating loads and hence increased energy consumption[2]. If the world's economy is to satisfy these expanding energy demands, the use of renewable energy sources such as biofuel, wind, solar and geothermal will be critical[5].

Buildings are responsible for one-third of total energy greenhouse gases emissions[6]. Buildings' thermal performance has been immensely improved over the past few years due to highly intensive energy savings measures and technologies. While this is mostly true in developed countries, the energy needs for cooling have significantly increased in the warmer developing world due to rising living standards, urban temperature increases, as well as global climate change[7]. For instance, the energy used by the construction industry for cooling has been significantly impacted by global climate change. As temperatures rise in Greece, researchers predict a 248% rise in energy consumption for building cooling by 2100, but a 50% decrease in energy demand for buildings[8]. In Europe, air conditioning raises the typical commercial building's overall energy usage to roughly 40 $kWh/m^2/y$[9,10].

Thermal comfort is directly linked to human productivity. So, office buildings must ensure that their thermal environment is of high quality. Heating systems are critical in cold climates for various reasons. They provide necessary comfort and sustain a living atmosphere by keeping interior temperatures comfortable throughout the winter seasons. Humans would be exposed to extremely low temperatures in the absence of heating equipment, causing discomfort, unproductivity, health problems, and even hypothermia.. Extreme cold can cause water to freeze and expand, resulting in broken pipes and structural issues. Heating systems assist in averting these problems by keeping indoors temperatures above freezing, thus safeguarding buildings and their occupants[11].

The minimisation of energy consumption and greenhouse gases emissions can be done by applying modern heating techniques like high-efficiency boilers, photovoltaic/thermal collectors, and geothermal systems (such as heat pumps and earth air heat exchangers). However, the type of energy source used by these systems gives the difference of their climate impact. In fact, to distinguish between the combustion of fossil fuels and biomass is essential. The combustion of fossil fuels causes additional CO_2 into the atmosphere. This is due to the release of underground storage of the aged carbon. Biomass burning emit CO_2 that was absorbed from the atmosphere during the growth of plant. The last type of combustion can be considered as a more sustainable and carbon-neutral option[12]. Moreover, as a contribution of the circular economy objectives and waste management, in addition to reduction of fossil fuels dependence, it is advisable to use alternative and waste biomass utilisation e.g. organic municipal or agricultural wastes and residues, animal manure or forest residues[13,14]. Potentially, this will support environmental preservation.

A passive climate control technology applicable to farm and residential buildings is an Earth Air Heat Exchanger (EAHE). This is a method based mainly on temperature distribution at the surface of the ground[15]. It relies on underground soil temperatures which remain fairly constant at a depth of about 2.5 to 3 m from the surface (Figure 2), throughout the year. It is usually greater or less than the ambient temperature of winter or summer, respectively. That reflects the average yearly air temperature of the region[16].This is commonly referred to as the ‘critical depth’.[17–19]. This study gives an overview of EAHE technology, with an emphasis on the way they could enhance building energy use and sustainability. By summarizing sevral recent research findings on the use of EAHE systems in buildings air conditioning purposes, the valuable potential of such suistanable, novel and energy-efficient solution for building are depicted. This review presents the state-of-the-art of EAHE technique, its functional fundamentals and the impact of soil properties on the performance of this system. Another interesting highlight in the installation of the EAHE is the design parameters of such system (pipe material, pipe diameter, length of the pipe and the buried depth of the EAHE pipe, in addition to speed of the air passing through the pipe). Therefore, this investigation aimed to concluded the recommended parameters based on various research. The main novel sections covered in this study:

- The operation concept of an EAHE and basic heat transfer modes that happen whitin the system;
- The major classifications of the EAHE systems (including closed- and open-loop system);
- The impact of various design parameters on the EAHE performance;
- Possibility of integrating EAHE with other HVAC system to enhance the energy saving.

1. State-of-the-art of EAHE technology

The use of Earth Air Heat Exchangers (EAHEs), which may offer natural ventilation and use the consistent ground temperature to provide cooling and heating, is one substitute for traditional heating and cooling systems. Research has anchored on enhancing several features of EAHE systems, including design, operation, and performance evaluation. A number of factors are investigated in studies [20–22], together with ground heat transfer, airflow patterns, heat recovery efficiency, and control strategies. These sustainable systems have many benefits over conventional heating and cooling systems[23–26]. Al-Ajmi et al.[27] developed an analytical model for the prediction of air outlet temperatures and cooling potential of EAHEs in hot and arid climates. Their model is based on the ratio of the thickness of the disturbed soil to the radius of the buried pipe, without considering the thermal resistance of the pipe material. This model was implemented into the TRNSYS environment after being validated with previous published experimental research. It examined the thermal performance of a typical house combined with an EAHE under Kuwaiti climate conditions. It was discovered that the EAHE can provide 30% of the summertime demand for cooling energy. There was an analysis for the thermal efficiency of vault roof buildings integrated with earth-to-air heat exchangers. The results revealed that during the winter months, the temperature in the room increased by about 5.1–15.7°C, whereas in the summer, it decreased within the same interval[28]. With the aid of the FLUENT software, a numerical simulation was conducted based on Computational Fluid Dynamic (CFD) to estimate the heating and cooling capacity of earth-air-pipe heat exchanger systems[29,30]. An additional study of a model used a one-dimensional transient analytical approach to detect the influence of burial depth on the thermal performance of EAHE systems[31].

According to Nayak et al.[32] another study evaluated EAHE system for greenhouse heating. The system in that study combines a photovoltaic/thermal collector (PV/T) and an EAHE in different configurations. During the winter months, it was seen that the greenhouse's interior temperatures rose by around 7.1-8.2 °C at night. It is worthy to note that different European countries have licensed REHAU Ecoair™ for the implementation of the EAHE system when constructing large-scale buildings. Beneath a TESCO supermarket building in Zdzieszowice, Poland, there were 0.2 m heat transfer pipes with 0.5 m header pipes. Regarding that project, REHAU used an EAHE system to address heating and cooling needs of 3,250 m^2 of this building space. Heat transfer and header pipes combined to have total lengths of 700 m and 50 m, with 2700 m^3/hour air flow, respectively. A temperature of 15 °C increment in air temperature (from -2 to 13 °C) in the winter season was achieved with this system. This provided nearly half of the annual heating demand and was estimated to save 2,000 € per year. Additionally, the system generated an annual cooling output of 10,700 kW h, which increased the savings by € 1,000 from the conventional air conditioner[33]. In the Italian climate, an EAHE system was also used for both cooling and heating of an office building. The study concluded that it is an economical and feasible system[34]. An experimental study of an EAHE was conducted in France for heating and cooling purposes of the dining room of floor area 380 m2. This system was combined with 11 pipes which were buried under the ground. The diameter of the pipes and their depth were 0.2 m and 2 m respectively. The result was 14 kW of cooling power at a flow rate of 7200 m^3/hour throughout the months of July and August[35]. Rodrigues et al.[36] created a transient, numerical model that simulates the thermal performance of an

EAHE system for several soil types at three distinct locations in a Brazilian coastal area. For the modeling of the air flow inside the tube, as well as the calculation of the air temperature inside the tube, a set of differential equations defining continuity, momentum, and energy was used. For the soil temperature distribution, heat conduction equations were utilized.

Siepsiak[37] evaluated an EAHE technique in Poland for about three years, with energy efficiency as an indicator in several freshening scenarios. The system provided approximately 124 W of cooling per hour and 257 W of heating. This highlighted the system's capability in improving indoor thermal comfort. The outcomes were useful to identify the ideal HVAC system scenarios for engineering designs. Brata et al.[38] evaluated the performance of a EAHE in Timisoara, Romania. The system featured a 35 m long exchanger pipe with a 0.2 m diameter, buried at a depth of approximately 2 m. During winter, it supplied around 31% of the energy required by the ventilation system. A research conducted by Amanowicz and Wojtkowiak for multi-and single pipe EAHE systems in Central Europe, concentrated on energy gains and power usage. The findings indicated that a multipipe EAHE can effectively alternate with a single-pipe system while maintaining similar thermal efficiency and pressure losses, provided that a tube with the appropriate diameter is selected. Thus, more appropriate for temperate climates[39]. Another investigation[40] examined the efficiency of an EAHE system in Bechar, Algeria. The setup had a PVC pipe with a diameter of 11 cm and 66-meter-long, buried at 1.5 m under the ground. During the humidification, this system achieved an increment of 19% in relative humidity and a drop of 27% during dehumidification. These findings highlight the EAHE's capability to improve hygrometry of buildings in arid regions. A study of EAHE systems with pipe lengths between 67 and 107 m, buried at approximately 2 m, and functioning under different air velocities (500 m^3/h, 2500 m^3/h and 3000 m^3/h) was conducted in Germany. A variation of 16 to 51 kWh/m^2 was realized for the yearly heating energy outcome of the system, while between 12 and 23.8 kWh/m^2 was reported for the annual cooling energy gain[41].

Kaushal[42] conducted an experiment in the Lower Himalayan region, where an EAHE system with 0.5 m/s airflow rate and pipe length of 60 m demonstrated a peak heating potential of around 28 kWh and cooling potential close to 15 kWh. The EAHE system also contributed to reducing energy consumption for heating by approximately 25–30%[43]. Xiao et al.[44] investigated the thermal behavior of an EAHE system integrated into a greenhouse in Northern China. The research merged CFD simulations with experiments to assess the system's effectiveness across different seasons. The outcomes of the investigations indicate that the EAHE system raised the greenhouse's night-time air temperature by 1.4 °C in winter, while in summer it decreased the daytime air temperature by 2 °C. Furthermore, the variations between the EAHE's inlet and exit air temperatures were 9.3 °C in winter and 10.6 °C in summer with an efficiency of 22.49% and 23.52%, respectively. Another study by Jilani[45] utilized CFD simulations to evaluate a Quonset-type greenhouse integrated with thin-film photovoltaics (GiTPV) and an EAHE system. The results demonstrated that the EAHE could enhance the greenhouse air temperature by 8.2 °C and the plant temperature by 9.1 °C at a mass flow rate of 0.5 kg/s. The GiTPV system enables self-sustainability in cold climates by delivering daily electrical energy production of 15 kWh. Khorchef et al.[46] employed a full factorial design to identify optimal configurations of EAHEs for winter and summer. The focus was on three variables, airflow, pipe length and thermal conductivity. The research highlights that air velocity has a considerable influence, thermal conductivity had a lesser, but still significant impact while pipe length had the most significant influence on the temperature regulation. The pipe length accounted for more than 59.3% of variability in winter and 49.5% in summer.

Goyal et al.[47] designed and analyzed a unique bank-type EAHE in an experimental setting. The research aimed to assess its effectiveness in the hot, dry, and humid climate of Ferozepur, India. With a decrease in ambient temperature to 29 °C, this study demonstrated an improved accuracy compared to previous investigations. Zhang et al.[48] investigated the operation and energy efficiency of EAHEs in Lanzhou, China. Applying orthogonal simulation, the research identified that the optimal system parameters are 7 m/s as airflow velocity, 20 m pipe length, 4 m burial depth and diameter of 0.1 m. These selection enhanced heat transfer efficiency by 38% and reduce unit heat transfer cost by 8,000 CNY/kW compared to the original design.

Table 1: Summary of new case studies on the EAHE behaviour in different sites.

Authors	**Location**	**Performance achieved / design parameters**	**References**
Siepsiak	Poland	The system supplied around 124 W of cooling per hour and 257 W of heating.	[37]
Brata et al.	Timisoara, Romania	The system has a pipe length of 35 m with a 0.2 m diameter, buried at a depth of approximately 2 m. During winter, it provided around 31% of the energy required by the ventilation system.	[38]
Sakhri et al.	Bechar, Algeria	The system had a length of 66 m, PVC pipe with a diameter of 11 cm and, buried at 1.5 m under the ground. During dehumidification this system achieved a drop of 27% and during the humidification, an increment of 19% in relative humidity.	[40]
Pfafferott	Germany	Pipe lengths between 67 and 107 m, buried at approximately 2 m, and functioning under different air velocities (500 m^3/h, 2500 m^3/h and 3000 m^3/h). Outcome of the system was between 12 and 23.8 kWh/m^2 as the annual cooling energy while,16 to 51 kWh/m^2 is as a yearly heating energy.	[41]
Kaushal	the Lower Himalayan Region	The setup has 0.5 m/s airflow rate and pipe length of 60 m. It demonstrated a peak heating potential of 28 kWh and cooling potential close to 15 kWh. The system contributed to reducing energy consumption for heating by almost 25–30%	[42], [43]
Xiao et al.	Northern China	The differential between the input and outlet air temperatures of the EAHE was 9.3 °C in winter and 10.6 °C in summer, with an efficiency of 22.49% and 23.52%, respectively.	[44]
Goyal et al.	Ferozepur, India	Assess EAHE effectiveness in the hot, dry, and humid climate. It show a decrease in ambient temperature to 29 °C	[47]
Zhang et al.	Lanzhou, China	The optimal system parameters are 20 m pipe length, 7 m/s as airflow velocity, diameter of 0.1 m and 4 m burial depth. This design reduce unit heat transfer cost by 8,000 CNY/kW and improved heat transfer efficiency by 38%.	[48]

2. EAHE system: Operating principle and Ground Temperature Profile

The fundamental concept of EAHE is based on multi- or single pipes that are buried under the ground. One terminal of the pipe system (the inlet) serves as an ambient outdoor air entry point, while the opposite terminal (the outlet) evacuates air into the inside of a building. Fresh air enters through the pipe inlet, moving within the pipe and exchanging heat with walls of the pipe which are in contact with the underground soil. In this manner, the air in the tube is conditioned as it travels down the pipe. Heat is transferred then by convection to or from the soil around it and by conduction in the pipe wall [49,50].

Profile of ground temperature indicates how soil temperature changes at different depths under the surface (Figure 1). It generally displays the fluctuations of temperatures near the surface which is in response to daily and seasonal variations. Meanwhile, deeper levels tend to sustain more consistent temperatures over the year. This profile plays an important role in the design of EAHE systems.

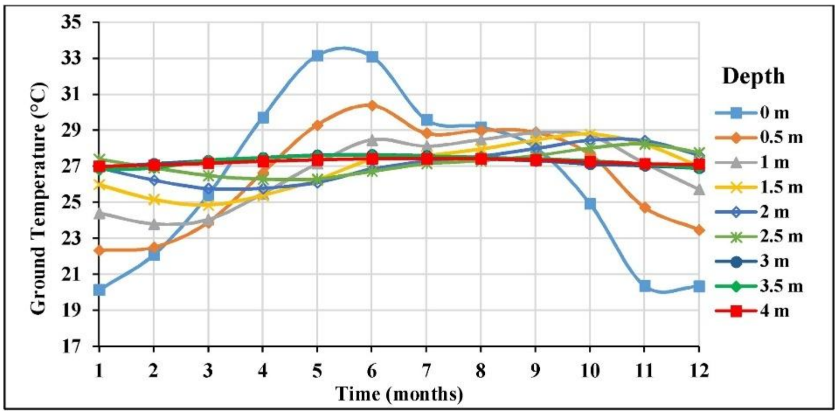

***Figure 7: Annual variation in temperature distribution at different depths in Ajmer, India**[51]*

3. Classification of the EAHE

The significant advancements of EAHE leads to diverse system types recognized by changes in configurations, materials and control strategies. The classification of this technology can be based on pipe orientation, pipe material, pipe configuration and airflow configuration. In addition to the factor of development in control strategies: combination and integration with renewable energy sources and automated control systems.

EAHE as sustainable solution can be effectively used alone, but recently, hybrid configurations is often selected. Several researchers are working on combining EAHE with various passive techniques to enhance system performance. Figure 2 presents the classification of this technology that aids in comprehending the development and optimization of EAHE systems.

The EAHE technique can be classified based on two macro categories:

a. Source of air entering the system:

- ***Open- loop system:*** the outdoor ambient air (fresh air) is passing through the EAHE pipes. While, the air is drawn into the buried pipes, it transfers thermal energy with the adjacent soil before it enters the room (Figure 3.(a)).
- ***Closed- loop system:*** recirculating indoor air is used rather than fresh air. The air is extracted from the inside of the building, transported through the subterranean pipes to facilitate heat exchange with the surrounding soil, and then returned to the building (Figure 3.(b)).

Based on the literature, the open-loop system is often chosen over the closed-loop system since it provides fresh air[52].

b. Pipe layout:

- **Horizontal EAHE system (HEAHE):** defined by the installation of pipes in parallel to the ground surface (horizontal lines). It presents specific benefits. Among them, its simplicity in the implementation in regions where groundwater levels are shallow. Though, it requires large ground space, this system still easier and cheaper to install. Particularly, in open spaces. However, its thermal efficiency may be affected by changes in soil temperature and moisture levels, which typically vary more strongly near the surface[53].
- **Vertical EAHE system (VEAHE):** the pipes are positioned in a vertical orientation within boreholes that extend deep into the ground. VEAHE are frequently favored in urban or highly populated areas where land is limited, as well as in situations that demand enhanced heat transfer rates[54]. This system offers multiple benefits more than the horizontal counterparts by tapping into deeper ground temperatures[55]. As the depth increases, ground temperature becomes less affected by external environmental conditions. This reduces the influence of seasonal surface temperature changes, leading to more consistent and reliable yearly heat transfer. That increase the system's overall performance[56,57]. However, it usually requires drilling equipment and is more expensive to install.

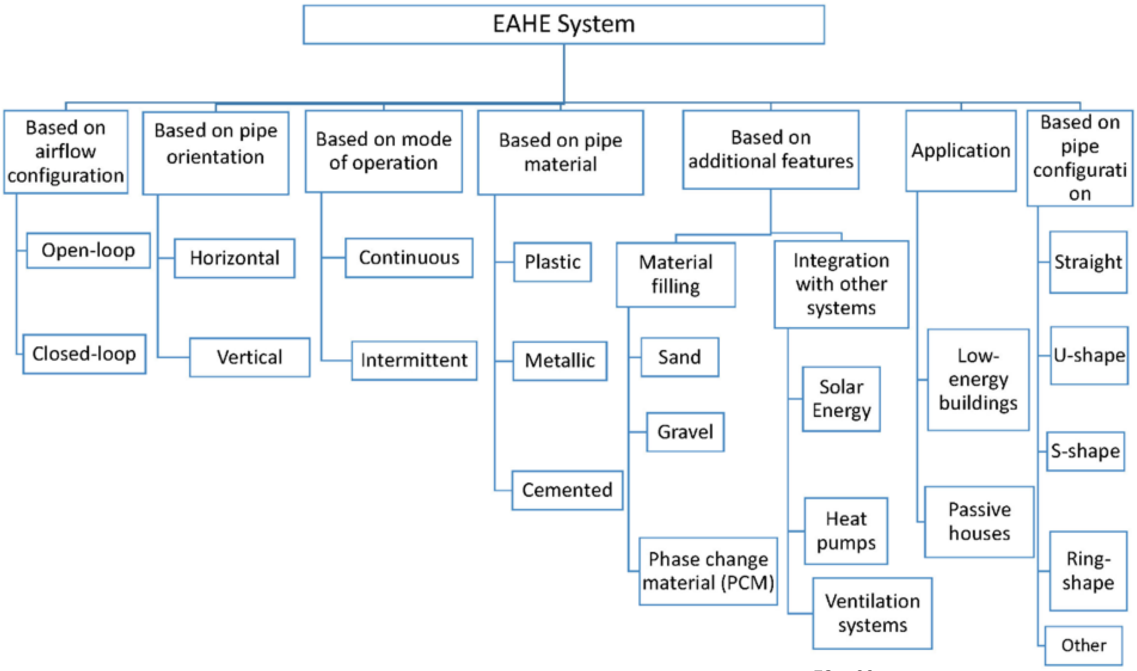

Figure 2: EAHE system classification[58 – 60]

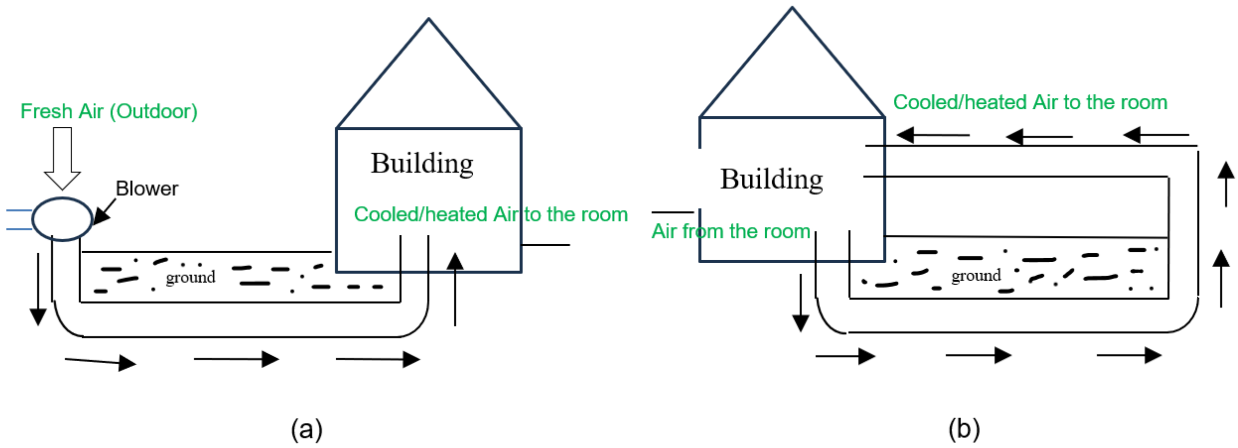

Figure 3: EAHE with (a) open loop and (b) closed loop

4. Heat Exchange Mechanisms within EAHE

a. Conduction and convection concept:

Heat exchange mechanisms enable the transmission of heat between the ambient air and the ground in EAHE systems. The fundamental principle of the operation of EAHE is based on two primary heat exchange mechanisms:

Conduction: using it as a means of transferring heat, the soil moves heat from warmer (higher temperature regions) parts to cooler parts (lower temperature regions). By passing through buried ducts or tubes in contact with the ground, the incoming ventilation air can gain or lose heat.

Convection: since the air and ground are at different temperatures, convection occurs when air flows through underground ducts. The heat exchange process is enhanced when cooler air absorbs heat from warmer ground and vice versa. Convection plays pivotal role in the heat transfer mechanisms for EAHE. This mechanism can be considered as natural convection. However, according to the literature, it is usually predominantly forced, driven by a mechanical blower responsible for moving the air within the pipes. Therefore, improving the heat exchange process. For example, Bansal et al.[61] analysed the performance of EAHE for cooling purposes by varying several factors (pipe material and air velocity). Their results presented that the air speed highly influenced the thermal behaviour of the system. In general, the effect of natural convection is negligible (minor) when comparing it to the forced convection impact.

Through a combination of these mechanisms, the ground temperature moderates the incoming ventilation air's temperature, bringing the indoor temperature closer to equilibrium and achieving a more comfortable indoor environment.

b. Fundamental equations in the EAHE physical model:

Heat transport and fluid dynamics define the performance of an Earth–Air Heat Exchanger (EAHE) system. Mass, momentum, and energy conservation are the basic equations applied in EAHE system modeling of physical phenomena. The following are the key equations typically applied:

- ***Energy Balance of the Air Stream***

Under the assumption of steady-state, one-dimensional flow with minimal axial conduction, the energy balance can be expressed as:

$$\frac{\partial Ta}{\partial t} + v\frac{\partial Ta}{\partial x} = \frac{hP}{\rho_a c_{p,a} A}(Ts - Ta)$$

where: *Ta*: temperature of air inside the pipe (K), *Ts*: temperature of the pipe wall or surrounding soil (K), *x:* distance along the pipe (m), *v*: velocity of air (m/s), *h*: convective heat transfer coefficient (W/m²·K), *P*: inner perimeter of the pipe (m), *A*: cross-sectional area of the pipe (m²) and ρ is the air density (kg/m³).

- ***Forced Convection and Thermal Conductivity:***

The process of heat transfer from the air to the inner wall of the pipe is dictated by forced convection. The convective heat transfer coefficient *h* is frequently determined through the Dittus–Boelter equation:

$$h = \frac{Nu.ka}{D} \quad \text{where } N_u = 0.023. Re^{0.8}. Pr^{0.3}$$

with: *Nu*: Nusselt number, *Re*=$\frac{\rho v D}{\mu}$: Reynolds number, $r = \frac{C_p \mu}{ka}$: Prandtl number, *h*: convective heat transfer coefficient (W/m²·K), *ka*: thermal conductivity of air (W/m·K), *D*: pipe diameter (m), *ρ*: air density (kg/m³), *v*: air velocity (m/s), μ: dynamic viscosity of air (Pa·s) and *cp*: specific heat of air (J/kg·K).

The adjacent soil is considered a semi-infinite medium, facilitating radial heat conduction from the buried pipe. The transient heat conduction in cylindrical coordinates is described as follows:

$$\frac{\partial Ts}{\partial t} = \alpha s \left(\frac{\partial^2 Ts}{\partial r^2} + \frac{1}{r}\frac{\partial Ts}{\partial r}\right)$$

where: *Ts*: temperature of the soil (K), *r*: radial distance from the pipe center (m), αs: thermal diffusivity of soil (m²/s), *ks*: thermal conductivity of soil (W/m·K) and *ρs*: soil density (kg/m³).

- ***Heat Transfer Equation in a Buried Pipe:***

The total heat transferred to the air while passing through a buried pipe is expressed as follows:

$$Q_h = \dot{m} C_p (T_{out} - T_{in})$$

where: $\dot{m}$ is air mass flow rate (kg/s), C_p is air specific heat (J/kg.K), T_{out} is EAHE pipe outlet air temperature (°C), and T_{in} is EAHE pipe inlet air temperature (°C).

- ***Pressure Drop in the Earth-to-Air Heat Exchanger (EAHE)***

The pressure drop in the pipe due to friction is a key factor in EAHE performance, as it affects fan power consumption. It is typically calculated using the Darcy-Weisbach equation:

$$\Delta P = f\frac{L}{D}.\frac{\rho v^2}{2}$$

with: ΔP: pressure drop (Pa), L: length of the pipe (m), D: internal diameter of the pipe (m) and $f = \frac{64}{Re}$ if Re < 2300 while $f = 0.3164 . Re^{-0.25}$ if Re > 4000[62,63]

The effectiveness ε of an EAHE system quantifies how efficiently the system transfers heat between the air and the ground, relative to the maximum possible heat transfer and it can be calculated as:

$$\varepsilon = \frac{Tout - Tin}{Tsoil - Tin}$$

where: *Tout*: temperature at the outlet of the pipe (°C), *Tin*: temperature at the inlet of the pipe (°C) and *Tsoil*: is soil temperature (°C).

5. Advantage of the EAHE system

EAHE systems provide an eco-friendly method for energy conservation by using the soil's consistent temperature for heating and cooling purposes. They serve multiple benefits:

- By harnessing the stable subterranean temperature to pre-treat incoming air, when it is functioning as a primary element unit to another HVAC system. It plays an important role in reducing the load of such HVAC system, contributing to significant energy savings in both heating and cooling seasons.
- Supporting sustainability and environmental protection aspect by cutting down energy consumption from conventional systems and reduces greenhouse gas emissions.
- It enhances building thermal comfort and indoor air quality.
- Featured by improving building energy saving when it is combined with other renewable energy technologies (e.g., solar chimneys, heat pumps).

6. Impact of design parameters on the EAHE performance

a. Soil’s undisturbed temperature

The soil's stable temperature is a crucial factor in the construction of an EAHE system. Given homogeneous soil with constant thermal diffusivity, the temperature at each depth z and time t may be approximated by the following formula [64,65]:

$$T_{z,t} = T_m - A_s \exp[-z \left(\frac{\pi}{365\alpha_s}\right)^{\frac{1}{2}}] \cos\{\frac{2\pi}{365}[t - t_0 - \frac{z}{2}\left(\frac{365}{\pi\alpha_s}\right)^{\frac{1}{2}}]\}$$

where temperature of the ground at depth z (m) and time t (s) is denoted at $T_{z,t}$, whereas T_m represents the average soil surface temperature (°C). The amplitude of soil surface fluctuation (°C) is denoted as A_s, and α_s representing soil thermal diffusivity (m²/s; m²/day), t signifies the time passed from the commencement of the calendar year (day), and t_o indicates the phase constant of the soil surface (s; days).

Accurately calculating the value of soil's undisturbed temperature is challenging due to the frequent lack of knowledge regarding soil properties. Furthermore, it is specified for average soil characteristics.

Thus, the undisturbed temperature of the soil is a theoretical value that may be regarded as equivalent to the yearly average soil surface temperature of a certain area. Additionally, usually the soil surface temperature is presumed to be equivalent to the ambient air temperature.

b. Impact of Burial Depth

The ground's temperature shows substantial depth-dependent fluctuation[66]. To maximize system performance while reducing installation costs, it is necessary to determine the ideal burial depth for EAHE systems. A clear temperature gradient where temperatures decrease as the depth increases have been noted in many investigations[67–69]. Nonetheless, it was noted that the enhancement in performance was minimal beyond depths of 4 m[70–72]. Variations in depth are impacted by variables including local ground temperature profiles, soil characteristics, and climatic conditions. Sanusi et al.[73] determined that 1 m is the ideal depth in Malaysia, while Khan et al.[74] advised 4.5 m for Lahore, Pakistan and Babar et al.[75] suggested 3.96 m as suitable for Sahiwal, Pakistan. In another investigation, Badescu[76] concluded that the depth of the buried pipe enhances the thermal potential of the system, however limited to a maximum of 4 meters. Mihalakakou et al.[77] examined the impact of pipe depth on performance in cooling mode, implementing depths of 1 m, 2.1 m, and 3.2 m. The analyses revealed that a pipe positioned at a depth of 3 m gave the most effective cooling results. Wu et al.[78] conducted an examination on the effectiveness of the EAHE system at different depths of buried pipe. The temperature variations of the air were observed to range from 7.2 ˚C to 31.7 ˚C, and from 5.6 ˚C to 30.6 ˚C at depths of 1.6 m and 3.2 m of the pipe, respectively.

c. Impact of pipe diameter and length

Ghosal and Tiwari[79] examined the influence of buried pipe diameter and length, its depth and mass flow rate of air temperatures inside a greenhouse in addition to soil types. Based on the result an increment of pipe length between 30-50 m affected the EAHE performance directly. Consequently, a rise in air temperature during the winter and a drop during the summer were observed. The primary reason for this is that an extended pipe length provides a greater duration for thermal heat exchange to occur between the air within the pipe and the ground[80.] Simultaneously, regarding the impact of the underground pipe diameter of the EAHE, an increase in diameter leads to reduced greenhouse air temperatures in winter and higher temperatures in summer. This phenomenon is attributed to the reduction in heat transmission from the soil or a decreased convective heat transfer coefficient resulting from an increase in pipe surface area and a decrease in air flow velocity. Another investigation[81] confirms that the diameter of the pipe plays a crucial role in determining the thermal efficiency of environmentally sustainable technology. At specific depths, the temperature of the basement stays stable, exhibiting higher values during the winter months and lower values in the summer. Ahmed et al.[82]examined the influence of pipe diameter on the thermal performance of a horizontal earth pipe system, utilizing pipes with diameters of 0.400m, 0.200 m, 0.125 m and 0.062 m. They found that the smaller diameter pipe yields the most effective cooling effect.

Regarding the length of pipe effect, Agrawal et al.[83] observed that the EAHE air temperature decreases in the summer and rises in the winter season as the length of the pipeline increases. Yet, the performance rate fluctuates based on climatic conditions and geographical location. In this experiment, it was observed that for the 50 m pipeline length, the outlet temperature of the EAHE system consistently matched the basement temperature. Bansal et al.[84] performed an analysis of thermal performance for different lengths of EAHE pipes in India. The study also examined the impact of soil thermal conductivity and the duration of continuous EAHE operation. The findings from an investigation by Zhang et al.[67] indicate that an optimal pipe length of 80 m is recommended to ensure effective pre-heating and pre-cooling performance for the EAHE-assisted building air conditioning system year-round. Given the balance between thermal efficiency and construction expenses of the EAHE system, an additional increase in pipe length might not result in beneficial results. In this investigation the influence of pipe diameter was also conducted. It ranges from 100 mm to 200 mm, affecting the airflow rate within the buried pipe. Increasing the pipe diameter has a minor effect on outlet air temperature, resulting in a small rise during summer and a decrease in winter. The typical precooling performance and daily cooling capacity range from 9.5 °C to 9.2 °C and from 20.1 kWh to 19.5 kWh, respectively. Comparable outcomes can be noted during the heating season. In an EAHE system, the difference in air temperature between the inlet and outlet of the pipe is enhanced by extending the length of the pipe[85], while it diminishes with a rise in pipe diameter[8682]

d. Impact of material of the pipe

The conclusion drawn from various studies indicates that pipe materials selection primarily centers on the material's availability and associated costs. The outlet temperature of the buried pipe can be more effectively reduced by using materials with a higher thermal conductivity. Parametric research was conducted in EnergyPlus software to compare several pipe materials, specifically PVC, polyethylene (PE), clay, Polyvinyl Chloride (PVC) and brick[73]. This research expands the classification of subterranean pipelines. The results indicated that clay pipes produce the lowest output air temperature between the four types of pipes. In another side, Bansal et al.[87] examined the thermal capacity and evaluated the air conditioning potential of two EAHE systems constructed mostly from steel and PVC materials. The authors determined that the pipe material had no strong effect on the effectiveness of the EAHE system. Serageldin et al.[88] tested the efficiency of an EAHE in Egypt's hot and cold climate. A mathematical model for energy conservation based on one-dimensional, unsteady and quasi-state equation were used or produced?. In addition, a three-dimensional steady-state CFD ANSYS Fluent simulation model for predicting air and soil temperatures have been developed. Three various pipe materials were utilized: PVC, steel, and copper. Output air temperatures were 19.8 °C for copper and steel and 19.7 °C for PVC pipe. This led to the conclusion that there is no noticeable difference in the output air temperature for the different pipe materials. Menhoudj et al.[89] conducted a comparison of the performance of the EAHE system using two pipe materials, Zinc and PVC. The findings indicated that the air temperature drop was 6.5°C for the Zinc pipe and 6°C for the PVC pipe. Consequently, the cost of the pipe material and its lifespan come out as the most important factors in the selection process, rather than the heat transfer properties. All the above-stated research results presented that the material of the pipe has a minimal (negligible) effect on the thermal performance of the EAHE system.

e. Impact of air flow

The airflow rate predominantly dictates the system's capability for cooling or heating and its overall performance[90,91]. Benrachi et al.[92] demonstrated that an increase in velocity of the wind from 2 m/s to 2.5 m/s led to a significant reduction in cooling effectiveness, dropping from 60% to 33%. Furthermore, Bhandari et al.[93] investigated how airflow velocity affects heat transfer rates, showing that a reduction in velocity and an increase in diameter lead to a lower pressure drop across the pipe length throughout airflow. Bansal et al. examined the influence of flow velocity (2.0, 3.2, 4.0, and 5.0 m/s) and contrasted the simulation results with the experimental data obtained. The outcomes showed a reliable agreement between experimental data and simulated results. Using a pipe length of 24 m gives cooling performance vary from 8 to 13 °C for the above speeds air[61,87]. Dubey et al.[94] observed a decrease in air temperature from 9 to 4.2 °C, alongside a reduction in the coefficient of performance (COP) from 6 to 3.7 as the air velocity varied from 4 to 12 m/s. A mathematical parametric study was carried out by Ahmed et al.[82] employing four separate airflow rates to assess the impact of air velocity on the thermal performance of the pipe–Earth technique during the cooling process. The report indicated that an air flow of approximately 1.4 m/s was the optimal choice for summer efficiency. Other studies by Mihalakakou et al.[95–97] documented how air velocity affects the EAHE system's ability to maintain thermal comfort. The researchers looked at the EAHE system's evaporative temperature and how it changed in response to a modest change in air velocity. It has also been noted that the system's heating capacity decreases as the air velocity increases. The effectiveness of an EAHE system may be measured by the number of Reynolds, according to Abdelkrim et al.[98]. They found that when the Reynolds number increases, the out-flow air temperature rises because the air residence time within the pipe reduces.

7. Effect of soil properties on the EAHE's system performance

The thermo-physical qualities of the soil have a significant impact on the thermal performance of an EAHE system. Soil thermal conductivity and diffusivity are two important parameters of the EAHE system. Due to the high temperature difference and rapid heat transfer rate, the system performs better as the thermal conductivity increases. High thermal diffusivity, on the other hand, increases the quantity of heat transmission from soil to pipes via conduction and from pipes to air via convection[17,51]. Thermal conductivity, specific heat, and density of soils are the most important thermo- physical properties that determine the performance of the EAHE system. Therefore, as the most important soil property for the EAHE system, thermal diffusivity plays a significant role. Because heat accumulates in the soil layers near the pipe and does not transfer to the next layers quickly, the soil gradually becomes thermally saturated, reducing the performance of the EAHE system[99]. There is a direct correlation between thermal conductivity and thermal diffusivity of soil. The investigation of Mathur et al.[100] present that soil with a higher thermal diffusivity transfer heat more rapidly from nearby soil to outer subsoil, which increases heat transfer rates. In this study the thermal performance of EAHE systems was evaluated using three different soil thermal diffusivities: $1.37\times10^{(-7)}$ m^2/s,$4.37\times10^{(-7)}$ m^2/s and $9.69\times10^{(-7)}$ m^2/s. It is important to note that soil thermal conductivity is significantly affected by temperature. In the study by Bansal et al.[84] the impact of duration of operation and the thermal conductivity of the soil on the EAHE performance was analysed by choosing 3 different soils. They highlighted the significance of involving soil thermal characteristics in the design and functioning of EAHE. They observed that even during extended continuous operation, EAHE system installed on soil with enhanced thermal conductivity has higher thermal performance. The phenomenon of improved thermal behaviour of soil characterised by high thermal conductivity is attributed to the fast dissipation of heat from the soil layers Moreover, Donde and Maurya[101] experimentally characterised the thermal property of soil for EAHE applications. They investigated the influence of different soil types on the system performance, particularly, assessing the soil's potential to store or dissipate heat. Their results stated that for prolonged continuous operation of EAHE, the soil with lower thermal storage capacity but higher thermal conductivity and diffusivity, is preferable. This soil may rapidly transfer heat from the pipe, ensuring a greater difference in temperature between the air within the pipe and the adjacent soil. Therefore, enhancing heat exchange efficiency.

8. Opportunities of integrating EAHE with other system (Future work):

In recent years, research and development towards energy saving has grown as a significant focus for researchers worldwide. For efficient energy saving, the use of EAHE as primary pre-conditioning unit to another system should be more analyzed.

Besides conditioning air for indoor comfort, the EAHE system may be modified for preheating the combustion air supplied to boilers, furnaces, or industrial burners in winter. This is particularly advantageous in settings where external temperatures fall significantly beyond the soil temperature; where the cold ambient air is drawn through the pipes of the EAHE and absorbs heat from the warmer ground. The preheated air is then fed into the combustion chamber. This reduces the energy needed to reach optimal combustion temperatures and provides complete combustion and lower emissions; helps in fuel saving while improving combustion quality.

In another applications, when combining passive geothermal energy with active air distribution, EAHE may be linked with an Air Handling Unit (AHU) to raise the energy efficiency of heating, ventilation, and air conditioning systems in buildings[102]. In this configuration, outdoor air is sent through underground pipes, typically located 1.5 to 4 m deep, where it participates in heat exchange with the surrounding soil. The air is cooled or heated depending on the season. Later, the temperature-moderated air exits the pipes and is delivered to AHU. It additionally filters, humidifies or dehumidifies, heats, or cools the air as necessary to achieve the preferred indoor comfort conditions. The AHU afterwards distributes the treated air within the building using several terminals. This will result in various benefits. For instance, in energy savings where it decreases the thermal load on the AHU by pre-conditioning the air; reduces the HVAC size and enhances comfort due to the better stable and comfortable indoor air conditions.

Conclusion

With the growing demand for sustainable building solutions and energy saving, EAHE systems are likely to become more widely adopted in the future. An overview of the EAHE system has been provided in this study, along with some important parameters to consider. These are the key conclusions.

- The EAHE system can provide adequate cooling and heating for small and large buildings with substantial energy savings.
- The performance of EAHEs is affected by various factors, such as the type of soil, the depth and length of the system, the airflow rate, and the thermal properties of the heat exchanger. This technology should also be designed to minimize heat losses during the heating and cooling cycles, to maximize the system's efficiency.
- The cooling and heating capacity of the EAHE system increases with installation depth. However, beyond a certain depth (more than 4 m), no substantial enhancement in performance is expected. Rather, the excavation cost of the trench escalates with the depth of the pipe.
- Research findings indicate that the pipe material has a minimal (negligible) effect on the thermal performance of the EAHE system. Consequently, the expense of the pipe, its longevity, and its corrosion resistance are essential criteria for choosing the pipe material.
- PVC pipe is favored for the EAHE system due to its low cost, flexibility, superior corrosion resistance and ease of installation.
- The length of the buried pipe plays a critical role, as it directly affects the heat transfer surface area and the residence time of the air-fluid. Therefore, the extended pipe offers an extensive route for heat transfer and 80-120m is the recommended pipe length.
- EAHE pipe with a smaller diameter offers the most effective cooling and heating impact.
- A higher moisture content and good thermal conductivity of the soil surrounding the EAHE pipe can improve the performance of the system. Thus watering the ground is a suitable solution to raise the thermal conductivity of the soil.
- Better thermal performance is achieved at lower air velocities compared to higher flow rates. This phenomenon occurs because the air remains in contact with the surrounding soil for a longer duration, allowing more effective heat exchange. In contrast, at higher velocities, the reduced residence time limits the air's ability to reach thermal equilibrium with the soil.
- A system such as this should be used in extreme atmospheric conditions since the temperature difference between the ambient air and undisturbed ground will be greater.

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Skúmanie vzduchového výmenníka tepla ako inovatívnej a udržateľnej aplikácie na chladenie a vykurovanie: výbery z literatúry

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Súhrn

Energetické potreby a alarmujúce emisie CO2 na celom svete pritiahli značnú pozornosť k vývoju a implementácii obnoviteľných zdrojov energie a systémov na úsporu energie. Dôležitým aspektom termodynamiky Zeme je, že jej teplota zostáva nízka a konštantná počas celého roka. V porovnaní s vonkajšími teplotami vzduchu. Teplota zeme sa používa v systémoch výmenníkov tepla zem-vzduch (EAHE) na predúpravu vzduchu pred jeho vstupom do budovy. Účinne znižuje spotrebu energie tradičných systémov vykurovania, vetrania a klimatizácie (HVAC). Tento článok poskytuje stručný prehľad aplikácie technológie EAHE pri vykurovaní a chladení priestorov. Článok tiež zdôraznil vplyv rýchlosti vzduchu, priemeru, hĺbky, typu materiálu a dĺžky zakopaného potrubia na tepelné správanie systému EAHE. Výkon EAHE nie je výrazne ovplyvnený materiálom potrubia, na rozdiel od dĺžky a priemeru potrubia. Zistenia naznačujú, že najúčinnejší chladiaci a vykurovací účinok zabezpečujú potrubia s menšími priemermi. Okrem toho je svedčiace o tom, že dlhšie potrubia zlepšujú chladiaci/vykurovací výkon v systéme EAHE. Celkovo dostupné finančné prostriedky na výstavbu určujú typ materiálu a dĺžku potrubia, ktoré sa majú použiť pre efektívny systém EAHE. Nižšie rýchlosti vzduchu poskytujú vyšší tepelný výkon ako vyššie prietoky. Okrem toho integrácia EAHE s inými systémami HVAC môže zvýšiť úsporu energie. Tieto systémy môžu typicky prispieť k zníženiu spotreby energie na vykurovanie približne o 25 – 40 %. Toto percentuálne rozpätie by mohlo viesť k účinnosti EAHE takmer 0,9.

Klíčová slova: *Teplota pôdy; systém výmenníka tepla zem-vzduch; udržateľná energia; tepelná pohoda; vykurovacie a chladiace systémy; obnoviteľná alebo zelená energia.*

Recyklácia textilu z automobilov po dobe ich životnosti a jeho možnosť využitia v praxi

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Súhrn

Rozvoj automobilového priemyslu vo svete, ako aj v Slovenskej republike, je kľúčový pre prosperitu a celkový rozvoj spoločnosti. Na Slovensku sa automobilový priemysel vypracoval na popredné miesto medzi jednotlivými odvetviami priemyslu vďaka štyrom (v budúcnosti už piatim) finálnym výrobcom. V príspevku sa autori zamerali na klasifikáciu problematického odpadu z automobilov po skončení ich životnosti z pohľadu jeho ďalšieho zhodnotenia, konkrétne na recykláciu textilných materiálov. Experimentálna časť v príspevku je zameraná na aplikácie a predikciu využitia vybraných problematických textilných odpadov z pohľadu ich zhodnotenia (v kompaktnom a sypkom stave), na vyhodnotenie vykonaných experimentov s využitím regresnej a korelačnej analýzy pri produktoch na zvukovú a tepelnú izoláciu. Autori príspevku sa vo svojej práci zamerali na výskum možností využitia rôznych textílií aplikovaných v automobiloch s cieľom využitia recyklovaných materiálov týchto textílií na vývoj zvukovo a tepelnoizolačných materiálov so širokým spektrom aplikácií.Závery výskumu preukázali vhodnosť daného materiálu pre uvádzané aplikácie.

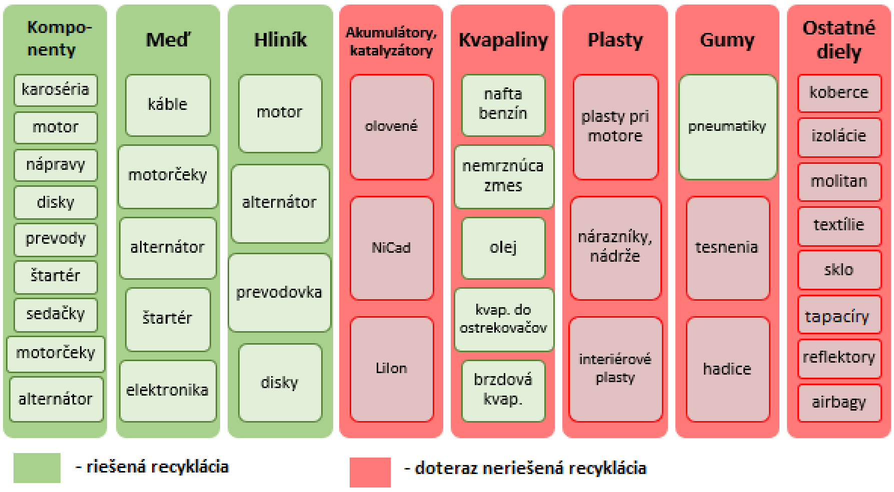
Kľúčové slová: *Automobilový priemysel, recyklácia textílií, koeficient zvukovej pohltivosti materiálu, index útlmu materiálu, tepelne izolačné vlastnosti materiálu*

Úvod

Vozidlá po skončení životnosti obsahujú celý rad komponentov (odpadov) rôzneho materiálového zloženia, ktoré by mali byť ďalej zhodnotené. Od 1. januára 2015 nadobudla účinnosť EU smernica 2018/849 a 2019/1020, ktoré menia smernice 2000/53/ES a 2005/64/ES. EU smernica 2018/849 stanovuje podrobné kvantifikované ciele pre výrobcov vozidiel a vybavenie automobilov, pričom musia pri navrhovaní a výrobe výrobkov prihliadať na demontáž, opätovné využitie a spätné získavania vozidiel. Výrobcovia musia zabezpečiť, aby boli nové vozidlá opätovne použiteľné a/alebo recyklovateľné na najmenej 85 % podľa hmotnosti vozidla a opätovne použiteľné a/alebo spätne získateľné na najmenej 95 % podľa hmotnosti vozidla.

V smernici sa vymedzujú opatrenia, ktorých cieľom je prevencia a obmedzenie odpadu z vozidiel po dobe životnosti a z ich súčiastok cez opätovné využívanie, recykláciu a spätné získavanie. Rovnako sa ňou stanovuje cieľ prispieť k udržateľnosti životného prostredia všetkými kooperujúcimi firmami zapojenými do životného cyklu vozidiel. [1, 2, 3]

Tieto požiadavky prinútili výrobcov automobilov zohľadniť použitie udržateľných materiálov vo výrobe. Na obrázku 1 je uvedený prehľad najpoužívanejších materiálov v automobiloch. ako sú napríklad prírodné vlákna, najmä na zvukovú a tepelnú izoláciu. Autori príspevku sa v nasledujúcich častiach zamerali na recykláciu textilu z automobilov. Schopnosť textilného materiálu izolovať mechanický hluk, vibrácie a udržiavať tepelné izolačné vlastnosti interiéru vozidla prispieva ku komfortu pri jazde a k výrazným energetickým úsporám z hľadiska využívania klimatizácie. Textil sa používa na podlahové krytiny, pod sedacie poťahy, na obloženie dverí, palubné panely, v motorovom priestore a na strope a pod. Vnútorné časti automobilov využívajú netkané textílie, ktoré sa ľahko vyrábajú v rôznej hustote, hrúbke a tvaroch, a to vďaka ich nízkej hmotnosti, jednoduchému spracovaniu, flexibilite a pórovitosti [4, 5, 6]. V interiéri automobilov sa zvukovo absorpčné netkané materiály používajú na pripevnenie k rôznym komponentom, ako sú napríklad podlahový koberec, stropné obloženie, bočné časti batožinového priestoru, zadný kryt, výplne dverí, podlaha batožinového priestoru, ochrana kolies, prídavná rohož, izolácia palubnej dosky a podložky, obrázok 2 [7].

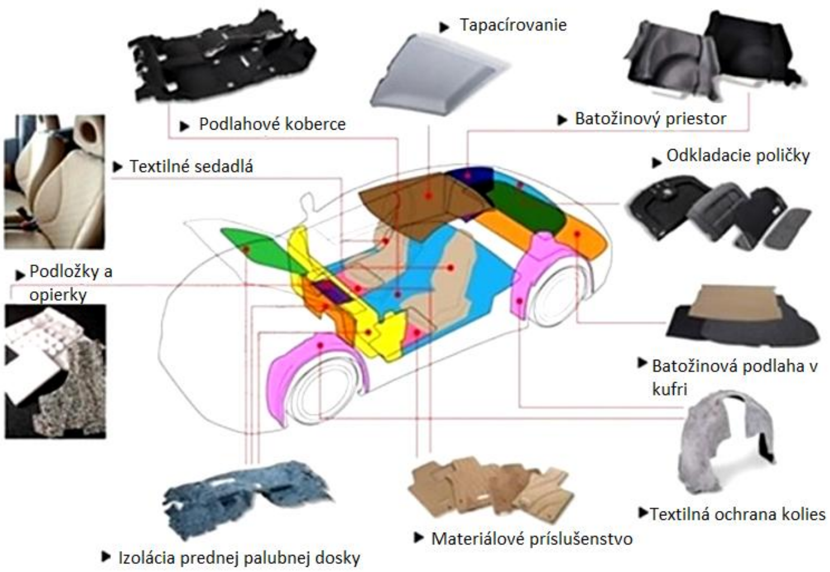


Obrázok 1: Prehľad najpoužívanejších materiálov v automobiloch

Netkané textílie používané v automobilových interiéroch majú vynikajúce vlastnosti v porovnaní s klasickými textíliami, ako sú nákladová efektívnosť, jednoduché tvarovanie, recyklovateľnosť a atraktívny pomer cena/výkon. Navyše je možné navrhnúť netkané textílie s konkrétnymi vlastnosťami, ako sú hrúbka, hmotnosť a objem [5].

Vďaka pórovitej štruktúre a veľkej povrchovej ploche sú netkané textílie vhodné pre technické textilné aplikácie, kde je potrebná absorpcia zvuku [4, 6].

Autori sa zamerali predovšetkým na problematické materiály z komponentov, ako sú pneumatiky, materiály z autosedačiek, kobercov, čalúnenia, airbagov a na vývoj technológií a postupov na zhodnocovanie odpadu do produktov pre akustickú a tepelnú izoláciu a iné využiteľné produkty [4, 6, 7, 8].



Obrázok 2: Vzorky textilných komponentov vo vozidle [4]

Technológie výroby zvukovo absorpčných materiálov a tepelne izolačných materiálov

Produkty z recyklovaných automobilových komponentov, ktoré je možné použiť na výrobu zvukovo absorpčných prvkov, zahŕňajú výrobky z recyklovaných pneumatík, autosedačiek, sedacích poťahov, kobercov a airbagov. Technológia recyklácie automobilových textílií alebo autosedačiek je špeciálny proces, ktorý je v podstate univerzálny pre následné zhodnotenie recyklovaných produktov spevňovaním, spájaním pod vplyvom tepla a tlaku [7, 9].

Environmentálnym prínosom recyklovaných produktov je ich použitie ako izolačných materiálov na báze recyklovaných textílií vďaka ich vysokej tepelná kapacite, čo znižuje požiadavky na vykurovanie a chladenie budov, zároveň znižuje množstvo textilného odpadu po zbere a môže čiastočne nahradiť výrobu izolácií z neobnoviteľných zdrojov. Vďaka nižším energetickým nárokom v porovnaní s klasickými minerálnymi izoláciami tiež znižuje uhlíkovú stopu výroby izolácií [9 - 16].

V ďalšej časti sa autori zamerali na využitie a spracovanie sekaných, strihaných textílií zmiešaných s plastami a gumou, drvenými textilnými kordami a drvenými materiálmi z autosedačiek a sedacích poťahov, t.j. na suroviny používané pri výrobe zvukovo a tepelnoizolačných prvkov [8]. Technológie na spracovanie a drvenie nových recyklovaných materiálov možno rozdeliť podľa použitých metód na :

- technológiu výroby lisovaním,
- technológiu výroby mikrovlnným ohrevom,
- technológiu výroby zvukovo absorpčných prvkov z mäkkej peny (polyuretánových pien),
- technológiu výroby a návrh produktov na báze sypaných granulátov [5,6,7].

Technológia výroby lisovaním využíva veľkoobjemové lisy – hydraulické alebo parné. Lisovanie sa vykonáva pod vysokým tlakom – minimálne 20,265 bar s ohriatymi lisovacími nástrojmi. Spodná časť je vyhrievaná na 120 °C, zatiaľ čo horná časť je zohrievaná na teplotu 90 °C. Lisovacia forma musí mať dobrý prestup tepla, t.j. zohrievanie formy a čas lisovaného materiálu musí byť čo najkratší. Zmes rozdrvených recyklovaných materiálov a spojiva sa pripravuje v mixéroch. Dávka surovín (drvená guma, textilné kordy, textílie, drvené autosedačky, sedacie poťahy alebo koberce) sa určuje na základe hrúbky jednotlivých vrstiev. Koncentrácia spojiva sa pohybuje medzi 12 – 16 % hmotnosti. Koncentrácia spojiva je určená podľa nasiakavosti materiálu a požadovanej tvrdosti produktu. Na urýchlenie chemickej reakcie viazania a spevnenia sa do spojiva pridáva katalyzátor v maximálnej koncentrácii 0,2 % hmotnosti. Ak je potrebná nehorľavá úprava, zmes sa obohacuje o 6 – 8 % spomaľovača horenia. Spojivo je založené na báze polyuretánu/polybutadiénu, zatiaľ čo spomaľovač horenia je na báze brómovej arómy a oxidu antimónu. Zmes textilných materiálov sa lisuje za horúca pod tlakom 12 – 15 minút v závislosti od hrúbky sendviča.

Nevýhodou tejto technológie je vysoká energetická náročnosť a pomerne dlhý technologický pracovný cyklus. Výroba jedného produktu trvá minimálne 25 – 30 minút, čo má vplyv na jeho cenu. Cena formy je tiež pomerne vysoká [6].

Technológia výroby sendvičov mikrovlnným ohrevom, nie je tak náročná ako lisovaním za tepla. Výhodou je podstatné skrátenie technologického cyklu z 12 – 15 minút na 4 – 5 minút. Nie je potrebné ohrievať formy na vysoké teploty ani aplikovať vysoký lisovací tlak či používať drahé formy. Podstata technologického procesu spočíva v príprave potrebnej zmesi v mixéri. Formy sú jednoduché a po uzatvorení sa pomocou dopravníka presúvajú do mikrovlnného tunela, kde dochádza k spojeniu vrstiev. Rýchlosť priechodu tunelom zabezpečuje, aby forma zotrvala v tuneli približne 4 – 5 minút. Napätie generujúce mikrovlny má približne 5 kV. Používa sa rovnaké spojivo, katalyzátor a spomaľovač horenia ako pri klasickom lisovaní. Pokusy nahradiť spojivo iným spojivom, napríklad na báze akrylátu, neboli úspešné. Hoci cena klesla (akrylátové spojivo je podstatne lacnejšie ako polyuretán/polybutadién), došlo k výraznému zhoršeniu tvrdosti produktov. Zvuková absorpcia sa mierne zvýšila, no produkty sa pri aplikácii rozpadali. Táto technológia umožňuje výrobu aj kombinovaných produktov, kde jedna z vonkajších vrstiev (zvyčajne spodná) môže byť z tvrdého materiálu, napríklad z pogumovaného betónu, Cetrisu alebo betónu. Vďaka jednoduchej konštrukcii foriem je technológia mikrovlnného ohrevu vhodná aj pre zložitejšie produkty z hľadiska tvaru, ako aj pre reliéfne povrchy. Produkty a technológia podliehajú autorským právam autorov projektu (úžitkový vzor č. 5721 „Kompaktné prvky z recyklovanej gumy vyrábané pomocou technológie mikrovlnného ohrevu“) [5].

Technológia výroby zvukovo absorpčných prvkov z mäkkej peny (polyuretánových pien) sú vyrobené prevažne z mäkkých, „pevnejších" materiálov z autosedačiek a sedacích poťahov. Vďaka vysoko pórovitej štruktúre má rozdrvený materiál vynikajúce predpoklady na výrobu zvukovo absorpčných prvkov. Vysoká pórovitosť materiálu vedie k vyššej spotrebe spojiva než v prípade spracovania drvenej gumy. Vysoká spotreba drahého spojiva je komerčne nezaujímavá. Dobrú zvukovú absorpciu bolo možné dosiahnuť pri hrúbke 20 mm. Nevýhodou produktov vyrobených touto technológiou je, že ich pevnosť klesá s ich klesajúcou hrúbkou. Proces spevňovania prebieha účinkom horúcej pary bez potreby vysokého tlaku ako je tomu v prípade lisovania. Táto technológia pozostáva z troch základných fáz: miešanie, naparovanie a tvrdnutie (dozrievanie). V procese "miešania" sa rozdrvené autosedačky a poťahy miešajú s lepidlom. Miešací cyklus trvá približne 10 minút a pripravená zmes sa vloží do formy. Po jej uzavretí nasleduje proces "naparovania". Pri "naparovaní" sa zmes spojí účinkom horúcej pary s teplotou 160 °C. Tento proces trvá približne 10 minút a počas neho sa zmes spevňuje. Naparovaná zmes sa nechá vytvrdnúť ďalších 10 minút a potom sa hotový produkt vyberie z formy. Najčastejšie sa vyrábajú bloky s hrúbkou 100 mm. Výrobný produkt je kompaktný a dostatočne pevný na to, aby sa mohol krájať na potrebnú hrúbku, dĺžku a šírku. Týmto spôsobom je možné vyrobiť produkty s hrúbkou 10 mm. Môžu sa vyrobiť aj produkty s vloženou výstužou, ako je kovová sieť alebo oceľové tyče, ktoré robia produkt samonosným, pričom hodnota zvukovej absorpcie sa nemení a technologický výrobný proces sa taktiež nemení [5, 6, 7].

Technológia výroby a návrh produktov na báze sypaných granulátov tvorí ďalšie možné riešenie pre použitie recyklovaných granulovaných (ale aj drvených, strihaných a trhaných) materiálov v akustických aplikáciách bez použitia spojív je ich využitie v protihlukových a tepelno izolačných bariérach vo forme sypaného materiálu. Predpokladom pre takéto využitie je vhodná konštrukcia panelu na ochranu proti hluku a tepelnú izoláciu a správna aplikácia sypaného materiálu s následným zhutnením.

Cieľom autorov projektu bolo čiastočne nahradiť nové materiály akusticky a tepelne vhodnými kompaktnými materiálmi, ktoré sú na báze recyklovaných materiálov z vybraných komponentov vozidiel po skončení ich životnosti, vyrobených pomocou lisovania pri určitých tlakoch a teplotách alebo bez použitia spojiva (spojenými len chemickou reakciu materiálov), sypanými materiálmi vyrobenými na báze granulátov z recyklačných procesov (sypaný granulát). Výhody použitia týchto tzv. „zelených" materiálov v akustických (a tiež tepelných) aplikáciách, ako sú protihlukové bariéry, v porovnaní s komerčnými materiálmi, spočívajú v kombinácii veľmi nízkej hmotnosti, vysokej fyzikálnej a chemickej stability, nízkych nákladov a vysokých hodnôt zvukovej absorpcie [5, 6, 7].

Experimentálna časť

Materiál – príprava textilného recyklovaného materiálu

Textílie v priemernom automobile tvoria až 2 – 2,5 % jeho celkovej hmotnosti, čo predstavuje 23 – 26 kg, pričom do roku 2025 sa očakáva nárast na 35 kg. Počas výroby nového vozidla vzniká 2,5 – 4 kg technologického odpadu. Medzi textílie z automobilov možno zahrnúť aj poťahy, textílie z detských sedadiel, airbagy a podobne.

Textilný materiál použitý na experimentálne testy merania tepelnoizolačných vlastností a meranie hluku bol dodaný spoločnosťou Stered PR Krajné, s.r.o. [5, 6].

V súčasnosti sa výskum zameriava na spracovanie a recykláciu automobilových materiálov v spolupráci so spoločnosťou Stered PR Krajné, s.r.o., kde boli vykonané experimenty. Experimenty sa začali výberom, zberom a uskladnením použitých odpadových materiálov z textílií, textilného odpadu z automobilov, ako je znázornené na obrázok 3. Ďalší krok spočíval v spracovaní odpadových textilných materiálov na približne rovnaké častice na deliacej a drviacej linke pomocou rezacích operácií, ako je znázornené na obrázku 4 [5, 6].

Obrázok 3: Triedený textilný odpad z materiálov z automobilov po dobe ich životnosti

Následne bol použitý proces formovania lisovaním, ktorý je zobrazený na obrázku 5. Konečný tvar kompaktného recyklovaného viazaného textilu je zobrazený na obrázku 6.

Obrázok 4: Textilný odpad po druhej operácii rezania a plnení foriem na lisovanie [6]

Obrázok 5: Forma na kompaktovanie textilu

Obrázok 6: Tvar recyklovaného textilu z formy

Všetky špecifické vlastnosti pôvodného materiálu sú prenesené do vlastností nového konštrukčného materiálu STERED. Výstupom recyklačnej jednotky je homogenizovaný produkt STERED S. Homogenizovaný materiál je tvarovaný do formátu dosky s pridaním spojiva na báze polyuretánového pre polyméru, ako je znázornené na obrázku 6. Vlastnosti produktu STERED S sú uvedené v tabuľke 1.

Tabuľka 1: Vlastnosti kompaktnej textilnej dosky [6]

Technický parameter	Jednotka	Hodnota
Hrúbka	mm	50 ± 5
Formát	mm	500 x 500 ±5 (1200x600)
Plocha dosky	m^2	0,25 (0,72)
Rovinnosť	mm	max ± 6
Hmotnosť dosky	kg	3,125 (9)
Objemová hmotnosť materiálu	kg/m^3	250
Počet kusov na palete	ks / m^2 / kg	104/ 26 / 325 (411 vlhké) 48/34,56/432 (518 vlhké)
Stlačiteľnosť	mm	max. 5
Plošné zaťaženie do max.10kN , 2 000 000 cyklov, stlačenie	mm	max. 8,6, trvalé 1,7
Krátkodobá nasiakavosť pri čiastočnom ponorení Wlp- postup A	kg/m^2	max. 20
Dlhodobá nasiakavosť pri čiastočnom ponorení Wlp - postup A	kg/m^2	max. 25
Priepustnosť vodnej pary µ	-	max.4 (-)
Zdravotná neškodnosť	-	v súlade s príslušnými ustanoveniami
Reakcia na oheň	-	E

Recyklovaný textilný materiál bol vložený do pripravených foriem, lisovaný a sušený. Výsledkom boli recyklované dosky, ktoré boli narezané na menšie testovacie vzorky podľa našich požiadaviek na ďalšie zvukové a tepelné testovanie. Variabilita rozmerov sa môže meniť v závislosti od požiadaviek testovania. Dodané vzorky textílií boli v týchto formách:

- Rezané alebo trhané jednotlivé frakcie textilu, merajúce približne 20 x 40 mm (Frakcie materiálov – rezané alebo trhané malé časti textilu pochádzajúce z rôznych častí textílií, ako sú poťahy, koberce z automobilov), obrázok 7.

Obrázok 7: Trhaný a rezaný recyklačný materiál z textilu vozidla

- Kompaktná textilná jednotka vyrobená z materiálov z automobilov lepených a lisovaných s rozmermi 300 x 300 mm, obrázok 8 (Pevné textilné dosky), obrázok 9 tvorí vzorka z dosky.

Obrázok 8: Kompaktné vzorky recyklovaného textilu

Obrázok 9: Kompaktná textilná valcová vzorka

Na základe dodaného testovacieho materiálu boli vytvorené testovacie vzorky pre meranie zvukovej pohltivosti a meranie tepelno izolačných vlastností:

- rezanie, trhanie textilného materiálu z automobilu po jeho konci životnosti (obrázok 7),
- v tvare valca s priemerom Ø 60 mm a výškou 60 mm, vyrobené z pevných panelových dosiek (obrázok 9).

Metóda merania zvukovo absorpčných a tepelne izolačných vlastností

Pre potreby stanovenia koeficientu zvukovej pohltivosti „α“ a indexu útlmu „TL“ bolo vyvinutých niekoľko meracích metód, pričom jednou z najpoužívanejších je meranie pomocou impedančnej trubice. Impedančná trubica má v porovnaní s inými metódami merania výhodu vďaka svojej kompaktnosti a možnosti rýchleho získania výsledkov.

Pre potreby merania skúmaných materiálov v recyklovaného textilu bola použitá impedančná trubica model BSWA SW 433 vo štvormikrofónovej konfigurácii, dĺžkou 500 mm s vnútorným priemerom Ø 60 mm a frekvenčným rozsahom 100-2500 Hz (obrázok 10).

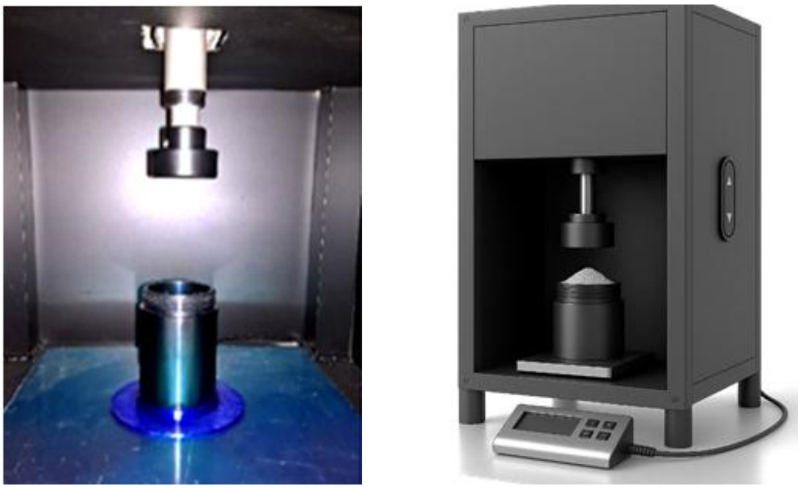
Obrázok 10: Pohľad na meraciu aparatúru - impedančnú trubicu BSWA TECH

Súčasťami meracej zostavy boli 4 – kanálový analyzátor MC3242 (0-20 kHz), zosilňovač PA 50 (50W) pre napájanie reproduktora v trubici, počítač so softvérom VA – LAB4, potrebná kabeláž a samotná impedančná trubica. Merania koeficientu zvukovej pohltivosti „α“ a indexu útlmov „TL“ boli realizované metódou transformačnej funkcie podľa normy STN EN ISO 10534 -2 (730537) [17].

Natrhaný alebo nastrihaný textilný materiál bol vložený do autormi navrhnutej testovacej kazety (Patent č. 289324), obrázok 11 [18] a zalisovaný zariadením na merané plnenie testovacích kaziet sypkými materiálmi (Úžitkový vzor č. 9665), obrázok 12 [19].

Obrázok 11: Testovacie kazety

Pre každú vzorku bolo vykonanrých 5 opakovacích meraní. Hodnoty teploty (22,5 ± 1°C) a relatívnej vlhkosti (48 ± 5 % RH) boli monitorované počas celého experimentu. Atmosferický tlak 986,07 kPa indikoval stabilné laboratórne prostredie vhodné pre opakovateľné merania.



Obrázok 12: Zariadenie na merané plnenie testovacích kaziet sypkými materiálmi

Koeficient zvukovej pohltivosti „α“ je bezrozmerné číslo pohybujúce sa od 0 po 1. Čím je nameraná hodnota bližšie k 1 alebo rovná 1, tým testovaná vzorka meraného materiálu bude vykazovať lepšiu (vyššiu) zvukovú pohltivosť. Koeficient zvukovej pohltivosti „α“ pri kolmom dopade zvuku sa vypočíta zo vzťahu:

$$\alpha = 1 - |r|^2 = 1 - r_r^2 - r_i^2 \qquad (1)$$

kde: r – je činiteľ odrazu, r_r – je reálna zložka a r_i – je imaginárna zložka [16, 20].

Index útlmu „TL“ sa udáva v (dB) a vyjadruje pomer medzi intenzitou zvuku dopadajúceho na prednú stranu vzorky a intenzitou zvuku preneseného cez testovaný materiál. Tento pomer umožní posúdiť účinne ako daný materiál tlmí zvuk. Čím vyššia bola nameraná hodnota index útlmu „TL“, tým lepšie sú tlmiace vlastnosti materiálu.

Index útlmu „TL“ sa vypočíta zo vzťahu:

$$TL = 10\log_{10}\left|\frac{W_i}{W_t}\right|, \qquad (2)$$

kde: W_i - je energia dopadajúcej zvukovej vlny, ktorá prichádza smerom ku skúšobnej vzorke,
W_t - je energia prenesenej zvukovej vlny, ktorá odchádza od skúšobnej vzorky.

Metóda merania tepelne izolačných vlastností recyklovaného textilu

Pre merania tepelne izolačných vlastností recyklovaného textilu bol použitý prístroj Testo 635, obrázok 13. Na výpočet koeficienta U prestupu tepla sa použila schéma, obrázok 14. Ako miesto merania bolo použité laboratórne okno, obrázok 15.

Obrázok 13: Merací prístroj Testo 635 s počítačom, meracia sonda a 3 meracie sondy pri meraní

Koeficient U sa udáva vo $W.m^{-2}.K^{-1}$ a určuje tepelný tok Φ (množstvo tepla Q za jednotku času), ktorý prestupuje cez povrch A o jednotkovej ploche 1 m^2 cez stenu, ak je rozdiel teplôt ΔT na obidvoch stranách steny rovný 1°K.

$$\Phi = U \cdot A \cdot \Delta T \ (W) \qquad (3)$$

Okrem samotnej jedno alebo viac vrstvovej konštrukcie sa do výsledného koeficienta U zahŕňajú aj koeficienty prestupu tepla α_p na vnútornom a vonkajšom povrchu konštrukcie vplyvom obtekania povrchu pevného prostredia s teplotou Tw prúdiacim médiom (vzduchom) s teplotou T_i a T_e, ako aj vplyvom sálavej zložky α_s.

$$\alpha = \alpha_p + \alpha_s \qquad (4)$$

Hodnoty súčiniteľov prestupov tepla na povrchoch konštrukcií sa volia z STN 73 0542, STN EN 17888-1, STN EN 673, STN EN ISO 10077-1 [21, 22, 23, 24].

V meracom prístroji Testo 635-2 a Testo 435-2/-4 je zadaný koeficient prúdenia na vnútornom vertikálnom povrchu $\alpha_i = 7{,}69\ W.m^{-2}.K^{-1}$ (DIN 4108) [25].

Princíp metódy vyplýva z rovnosti hustoty celkového tepelného q prestupujúceho cez všetky vrstvy z interiéru o teplote T_i do exteriéru o teplote T_e a hustoty tepelného toku prechádzajúceho napr. z interiéru o teplote T_i na stenu s teplotou T_{wi}.

$$q = U.\,(T_i - T_e) = q\alpha_i = \alpha_i\,(T_i - T_{wi})\ (W.m^{-2}) \qquad (5)$$

potom pre U

$$U = \alpha_i\,(T_i - T_{wi}) / (T_i - T_e)\ (W.m^{-2}.K^{-1}) \qquad (6)$$

Na určenie koeficienta U nám teda postačuje súčasne merať teplotu vzduchu interiéru T_i, teplotu konštrukcie na vnútornom povrchu T_{wi} pomocou príložného snímača a merať vonkajšiu teploty vzduchu T_e, napr. pomocou rádiovej Testo AG, Market launch documentation Testo 557 6/16 sondy.

Patentovaný teplotný snímač Testo pre určenie koeficienta prechodu tepla U (0614 1635) umožňuje :

- merať povrchovú teplotu konštrukcie pomocou sondy, ktorá združuje 3 snímače teploty (termočlánok K),
- merať aj teplotu vzduchu v interiéri (snímač je umiestnený v rúčke snímača na meranie povrchovej teploty).

Veľmi podstatné je, aby merací prístroj bol v súlade s odporúčaním výrobcu počas merania umiestnený aspoň 30 cm od vnútornej steny, oproti miestu, kde je umiestnený snímač teploty steny T_w.

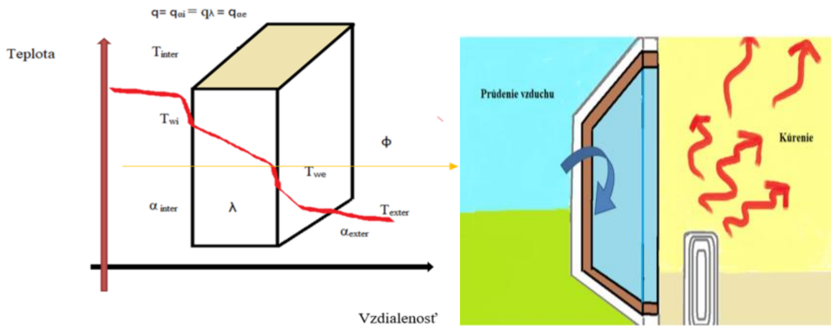
Výpočet sa môže dosť podstatne líšiť od merania, nakoľko normy často používajú normované hodnoty tepelných vodivostí materiálov, ktoré sú často nižšie, ako sú priemerné hodnoty udávané výrobcami. Preto potom vypočítané U hodnoty sú vyššie ako skutočne namerané.

V niektorých prípadoch však namerané hodnoty môžu byť vyššie ako vypočítané. Dôvodom často býva zvýšená vlhkosť materiálov konštrukcie a interiéru.

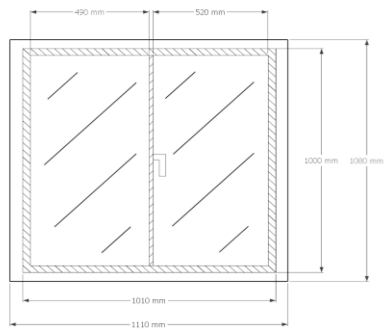
Blízko vnútornej konštrukcie spojenej s meranou obvodovou stenou sú namerané hodnoty koeficienta U podstatne nižšie ako vo väčšej vzdialenosti. Spôsobuje to vyššia povrchová teplota steny T_w vplyvom vedenia tepla z teplejších vnútorných priečok.

Ak sa umiestni prístroj bližšie alebo dokonca, napr. na rám okna potom môže snímač teploty vzduchu v interiéri T_i (v zástrčke snímača T_w) namerať nižšiu teplotu, ako je skutočná teplota okolia.

Teplotný rozdiel medzi teplotou v interiéri a exteriéri by mal byť väčší ako 15 °C.



Obrázok 14: Schéma prestupu tepla



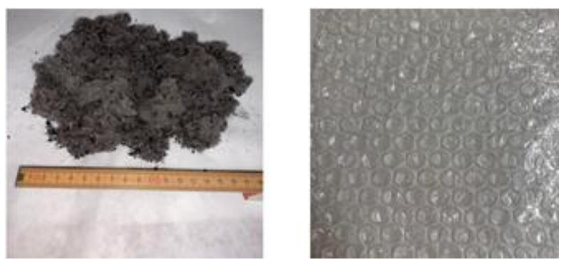
Obrázok 15: Laboratórne okno s rozmermi

Pre potreby experimenty sa použili:

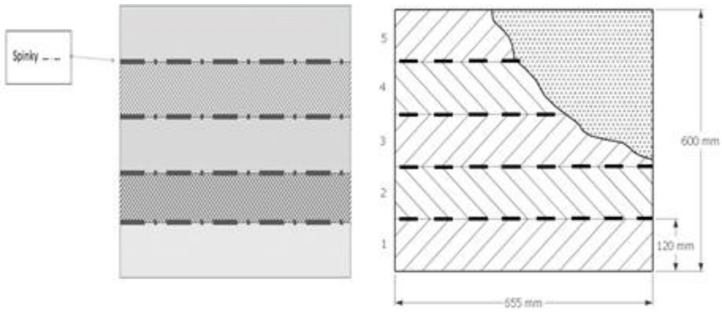
- kompaktné skúšobné vzorky, obrázok 16,
- trhané (sypké) textilné skúšobné vzorky, obrázok 17,
- vytvorená kapsula z bublinkovej fólie, obrázok 18 (Možno použiť ako obal aj iný materiál).

Po vytvorení kapsule so sypkým materiálom sa skúšobná kapsula uložila na okno, obrázok 19.

Obrázok 16: Kompaktný recyklovaný textilný materiál



Obrázok 17: Sypký textilný materiál a fólia



Obrázok 18: Schéma kapsuly pre sypký recyklovaný textil

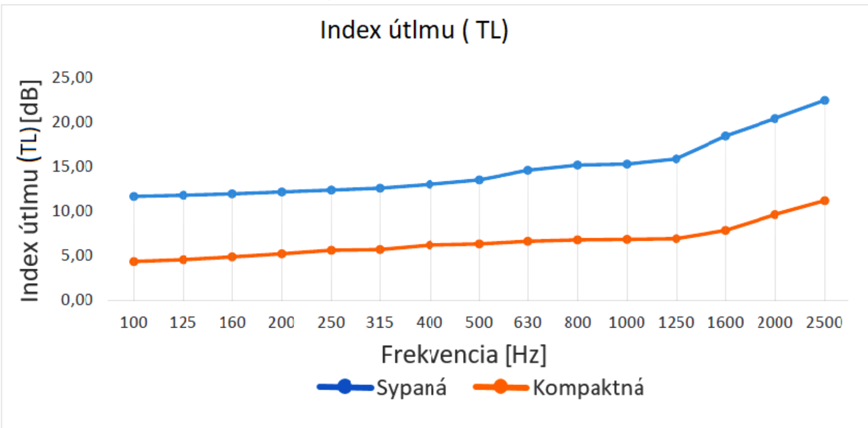
Obrázok 19: Kapsula naplnená textilom

Výsledky a diskusia

Meraním akustických vlastností textilných recyklovaných materiálov boli hodnotené dve typy vzoriek:

- prvá vzorka (obrázok 8,16) bola vyrobená z kompaktného recyklovaného textilného materiálu (STERED),
- druhá vzorka (obrázok 7,1 7) bola pripravená z rovnakého recyklovaného trhaného (sekaného) sypaného textilného materiálu - sypká frakcia, ktorý nebol upravovaný do kompaktnej podoby.

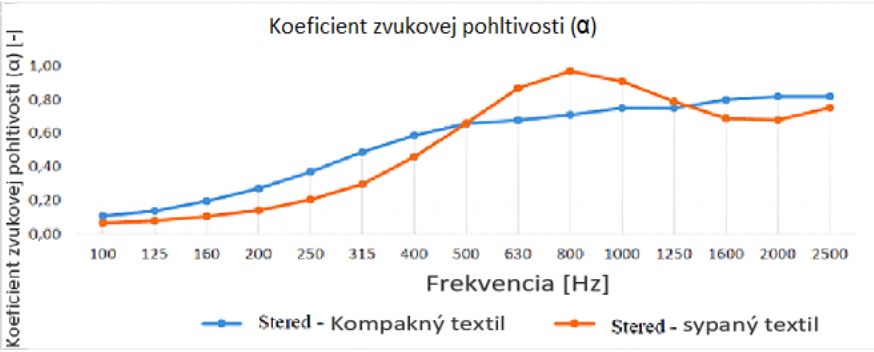
Na základe získaných výsledkov z merania indexu útlmu (TL), že kompaktný textilný materiál vykazuje lepšie akustické vlastnosti v celom frekvenčnom pásme (obrázok 20).



Obrázok 20: Indexu útlmu „TL" pre kompaktné a sypané testované materiály

Tento výsledok sa dal predpokladať, keďže objemová hmotnosť kompaktného textilného materiálu je 4-krát vyššia, ako je objemová hmotnosť voľne sypaného textilného materiálu.

V prípade koeficientu zvukovej pohltivosti (α) výsledok z meraní už nebol taký jednoznačný (obrázok 21).



Obrázok 21: Koeficient zvukovej pohltivosti „α“ pre textilný materiál

Hodnoty koeficientu zvukovej pohltivosti (α) sú priaznivejšie u sypaného textilného materiálu v intervale frekvencií od 500 -– 1250 Hz. Hluk z dopravy sa pohybuje v okolí frekvencie1000 Hz, čo znamená, že materiál je vhodný pre konštrukcie protihlukových stien. V intervaloch od 100 Hz do 500 Hz a 1250 Hz do 2500 Hz priaznivejšie hodnoty koeficientu zvukovej pohltivosti (α) boli identifikované u kompaktného textilného materiálu.

U koeficienta zvukovej absorpcie môžeme dospieť k záveru, že kompaktný textilný materiál dosahuje lepšie parametre v frekvenčných pásmach 100 – 500 Hz a vo frekvenčnom pásme 1600 – 2500 Hz. Voľný textilný materiál dosahuje lepšie absorpčné parametre v frekvenčnom pásme 500 – 1250 Hz.

Pri meraní tepelno izolačných vlastností recyklovaných textilných materiálov boli hodnotené dve typy vzoriek, kompaktná vzorka a sypké frakcie textilu v kapsule. Obidve skúšobné vzorky sa umiestnili na vybrané laboratórne okno (obrázok 20). Na základe merania prestupu tepla pomocou prístroja Testo 635, boli vyhodnotené výsledky a vypočítané hodnoty „koeficienta U prestupu tepla“ jednotlivých skúšobných vzoriek.

Výsledky jednotlivých meraní skúšobných vzoriek sú uvedené v tabuľke 2 pre kompaktný materiál a v tabuľke 3 pre sypký textilný materiál v kapsule. Pre prestup tepla kapsula vykázala lepšie výsledky ako kompaktný textilný materiál, kvôli vzduchovým medzerám v kapsule, pretože vzduch je dobrý izolant, tabuľka 4.

Tabuľka 2: Namerané hodnoty pre výpočet prestupu tepla pre kompaktný textilný materiál

	Min:	Max:	Mean:
C:1 W/m2K	0.027	12.815	1.816
C:2 [°C] Tw	23.69	24.52	24.05
C:3 [°C] Ti	23.67	23.84	23.81
C:4 %rH	33.50	36.40	34.35
C:5 °C	22.50	22.70	22.56
C:6 td °C	5.71	6.87	6.08
C:7 [°C] psyc	13.15	13.62	13.32

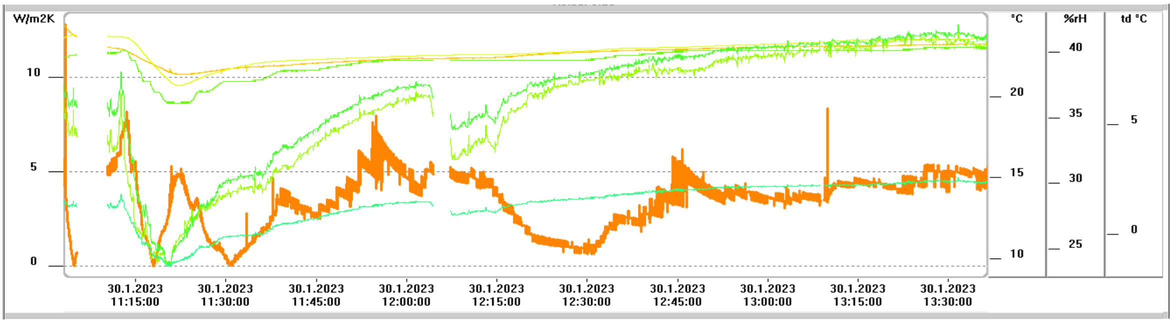
Tabuľka 3: Namerané hodnoty pre výpočet prestupu tepla pre sypký textilný materiál v kapsule

	Min:	Max:	Mean:
C:1 W/m2K	0.858	188.901	4.008
C:2 [°C] Tw	20.87	22.20	21.09
C:3 [°C] Ti	21.42	22.90	21.63
C:4 %rH	29.90	56.40	43.90
C:5 °C	20.40	25.90	22.69
C:6 td °C	5.29	12.16	9.70
C:7 [°C] psyc	12.16	16.88	14.95

Tabuľka 4: Hodnoty koeficienta U prestupu tepla skúšaných testovaných materiálov

Koeficient U [W/m²K]			
Materiál	Minimálna hodnota	Maximálna hodnota	Priemerná hodnota
Kapsula - sypký	0,858	188,901	4,008
Kompaktný	0,027	12,815	1,816

Príklad graficky nameraných hodnôt z meraní prestupu tepla kompaktného materiálu je uvedený na obrázku 22.



Obrázok 22: Príklad z merania prestupu tepla z kompaktnej testovacej vzorky

V rámci experimentov zameraných na meranie tepelno izolačných materiálov sa použilo viacero materiálov a ich kombinácie. napr viacvrstevný kartón, materiál z firmy Obifon. U viacvrstevného kartónu hodnota koeficientu U prestupu tepla bola nameraná U = 1,092. Pri materiáli Obifon bola hodnota U = 8,89.

Avšak pre veľký rozsah experimentov sa v príspevku použili a porovnali len dva z nich, ktoré obsahovali najviac recyklovaného textilu. Autormi vykonanými experimentami boli zistené nasledujúce hodnoty koeficientov U prestupu tepla u kompaktného recyklovaného textilu U = 1,816 a sypaného recyklovaného textilu v kapsule U = 4.008. Vykonané experimenty potvrdili vhodnosť kompaktného recyklovaného textilného materiálu pre potreby tepelnej izolácie. Sypaný textilný materiál uložený v kapsule z bublinkovej fólie, aj napriek tomu, že vykazuje horšie tepelno izolačné vlastnosti oproti kompaktnému textilnému materiálu je vhodný pre tepelno izolačné aplikácie.

Závery

Cieľom príspevku bolo zamerať sa na vývoj technológií a techník pre zhodnocovanie odpadu na akustické a tepelné izolačné produkty. Dôraz bol kladený na využitie takých komponentov z automobilov na konci životnosti, ktoré majú problematické recyklovanie a najmä na následné využitie extrahovaného surového textilného materiálu. Autori sa zamerali na využitie materiálov z autosedačiek, poťahov sedadiel, bezpečnostných pásov, kobercov a airbagov, ktoré doteraz využíval a spracovávala firma PR Krajné, s.r.o. Snaha bola nadviazať kontakt s firmami, ktoré tieto komponenty recyklujú alebo o ich recyklácii uvažujú. Autori získali množstvo frakcií rôznych materiálov pre svoju súčasnú a budúcu prácu.

Autori sa tiež zamerali na výrobu tepelných a izolačných produktov použiteľných pre potreby protihlukových stien, alebo tepelne izolačných stien zo sendvičových konštrukcií využívajúce recyklovaný textilný materiál z automobilov. Dôraz bol kladený na výrobu absorpčných elementov z textilného a iného odpadu z automobilov. Vykonané merania jasne preukázali vhodnosť recyklovaných textilných materiálov z automobilového priemyslu, či už v kompaktnej alebo sypanej forme na výrobu akustických a tepelne izolačných produktov. K výhodám týchto sypaných materiálov oproti komerčne vyrábaným recyklovaným panelom patrí nižšia hmotnosť, väčšia ekonomická efektívnosť, vysoká fyzikálna a chemická stabilita a lepšie hodnoty zvukovej pohltivosti. Táto myšlienka využitia sypaného textilného odpadového materiálu sa dá využiť aj v sendvičových štruktúrach vyrobených dvoma technológiami a to stláčaním a mikrovlnným zahrievaním. Autori sa zamerali tiež na výrobu zvukovo absorpčných elementov z mäkkých pien (polyuretánových pien).

Poďakovanie

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Recycling of textiles from cars after their service life and its possible use in practice

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Summary

The development of the automotive industry in the world, as well as in the Slovak Republic, is crucial for the prosperity and overall development of society. In Slovakia, the automotive industry has developed into a leading position among individual industrial sectors thanks to four (in the future, five) final manufacturers. In the paper, the authors focused on the classification of problematic waste from cars after the end of their service life from the point of view of its further recovery, specifically the recycling of textile materials. The experimental part of the paper focuses on applications and prediction of the use of selected problematic textile waste from the point of view of their recovery (in compact and loose state), on the evaluation of the experiments performed using regression and correlation analysis for products for sound and thermal insulation. The authors of the paper focused their work on research into the possibilities of using various textiles applied in automobiles with the aim of using recycled materials from these textiles to develop sound and heat insulation materials with a wide range of applications. The research findings demonstrated the suitability of the given material for the mentioned applications.

Keywords: *Automotive industry, textile recycling, sound absorption coefficient of a material, attenuation index of a material, thermal insulation properties of a material*

Proposal of waste quality monitoring and contamination detection approach in the context of modern standards and technologies

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Abstract

The paper presents a comprehensive proposal of waste contamination detection approach, with focus on early phases of waste streams. We have systemically analysed current waste quality control procedures in waste sorting centres, commonly used approaches and methods for waste quality monitoring. Based on the current requirements for contamination detection, we have proposed and designed early contamination detection approach, deployed at the beginning of the waste stream. Our proposal outlines the necessary steps to design a state of art detection approach using modern multi sensor detection in combination with artificial intelligence. The focus is given on specifics of contamination detection in different recycled materials, like plastic and paper.

Our proposal creates a basis for a future research and development phase focused on creating an adaptive contamination detection system that will combine radar and camera data with artificial intelligence detection.

Key words: *waste contamination, waste quality, recycling, radar technologies, multisensory identification*

Introduction

In recent decades, the topic of waste management has gained strategic importance in connection with the tightening of environmental standards, the growth of production and consumption volumes, as well as the introduction of circular economy principles. Effective waste management is the key to returning secondary raw materials to production, reducing landfilling and CO_2 emissions, and rational use of resources. Modern waste sorting centres face increasing heterogeneity of the waste stream: differences in shape, composition, degree of contamination, and the presence of multilayer packaging complicate the task of automatic identification and separation of fractions.

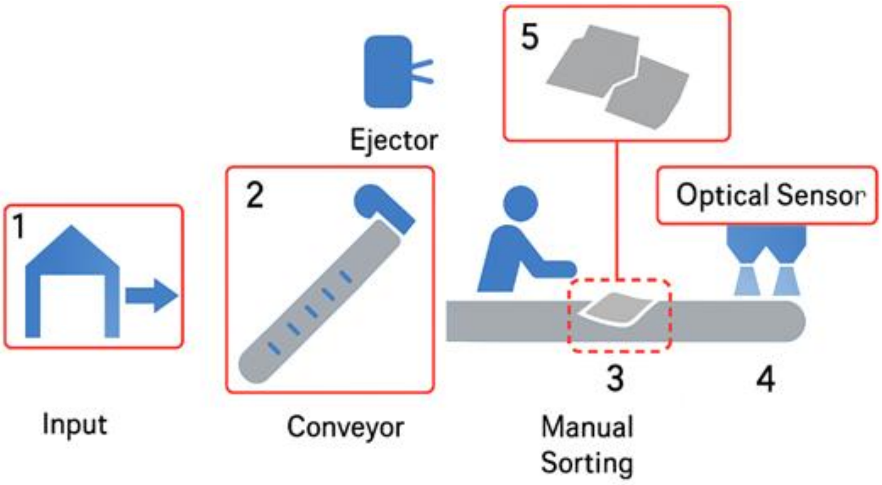

Figure 1: Schematic representation of a typical waste sorting line

Despite the introduction of optical and spectroscopic sensors, the share of unidentified, incorrectly sorted, or completely lost secondary material remains high, especially when processing mixed waste streams (Fig. 1). To achieve the EU's goal of increasing the recycling rate to 65% by 2035 [1], innovative solutions going beyond traditional technologies are needed. The municipal waste recycling rate in Slovakia was 50% in 2022. For comparison the municipal waste recycling rate in Czechia in the same year was 53% and the EU average rate was 49% [2,3,4].

Technological approaches to automatic sorting and material identification

In the last two decades, significant improvement has been achieved in the field of municipal solid waste (MSW) processing and sorting thanks to the introduction of automated systems based on modern sensor technologies and machine vision algorithms. In most sorting facilities (SF), optical sensors, spectroscopic analysers, X-ray devices, and specialized software based on artificial intelligence (AI) are currently used [5,6]. These systems can determine the composition of materials with high accuracy according to colour, spectral characteristics, and geometric features.

The most widespread are combinations of RGB cameras and near-infrared (NIR) scanners, which have been further explored using AI-based sensor-fusion techniques to boost object detection accuracy[7]. X-ray detectors (XRT) are also introduced to solve specific tasks, which can separate metals, glass, and mineral impurities, and in some facilities, hybrid schemes with manual sorting are implemented [8]. Computer vision algorithms, including deep learning methods, have significantly increased the accuracy of recognizing individual waste categories, which has made it possible to automate sorting in large facilities in EU and North American countries.

Despite the successes of recent years, existing technical solutions have several limitations that hinder further improvement of sorting efficiency. One of the main problems remains the inability to identify hidden or multilayer materials, when, for example, a layer of plastic is covered by paper or another opaque component. Modern optical and spectroscopic methods are sensitive to colour and surface contamination but lose information value when working with black, contaminated, or thermally deformed plastic fractions. This leads to significant losses of valuable materials, primarily polyethylene terephthalate (PET) and aluminium, and also increases the amount of manual work in the final sorting stages [9].

A specific problem remains the high cost and complexity of creating universal datasets for training AI systems. Regional specifics of MSW composition require flexible adaptation of algorithms and regular updating of models, which is associated with large time and financial costs. As researchers from Fraunhofer IOSB and several industrial companies (e.g., TOMRA and STADLER) point out, further efficiency improvement is possible only if new sensor principles are introduced that make it possible to obtain data about the internal structure of objects, and not only about their surface properties [10,11].

In recent years, experimental solutions based on the use of lidars and radars, taken from mining, agriculture, and warehouse logistics, have attracted attention. These technologies have the potential to penetrate multiple material layers, identify hidden impurities, and evaluate the physical parameters of objects (for example, density, weight) [12].

However, increasing the number of sensors used leads to a more complex system architecture. It also requires integration and synchronization of data from diverse sources. Additionally, it results in higher implementation costs. It is important to consider not only the technical efficiency but also the economic justification of such solutions, especially under the conditions of the limited budget of medium and small SFs.

Despite significant progress in waste sorting automation, achieving strategic goals such as increasing the recycling rate and reducing negative environmental impact still requires new approaches. These approaches should combine multisensory technologies with intelligent data fusion algorithms (sensor fusion). Solving the task of identifying hidden and complex materials requires the development of adaptive, scalable, and economically efficient architectures that integrate optical, radar, and spectroscopic methods supported by artificial intelligence.

Specific sensor configurations

The most common sensor combinations include:

- **RGB + NIR:** An optical camera and a near-infrared camera make it possible to distinguish most transparent and coloured plastics, and to separate paper from plastic. However, their performance is limited when dealing with black or contaminated materials. They are also unable to detect internal object structures or identify features hidden beneath surface layers. Recent research has also demonstrated that low-cost multi-spectral NIR sensors, combined with deep learning, can provide effective plastic waste recognition with minimal hardware investment, offering a more economically viable solution for smaller facilities [13].
- **Hyperspectral cameras (VIS-NIR-SWIR):** significantly increase the “depth” of spectral analysis, making it possible to identify a wide range of polymers, composites, and even some types of contamination. Limitations are related to the high cost of the equipment and the need for complex calibration [14].
- **XRT:** used for separation by density and structure, it is well suited for removing metals, foreign impurities in glass, and construction waste. A significant disadvantage is the inability to distinguish materials with similar density (for example, certain plastics and organic waste), as well as high requirements for protecting personnel and equipment [8].
- **LIBS/LIFS (laser spectroscopy):** provides the most accurate chemical analysis but requires complex integration and is often inefficient at high stream speeds.
- **LIDAR/3D scanning:** provides precise object geometry, is suitable for shape and size control, helps with spatial separation of fractions, but does not distinguish material [15].
- **Radar systems (FMCW, millimetre band**): rarely used yet, but they can detect the internal structure even under thin layers of material and identify the presence of hidden impurities causing contamination [16].

In modern operations, systems in which multiple sensors work together, and the results of their analysis are combined (sensor fusion) using artificial intelligence are considered the most effective. Such solutions make it possible to increase the reliability of classification even with complex overlaps, the presence of contamination, and high conveyor belt speed. Nevertheless, the main challenges of multisensory systems lie in increased implementation costs, the need to synchronize data streams, demands on computing resources, and operator qualification.

The choice of sensor configuration for a sorting line is therefore the result of balancing requirements for accuracy, speed, economic constraints, and the specifics of the waste stream. The introduction of penetrating sensors, such as radars or lidars, opens new possibilities for identifying complex or masked fractions, but at the same time requires new approaches to processing and merging information – and this forms the core of the architecture we propose.

Proposal of early waste contamination detection

The common approaches to waste quality control detection that are currently used have multiple issues that need to be addressed to improve waste recyclability. Quality control is currently performed only at the waste collection yards and their sorting centres, i.e. quite late in the waste stream, and makes it impossible to identify sources of waste contamination and trace the waste contamination in more detail. Therefore, it is necessary to detect contamination in waste streams as soon as possible, ideally at the origin of the waste stream.

This early detection brings clear benefits across environmental protection, operational efficiency, and regulatory compliance, namely:

- Reduces the volume of contaminated waste sent to landfills or incinerators, instead of material recovery facilities.
- Reduce manual sorting efforts in material recovery facilities.
- Maintain eligibility for subsidies or recycling credits.
- Reduction of loads that must be rejected or surcharged.
- Encourages residents and businesses to participate in proper recycling.

However, early detection requires evaluating the quality of the waste and detecting contamination preferably in waste containers or during waste collection process, which represent the earliest points in the waste stream. Our proposal identified large-volume waste containers in residential areas and waste collection trucks as the most suitable places for early contamination detection. These detection places represent different technological challenges and limitations, compared to traditional detection in waste sorting centres.

Based on the comprehensive analysis of waste quality, waste categories, detection approaches, and AI detection techniques, we have proposed an approach for designing early contamination detection. The central element of this proposal is the integration of multiple sensor technologies into a single adaptive solution. The combination of radar sensors (especially in the millimetre wave band) and optical cameras (RGB/NIR), processed with artificial intelligence, makes it possible not only to identify the surface properties of waste, but also to penetrate beneath the surface and obtain information about its internal structure, composition and density. The radar and camera data are collected, processed, and evaluated in parallel, to allow artificial intelligence methods to fuse the data together and utilise sensors that are more suitable for given detection. This will allow us to improve detection of waste contamination and better evaluate the overall waste quality early in the waste stream.

One of the main limitations of the multi-sensor approach is the high cost of radar and multispectral sensors, which are not always feasible for large-scale deployments. The currently available radar sensor solutions on the market range from 300 € to 30 000 €, depending on their features, detection accuracy, and quality. The ever-changing environmental conditions, like dust, moisture and vibrations can also improve or degrade sensor performance.

The proposal, captured in Fig. 2 as a process diagram, is comprised from three main phases, to ensure the suitability and accuracy of waste contamination detection.

The **first stage** represents a proof-of-concept phase, to evaluate suitability of detection technologies on the different structure of waste, that the waste collection centres are collecting. This step is important, since different centres can have different structure of waste and different types of waste contamination. In the waste collecting centres we have analysed is most of the sorting efforts focused on plastic and paper waste, of which the collecting centres have most valuable information.

To obtain the required data from radar, camera and other sensors, a suitable place must be identified in the waste sorting process, that will not interfere with their sorting operations but will allow us to obtain required sensor measurements. The identified installation place must be able to accompany the sensors as well as required data collection infrastructure and provide the necessary utilities (e.g. electricity and network connection). To keep the infrastructure more compact, a data processing in cloud was utilised, to decrease the computation requirements on site.

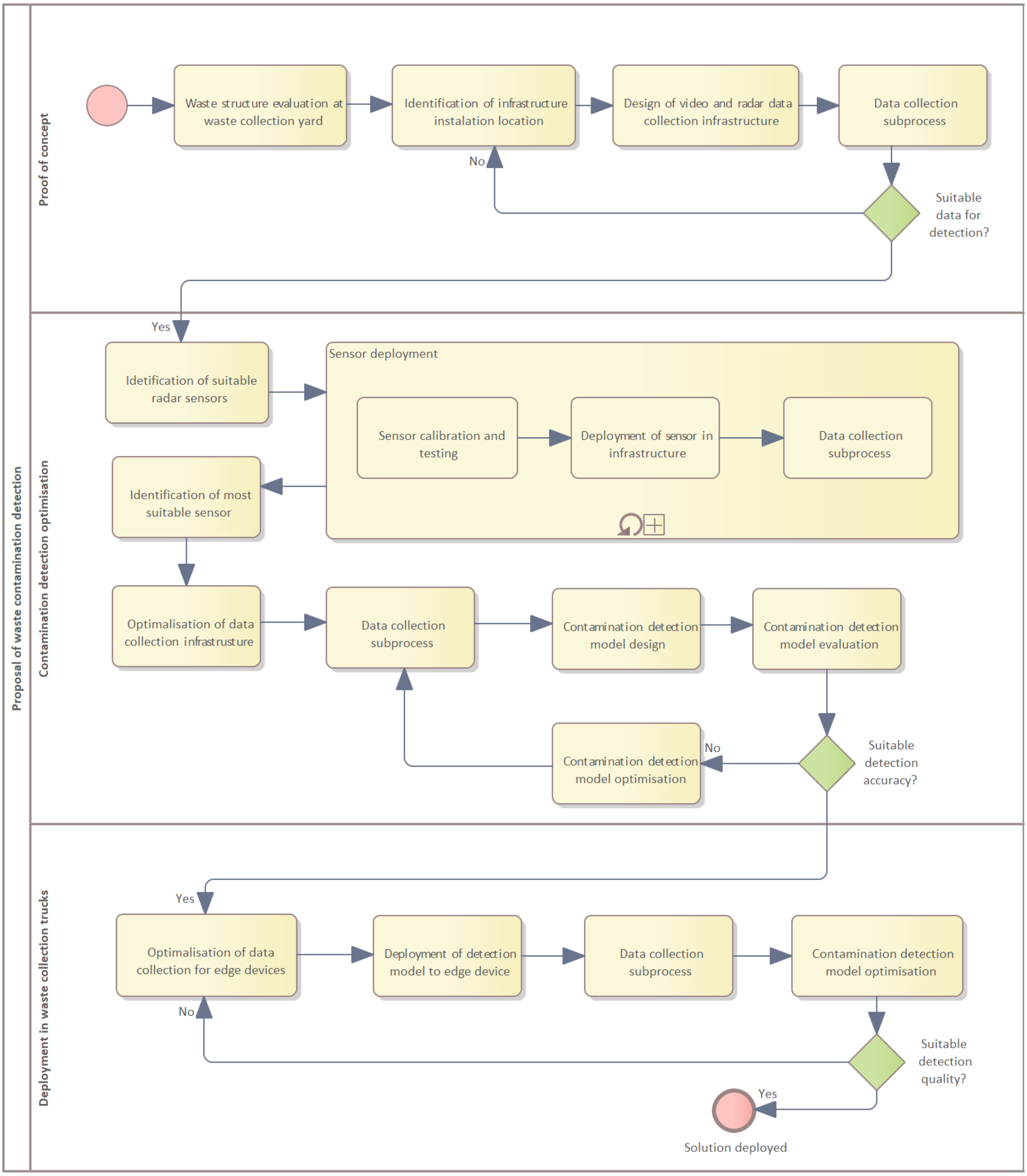

Figure 2: Proposal of waste contamination detection

After the installation of infrastructure, a data collection process must be carried out, to obtain enough data to be able to evaluate suitability of selected sensors, and to obtain data necessary for further evaluation. The combination of radar and camera sensors in our proposal lets us compare radar information with camera images. This allows us to obtain comprehensive data set, that enables radar data evaluation by comparing them with camera data. The duration of data collection should be based on amount and quality of obtained data, where longer collection period can improve the accuracy of gained results. The data collection is carried out in multiple phases of the proposed approach, with very similar steps. The main objective of this subprocess, is to obtain, analyse and evaluate the collected radar and video data, as outlined on Fig 3.

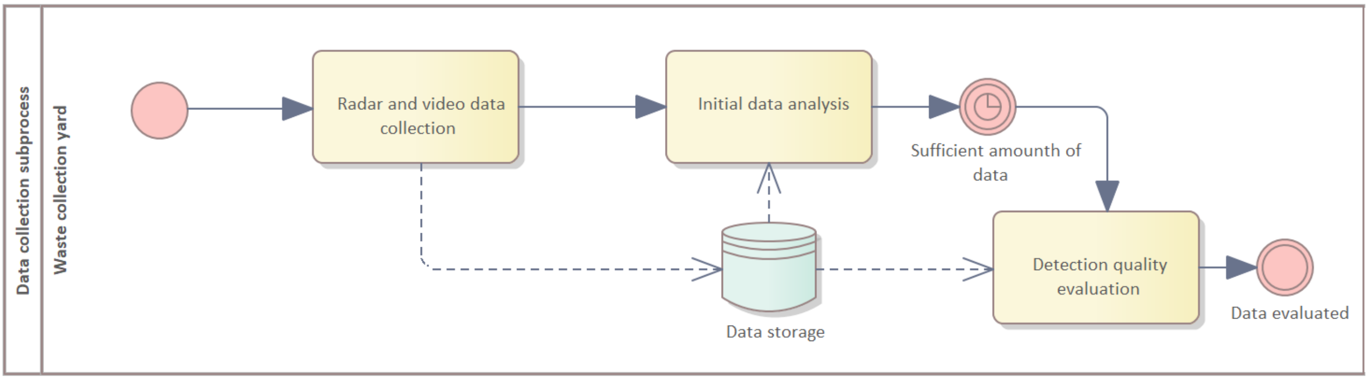

Figure 3: Data collection subprocess

The results obtained from the first phase must be evaluated, based on the suitability of selected sensors for contamination detection and quality monitoring, to ensure usability and practical applicability of developed solution.

The **second stage** focuses on optimisation of contamination detection and quality monitoring, by improving the design from the proof-of-concept phase.

The main focus of improvement is on optimisation of radar and multispectral sensors, whose correct selection can bring major improvements in the accuracy of obtained results. The importance is also given on calibration and fine tuning of radar sensors with variable wave lengths, that can provide different results for different types of waste and their contamination.

Each of the selected sensors must be calibrated and tested in testing environment, and deployed and evaluated in real world conditions, i.e. waste collection centre. The essential part is collecting data from these sensors, to be able to evaluate and compare them.

Based on the individual sensor's performance, an identification of the most suitable ones should be carried out, to identify sensors, or sensor combinations providing best accuracy of contamination detection. Deployment of these identified sensors must be hand in hand with modification and optimization of data collection infrastructure, since the mounting plates and preferred measuring positions can differ between sensors.

Although the selected sensors were used in data collection process, and we have obtained data from these evaluation deployments, due to the modifications in data collection infrastructure a new data collection process should be carried out. This will allow us to improve the overall quality of the data set, and its suitability for detection using machine learning and artificial intelligence methods.

Based on this collected data set a contamination detection model must be designed and evaluated. In our analysis we have identified multiple open-source detection models used in this area, as well as multiple commercial solutions. These will serve as a basis for our contamination detection model. Since different models and approaches can yield different results, a detection model optimisation should be carried out, to achieve suitable detection accuracy.

After achieving sufficient accuracy of our detection model, the designed system must be scaled down for deployment at the beginning of the waste stream.

Therefore, the **third stage** focuses on deployment of contamination detection in large-volume waste containers in residential areas or waste collection trucks.

Deployment of detection in identified areas requires to solve technological challenges, to achieve accurate a robust contamination detection. Therefore, it is necessary to utilise edge devices, that provide suitable computation performance for the required detection. Allthrough the model design requires significant computation capacity for learning, the learned model can perform detection with low power requirements, ideal for deployment on battery powered edge devices.

The infrastructure required for model optimisation differs from the infrastructure required in the final deployment. These modifications must be carried out carefully, with focus on optimal measurement requirements gained in previous phases. These steps are important to significantly accelerate the measured and analysed data quality, required for the final deployment evaluation and optimisation. Due to the different changes to the collection infrastructure and model optimisations, it requires to collect new sets of data, since obtained parameters can differ from data in data sets collected in previous phases, making them incompatible with each other. The successful deployment requires achieving suitable detection quality and accuracy, to be able to detect contamination and monitor waste quality.

Our proposal creates a basis for a future research and development phase focused on creating an adaptive contamination detection system that will combine radar and camera data with artificial intelligence detection. Attention will be given on precise calibration and configuration of radar sensors, unification of radar and video data and development of a artificial intelligence model for the complex detection of waste contamination with high accuracy and reliability.

The proposed solution is suitable for modern waste quality management, providing high degree of automation with improved decision support of waste streams. By integration with a higher-level system, it could serve as a tool to ensure compliance with environmental regulations, thereby contributing to more efficient, sustainable, and documentable waste management required in modern Europe.

Conclusions

The quality monitoring of waste is today a key condition for achieving the strategic goals of the European Union in the field of circular economy and recycling. Under the conditions of rapidly increasing requirements for the purity level of secondary materials, especially plastics, the importance of a comprehensive approach to quality control in all phases of the sorting process is growing.

This paper presents a proposal of waste contamination detection approach, as part of the waste quality management. We have systemically analysed current waste quality control procedures in waste sorting centres, commonly used approaches and methods for waste quality monitoring. Based on the current requirements for contamination detection, we have proposed and designed early contamination detection approach, for deployment at the beginning of the waste stream. Our proposal outlines the necessary steps to design a state of art detection approach using modern multi sensor detection in combination with artificial intelligence. The focus is given on specifics of contamination detection in different recycled materials, like plastic and paper.

Our proposal creates a basis for a future research and development phase focused on creating an adaptive contamination detection system that will combine radar and camera data with artificial intelligence detection. The proposed solution is suitable for modern waste quality management, providing high degree of automation with improved decision support of waste streams. By integration with a higher-level system, it could serve as a tool to ensure compliance with environmental regulations, thereby contributing to more efficient, sustainable, and documentable waste management required in modern Europe.

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Návrh prístupu k monitorovaniu kvality odpadu a detekcii kontaminácie v kontexte moderných štandardov a technológií

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Súhrn

Článok predstavuje komplexný návrh prístupu k detekcii kontaminácie odpadu so zameraním na skoré fázy zberu odpadu. Systematicky sme analyzovali súčasné postupy kontroly kvality odpadu v triediacich strediskách odpadu, bežne používané prístupy a metódy monitorovania kvality odpadu. Na základe súčasných požiadaviek na detekciu kontaminácie sme navrhli a vytvorili prístup k detekcii kontaminácie na začiatku toku odpadu. Náš návrh zahŕňa potrebné kroky na návrh najmodernejšieho prístupu k detekcii s využitím modernej multisenzorovej detekcie v kombinácii s umelou inteligenciou. Dôraz sa kladie na špecifiká detekcie kontaminácie v rôznych recyklovaných materiáloch, ako sú plasty a papier.

Náš návrh vytvára základ pre budúci výskum a vývoj zameraný na vytvorenie adaptívneho systému detekcie kontaminácie, ktorý bude kombinovať radarové a kamerové údaje s detekciou pomocou umelej inteligencie.

Kľúčové slová: *kontaminácia odpadu, kvalita odpadu, recyklácia, radarové technológie, multisenzorická identifikácia*

The Secret of the Black Bins: Results of Physical Analyses of Mixed Municipal Solid Waste in the Czech Republic in 2018 – 2022

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Summary

This paper presents a comprehensive analysis of mixed municipal solid waste (MMSW) based on material composition conducted in Czech municipalities between 2018 and 2022. The study identifies key trends in mixed municipal waste generation, evaluates the efficiency of waste separation at source, and highlights the potential for improving municipal waste management practices. The findings reveal that a significant proportion of MMSW consists of recyclable fractions (65.6%). The largest share is represented by biodegradable waste (33.6%), followed by plastics (8.8%), textiles (6.5%) and paper waste (6 %). Trend analysis revealed a gradual decline in composite packaging materials, plastics and textiles, whereas a slight uptick in biodegradable waste indicated limited availability of separate collection systems in municipalities. These findings emphasize the need for better waste sorting systems and educational initiatives. On the other hand it yet suggests that the existing fee structure and collection infrastructure do not sufficiently alter household behaviour, resulting in substantial losses of valuable materials and energy. Wider adoption of pay-as-you-throw schemes, expansion of door-to-door biodegradable waste collection, and introduction of deposit-return systems for high-value packaging materials are therefore recommended. Finally, it is proposed that municipalities incorporate regular physical MMSW analyses into strategic planning to enable continuous assessment of the effectiveness of implemented measures.

Keywords: *municipal solid waste, physical waste analysis, waste management, circular economy, waste sorting*

1. Introduction

Municipal solid waste (MSW) management plays a crucial role in achieving sustainability goals and transitioning to a circular economy. Physical waste composition analyses provide essential data for evaluating the efficiency of waste sorting systems and identifying improvement areas. Previous studies on waste management in the Czech Republic and other European countries indicate that a large fraction of MMSW consists of biodegradable and recyclable materials, which are often not properly sorted and end up in landfills.

The following issue manifests at both the beginning and end of supply and value chains. On the input side, a key factor is the intensive extraction of primary raw materials, which is associated not only with significant environmental burdens, but also particularly in recent years with increasing economic uncertainty due to rising commodity prices.

On the output side, the persistent challenge lies in the generation of mixed, unrecycled, and further unutilised waste. Despite the availability of alternative waste management methods, landfilling remains the most commonly employed approach, both in the Czech Republic and in many EU countries. This results in the irreversible loss of valuable and often hard-to-obtain resources, except in cases where landfill mining is pursued — a highly limited and infrequently applied strategy with negligible material recovery at present.

1.1. What can be deduced from physical analyses of waste?

Physical waste analyses offer unique insights into consumer behaviour and help identify trends in waste generation. For example, in recent years, several European countries have seen an increase in the share of electronic waste in municipal solid waste, with particular attention drawn to emerging waste types such as electronic cigarettes and batteries.

Another key benefit of these analyses is the ability to pinpoint materials that are not being effectively captured by current sorting systems. In the Czech Republic, for instance, waste composition studies have revealed that significant amounts of recyclable plastics and paper still end up in residual waste, despite the wide availability of collection containers[1]. An important insight into the composition of mixed municipal waste is also provided by the company EKO-KOM, which conducts analyses at 160 locations every two years. Beyond environmental considerations, physical analyses can also enhance the economic efficiency of waste management. In Italy[2], for example, collection logistics were adjusted based on analysis results, leading to a reduction in operational costs.

1.2. Municipal Solid Waste Composition in the Czech Republic

In the Czech Republic, the responsibility for waste management falls primarily on municipalities rather than individual households. This is because Czech law mandates that municipalities are responsible for organising and ensuring the collection, transportation, and disposal of municipal waste, which includes waste generated by households. The relevant legislation is Law No. 541/2020 Coll. Waste Act, which clearly defines the role of municipalities as waste managers within their jurisdictions. They are also required to designate facilities for the separate collection of various waste fractions, including hazardous waste, paper, plastics, glass, metals, biodegradable waste, used edible oils and fats, and beginning 1st January 2025, textiles. Furthermore, municipalities must publish, at least annually and in a format accessible remotely (e.g. via the municipal website), detailed information on the scope and methods of separate waste collection, the amounts collected, the management of municipal waste, prevention and minimization measures, as well as the associated operational costs of the waste management system. Moreover, the Act establishes recycling targets for recyclable municipal waste: at least 60% by 2025, 65% by 2030, and 70% by 2035. These targets form part of the broader national Waste Management Plan (Plán odpadového hospodářství České republiky), embedding the principles of circular economy into local waste policy.

Landfilling remains a significant issue in the Czech Republic. While the overall landfill rate across all waste streams stands at 13 %, the situation is markedly more critical in the domain of municipal waste, where approximately 45 % of the total 5.8 mil. tonnes generated are landfilled, substantially exceeding the EU average of 23 %. The total volume of waste designated for disposal in 2022 amounted to 769 million tonnes. This category includes waste deposited in landfills, incinerated without energy recovery, or disposed of by methods such as deep-well injection or surface impoundment.[3]

1.3. Situation of Municipal Solid Waste Composition across Europe

In recent years, the European Union has adopted several strategic documents highlighting the importance of detailed waste composition monitoring. The European Green Deal sets ambitious goals for waste reduction and the promotion of recycling[4]. Complementing this, the Circular Economy Action Plan introduces concrete measures, including requirements for more detailed waste analyses to inform the development of future waste management policies[5].

According to Eurostat (2023), approximately 225 million tonnes of municipal waste were generated in the European Union in 2022, of which only 48 % was recycled[6]. Detailed physical waste composition analyses provide valuable insights into which waste fractions are not being effectively collected. These findings can inform improvements in waste management practices, such as expanding collection infrastructure or implementing targeted public awareness campaigns. For example, Estonian studies have revealed that despite established source-separation schemes, a substantial amount of plastics and biodegradable waste still ends up in the mixed municipal waste stream. This study has used such analyses to identify gaps in its collection systems and to guide efforts aimed at increasing recycling efficiency.[7]

The availability and frequency of physical waste composition analyses across Europe vary significantly. While some countries (such as Austria, Germany, and Denmark) regularly publish the results of detailed studies on municipal solid waste, others provide only limited data.

Across Europe, mixed waste analyses serve as an essential tool for evaluating the effectiveness of separate collection programmes, identifying weaknesses in collection infrastructure, and supporting the circular economy objectives set by the European Union. For example, in Austria[8], physical waste composition analysis is a common foundation for formulating waste minimisation strategies and enhancing recycling rates.

In Germany[9], study found that nearly 40% of this mixed waste consists of organic waste (mainly kitchen and garden waste), 32.6% is residual waste (e.g., hygiene products and ash), and 27.6% consists of still-recoverable dry materials such as plastics, paper, or glass. Special attention was given to hazardous waste (e.g., batteries), which is still found in small amounts in household waste. The study recommends improving public communication, expanding return and collection services, and implementing a mandatory nationwide system for organic waste collection in order to improve waste separation and reduce the overall volume of waste.

Similarly, in Greece, waste composition studies have been instrumental in revising national waste management legislation. The analyses highlighted deficiencies in waste collection infrastructure and the need for more effective recycling measures[10]. A study conducted in Crete identified three dominant waste biodegradable, paper, and plastics, which together constituted approximately 76% of total MSW. Putrescible waste alone represented 39%, while plastics and paper accounted for 17% and 20%, respectively. The share of glass (7%) was also notable, primarily consisting of disposable (non-refillable) bottles. In tourist-heavy areas such as Hersonisos and Malia, the proportion of glass rose to 18% during the autumn season[11].

As another example, in Estonia, SEI Tallinn completed a national waste composition study in 2020. The findings suggest that the composition of mixed municipal waste has remained relatively stable over the past decade. Compared to the 2012 study, the proportion of biodegradable waste has remained largely unchanged, while the share of plastics, paper, and cardboard has increased. Packaging waste now constitutes 32% of the MMSW. On average, biodegradable waste accounts for 32% of the MSW, primarily in the form of kitchen and food waste. These results are used to assess the performance of current collection and recycling systems and to identify areas for improvement[12].

On the other hand, Slovakia[13] presents a similarly concerning picture of up to 78% of the analysed mixed waste was theoretically recyclable. The largest fraction consisted of biodegradable kitchen waste. A localized analysis in the Košice region and a comprehensive 2020 survey of 31 municipalities, biodegradable waste consistently emerges as the predominant fraction, collectively accounting for nearly 40 % of the MSW stream, with 254% of planted-based biodegradable waste and 13.7% of kitchen waste [14]. Across the composition analysis in Slovakia, packaging waste accounts for roughly one quarter of the

MMSW mass, of which plastics are the single largest fraction. In Košice (urban) and Poproč (rural), packaging represented 24% and 29%, respectively[15]. While the average share of municipal waste ending up in landfills across the European Union is around 24 percent, Slovakia significantly exceeds this figure, with approximately 40 percent of its municipal waste still being landfilled. The share of waste being landfilled has been decreasing only marginally in recent years. In 2022, Slovakia's households sent approximately 1.1 mil. tonnes of waste to landfills - just 200,000 tonnes more than a decade earlier. In addition to household waste, around 16 percent of other waste types also end up in landfills[16].

The European Union's Waste Framework Directive mandates increased recycling rates and the reduction of landfill disposal, placing additional responsibility on municipalities to improve waste management strategies. In response, Czech municipalities have been conducting physical waste analyses to gain insights into waste composition and optimize waste collection systems. This paper presents a summary of such analyses conducted between 2018 and 2022, highlighting key trends and challenges in waste management.

This article presents the findings of over 50 physical analyses of mixed municipal waste conducted in the Czech Republic, thereby contributing valuable data to fill existing gaps regarding waste composition across Europe. These analyses focus on changes in waste composition over the past decade and enable the tracking of key trends in waste generation, such as the decline in plastic and textile waste and the increase in biodegradable waste, the latter attributed to improvements in source separation infrastructure.

2. Materials and Methods

Physical waste analyses represent a vital tool in waste management, providing essential data for the improvement of recycling systems, the optimisation of collection networks, and the identification of emerging waste streams. These analyses are increasingly integrated into the environmental policies of European countries, not only in response to the EU’s recycling targets, but also due to their economic and strategic benefits.

This study was designed to analyse the physical composition of MMSW among Czech municipalities, with a specific focus on household waste remaining after the separation of all recyclable fractions of municipal waste. This analysis was intended to provide information about which recyclable or non-recyclable waste fractions are present in MMSW samples and in what quantities, aiming to determine the share of individual fractions present in MMSW and evaluate the potential for improving MMSW separation. The proposed methodology standardizes the analytical procedure, ensuring comparability and reproducibility of results across locations and periods. This analytical procedure can be used for determining the composition not only of MMSW but also of other types of municipal waste, e.g. determining the composition of biodegradable municipal waste (BMW) produced in households.

The methodology was developed in accordance with the Methodological Instruction for Waste Sampling of the Ministry of Environment (2008) and the Ministry-certified Methodology for Determining the Composition of MSW (2021), with modifications to the classification of individual MSW fractions to enhance the clarity of results and their interpretation and to align with the specific objectives of this analysis. These modifications primarily concerned more detailed classification of certain MSW fractions that were not sufficiently distinguished in the original methodology, such as the detailed division of biodegradable or plastic waste.

The study design incorporated a comprehensive approach to deliver a detailed characterisation of the physical composition of MMSW (mixed municipal solid waste), quantifying the proportional contribution of each fraction to the overall amount of the residual waste. Analysis combined manual sorting of representative waste samples with sieve analysis, which utilized a 40 x 40 mm mesh sieve. MMSW underwent a complete material analysis, including the undersize (< 40 mm) fractions. Statistical methods were employed to analyse relationships between population characteristics and waste composition, enabling robust data interpretation and identification of significant trends.

2.1. Description of Sampled Waste and Municipalities

The subject of analysis is mixed municipal solid waste remaining after the separation of all recyclable fractions of municipal waste, classified as Mixed Municipal Waste under catalogue number 20 03 01 “směsné komunální odpady” in the Czech Waste Catalogue. Thus, the composition of the MMSW mainly consists of polluted packaging, kitchen waste, and general mixed waste.

A representative sample consisted of a predetermined amount of MMSW for which the material composition analysis was conducted. The research encompassed a total of 50 waste composition analyses carried out between 2018 and 2022 across 38 Czech municipalities with significant variation in population size. For these analyses, municipalities with populations up to 49,999 inhabitants were selected, reflecting the predominant small-scale settlement structure characteristic of the Czech Republic. By excluding only the largest cities exceeding 50,000 inhabitants, the analysis captures the diverse spectrum of predominantly rural and small-town settlement patterns that define the Czech territorial structure, while maintaining focus on communities where local governance dynamics and citizen participation patterns differ significantly from those in major urban centers. In several municipalities, analyses were conducted repeatedly in different years and seasons to capture potential temporal variations in waste composition, which explains the higher number of analyses compared to the number of municipalities. This approach also allowed for a more robust dataset reflecting both geographic and temporal diversity within the Czech Republic.

2.2. Sampling Procedure

The sampling process required close cooperation with local authorities who provided essential support. The site selection and positioning method for the representative sample for field analysis were determined based on local conditions, current weather, and the needs of the sampling group. The site chosen considered the time and financial costs of preparation and execution of the analysis. The area designated for analysis was clearly marked and secured against unauthorized entry. A tarp placed both under and over the sampled material prevented waste leakage. An ideal location for analysis is a waste collection center (WCC), usually located within or near the municipality, facilitating the transportation of the representative sample. These sites are usually fenced and secured, allowing temporary restricted access during the survey period. Utilizing WCCs is advantageous as municipalities typically manage them, simplifying necessary arrangements and organizational logistics.

Sampling events were scheduled to coincide with regular MMSW collection days. Based on agreements with municipalities and waste collection companies, a set of MMSW batches (approximately 1 ton) collected from residential buildings were delivered to the designated research site immediately after collection by municipal technical services. From this batch, representative samples of 500 kg were compiled. Representative samples were constructed from individual sub-samples randomly collected from different layers and sections of the delivered waste batch, ensuring random data selection conditions. The collected samples typically represented MMSW production in households over a period of 1 – 2 weeks, depending on the collection frequency in the given locality. It is important to note that the survey was always conducted without prior notification to citizens, in order to preserve the authenticity of their normal waste production behaviour and obtain a realistic picture of MMSW composition unaffected by the ongoing investigation.

2.3. Pre-sampling Preparation and Safety Measures

Prior to each sampling event, the number of personnel involved in the analysis (samplers) was set at 4 – 6 workers per analysis. All samplers underwent thorough training on hygiene and safety principles that needed to be maintained throughout the survey. Given that workers come into contact with potentially hazardous substances during MMSW handling, it was essential to handle samples with increased caution.

Sanitary facilities (toilet with running water and disinfectant) and a first-aid kit equipped for minor injury treatment were always available at the analysis site. Workers were equipped with necessary protective equipment throughout the duration of the analysis, including long, cut-resistant gloves, protective glasses, face shields, respirators, work clothing, work coveralls, rubber boots, head coverings, and reflective vests indicating ongoing research.

The following tools were always available during analysis: rakes, brooms, shovels, knives, scissors, brushes, sturdy large-volume bags (50 l) for waste sorting, digital scales for determining the weight of individual fractions, and a set of sieves. Sieves were used to separate the undersized fraction from other MMSW fractions, using combinations of sieves with mesh size 40 × 40 mm.

Strict hygiene protocols were emphasized throughout the survey. Workers were prohibited from consuming food or drink during analysis. Breaks for refreshments and fluid replenishment were scheduled at predetermined intervals and only after proper hand washing and disinfection. Upon completion of work, thorough body disinfection was performed, and all used protective equipment was deposited at the collection yard for disposal.

2.4. Waste Sampling Methodology

The methodology followed the official Methodological Instruction for Waste Sampling of the Ministry of Environment (2008) and the Ministry-certified Methodology for Determining the Composition of MSW (2021). Modifications were introduced to enable a more detailed breakdown of individual MSW fractions and to improve the clarity of results in relation to municipal waste management practices. These adjustments allowed for a clear identification of material streams with the high potential for separate collection and recycling.

The waste sampling was always commenced in the morning, following a standardized methodology to ensure consistency and accuracy. The representative MMSW sample, after being deposited in the designated area, was manually sorted into 12 categories and detailed subcategories according to waste types, as different types of plastics and paper, metals or container glasses. Each waste fraction was placed into 50-liter plastic bags before being weighed to determine the mass balance of the individual waste fractions. The monitored indicator was the weight of individually sorted MSW fractions contained in the waste samples. For each material group, the total weight and its proportion of the total sample weight were determined separately.

A Solid Bench bridge weighing device with a capacity of up to 150 kg and an accuracy of 0.05 kg was used to weigh individual fractions. Weighing was carried out continuously after filling each collection bag, and the total weight of individual fractions was determined by summing the weights of the partial collection bags and recorded in the prepared protocol. The entire analysis was carefully photographically documented to enable retrospective verification of the correctness of the procedure and possible additional evaluation of the sorted fractions. After sorting and weighing were completed, all analysed waste was emptied into pre-prepared collection containers for proper disposal by municipal services. No laboratory samples were required for this particular study, as the analysis focused solely on the composition and weight distribution of municipal waste fractions.

The results of this waste analysis provide insight into the composition of municipal waste and potential opportunities for improved waste management and separation strategies. The findings support municipal decision-making regarding future waste reduction measures and the elimination of hazardous and critical waste fractions.

2.5. Classification System for Waste Fractions

The physical waste analysis classified the collected waste into distinct fractions based on their recyclability and material composition, reflecting the final categorization scheme applied in the study. Waste was divided into two primary categories: non-recyclable waste and recyclable waste. The non-recyclable fraction included mixed municipal solid waste (MMSW) and miscellaneous waste (MW) as other residual waste including hazardous waste or infectious waste that could not be assigned to recyclable categories. The recyclable fraction encompassed biodegradable waste (BIO), which includes both plant- and animal-based organic materials; plastic waste; textile waste; paper waste; glass waste; metal waste; waste from electrical and electronic equipment (WEEE); composite packaging materials (CPM); treated wood waste (WW) and batteries and accumulators (BaA). Each fraction was quantified as a share of the total waste composition, enabling further evaluation of material recovery potential and contamination levels. Batteries and accumulators were identified but not present in the analysed samples.

Figure 1: The physical analysis, captured by unmanned aerial vehicle, offering a comprehensive view of the manual sorting of MMSW, 2023

2.6. Statistical Analysis

For statistical evaluation, the proportions of individual waste fractions (e.g., plastic, paper, glass, metal) were analysed based on manual sorting of mixed municipal waste samples collected from 38 selected cities. Prior to analysis, the data were cleaned to remove errors and extreme values, standardized, and converted into a machine-readable format suitable for processing in the R programming environment (version 4.5.0)[17].

The statistical analysis focused on identifying potential relationships between waste composition, time of sampling, and the population size of municipalities. To estimate temporal trends in the time series, several regression approaches were applied:

- Classical linear regression model (LM) – baseline estimation assuming homoskedasticity and independence of errors.
- Robust linear model (RLM) – downweights the influence of outliers by weighting observations according to residuals, producing estimates less sensitive to extreme values.
- Linear model with cluster-robust standard errors – accounts for potential non-independence of observations due to repeated measurements within the same municipality. Standard errors were adjusted using a cluster-robust approach (sandwich estimator) with CR2 correction, clustering by municipality.
- Linear mixed-effects model (LMM) – includes municipality-level random intercepts to account for the hierarchical structure of the data and unobserved heterogeneity between municipalities.

Model assumptions, including the normality of residuals and homoscedasticity, i.e., that the variance of the error terms is constant across all levels of the independent variables, were evaluated using diagnostic plots[18]. In case of potential violations of model assumptions, robust regression was applied using the rlm function from the MASS package in R19. This method reduces the influence of outliers and non-constant variance by iteratively reweighting observations, offering more reliable estimates in the presence of heteroskedasticity or non-normal residuals. To further account for intra-group correlation and potential violations of the independence assumption across observational units, cluster-robust standard errors were computed. Specifically, the vcovCR() function with the CR2 estimator was used to correct the standard errors for clustering at the municipal level[20]. Results were presented asregression curves or point estimates with confidence intervals to highlight systematic temporal changes in the composition of the waste samples. Visualizations were created using the ggplot221 package in R, based on pre-computed model predictions.

Temporal trends in the proportion of waste types were assessed using linear mixed-effects models implemented via the lmer function from the lme4 package in R[22]. In these models, the proportion (pW) for each waste category was expressed as a function of time (date), with a random intercept for municipality (muni) to account for unobserved heterogeneity and the hierarchical structure of the data. Estimation was performed using restricted maximum likelihood (REML), which provides unbiased estimates of variance components under normality assumptions[23].

3. Results

The physical waste analyses were conducted over a five-year period from 2018 to 2022, with a total of 50 samplings from 38 Czech municipalities (Fig. 2). The municipalities ranged in population from 547 to 49,705 inhabitants, representing the characteristic fragmented settlement structure of the Czech Republic. The population distribution of the 38 studied municipalities demonstrated positive skewness, with the mean population (6,557.5 inhabitants) being higher than the median (3,567 inhabitants). This disparity indicates that while the majority of municipalities were small communities, a few larger municipalities approaching the 10,000 inhabitant limit pulled the mean upward. The median provides a more representative measure of the typical municipality in the sample, demonstrating that most waste composition analyses were conducted in smaller Czech municipalities, which reflects the general pattern of Czech municipal demographics characterized by numerous small communities.

The number of analyses increased notably from 4 in 2018 to a peak of 19 in 2019, followed by a decline to 7 in 2020 (influenced by COVID-19 pandemic restrictions). On average, 10 analyses were performed annually. Fig. 3 masks the substantial year-to-year variation. Seasonal distribution revealed a strong bias toward spring and autumn sampling, which together accounted for 58 % of all analyses. Summer and winter periods were mildly underrepresented due to the weather conditions. This seasonal pattern reflects practical considerations such as weather conditions and accessibility for waste sorting activities.

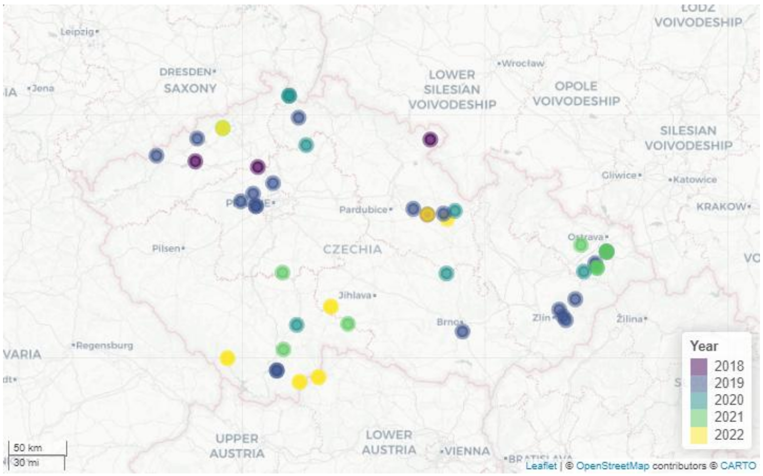

Figure 2: Geographical distribution of analysis sites in the Czech Republic, 2018 – 2022

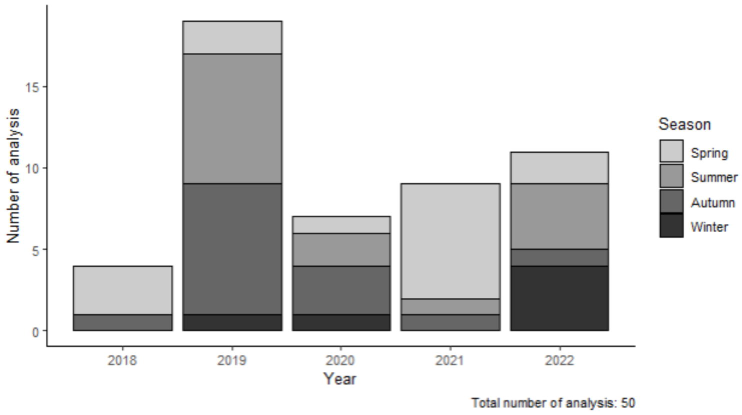

Figure 3: Temporal distribution of analyses conducted in 2018 – 2022 categorized by season

Waste samples contained MMSW from households, with each sample weighing an average of 500 kg. MMSW fractions were identified and manually sorted into 12 categories and subcategories. As a result of the study, the average composition of the waste samples was determined. The category of non-recyclable waste included waste fractions that could not be further materially utilized, encompassing hazardous waste, infectious waste, sub-sieve fraction, and residual mixed waste that cannot be recycled or reused. The average proportion of materially non-recyclable waste in municipalities amounted to 34.44% of total MMSW amount, while recyclable waste comprised 65.56 % (Tab. 1).

The comprehensive analysis revealed highly heterogeneity in waste composition. Biodegradable waste constituted the largest proportion in waste samples with an average rate of 33.62%, consisting of compostable and non-compostable fractions. Given the significant share of biodegradable waste in MMSW and its environmental impact, this waste category was further subdivided. The compostable biowaste was further categorized into biodegradable waste originating from gardens, parks, and urban greenery, and kitchen waste of plant origin. Non-compostable biodegradable waste predominantly comprises materials of animal origin, including meat residues, bones, eggs, and food products that have undergone thermal or other forms of processing. Besides biowaste, the next most numerically represented recyclable fractions in the MMSW samples was plastic waste with a share of 8.84%, followed by paper fraction representing 5.93% of total MMSW weight and textile waste comprising 6.46%.

Non-recyclable MMSW fractions, which should theoretically constitute the predominant portion of the waste sample, actually occupied slightly over one-third of the total waste samples, with 29.23 % comprising MMSW and an additional 5.21 % consisting of miscellaneous waste. Although residual MSW represents the second-highest proportion in the physical waste analysis, its representation was surprisingly low, particularly considering that the analysed MMSW sample represented residual waste following the separation of all recyclable fractions. The sample should theoretically consist of a large percentage of non-recyclable mixed waste, while recyclable waste should appear in minimal quantities after sorting (Fig. 4).

Table 1: Average percentage share of waste fractions in MMSW

Utilization	Waste Type	Share [%]
Non-recyclable waste 34.44 %	Mixed municipal solid waste (MMSW)	29.23
	Miscellaneous waste (MW)	5.21
Recyclable waste 65.56 %	Biodegradable waste (BIO)	33.62
	Plastic waste (PL)	8.84
	Textile waste (TE)	6.46
	Paper waste (PA)	5.93
	Glass waste (GL)	5.06
	Metal waste (ME)	2.73
	Waste from electrical and electronic equipment (WEEE)	1.17
	Composite packaging materials (CPM)	0.96
	Wood waste (WW)	0.79
	Batteries and accumulators (BaA)	0.00

Note: A three-tiered color-coding system is applied to categorize constituent materials based on their proportional representation in the waste stream: Red (>15 %); Orange (5-15 %); Blue (<5 %)

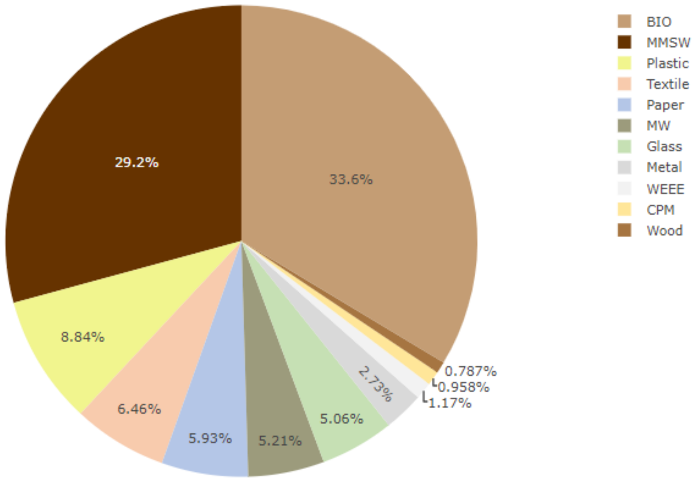

Figure 4: Proportional representation of individual waste fractions in samples of MMSW. Abbreviations: BIO: biodegradable waste; MMSW: Mixed municipal solid waste; MW: Miscellaneous waste; WEEE: Waste from electrical and electronic equipment; CPM: Composite packaging materials, 2018 – 2022

The physical analyses results reveal considerable heterogeneity in MMSW composition and variability in the proportions of individual fractions identified across the monitored Czech municipalities. This diversity may be attributed to several factors influencing waste characteristics and composition in Czech municipalities. One primary factor is the varying effectiveness of waste sorting systems implemented across different municipalities. Some municipalities have established efficient waste sorting systems with extensive collection container networks, frequent collection schedules, and adequate public awareness. These municipalities may exhibit lower proportions of recyclable fractions in MMSW. Conversely, municipalities with less developed waste sorting infrastructure can be expected to show higher representation of potentially recyclable fractions in MMSW. Beyond these primary factors, additional variables may influence waste composition, including seasonal fluctuations in waste production (e.g., higher biodegradable waste production during summer months), local economic conditions affecting consumption patterns, and regional specificities (recreational areas) [24, 25, 26, 27, 28].

The statistical analysis included an experiment examining relationships between the proportions of waste fractions present in MMSW samples, the time of sampling, and the population size of individual municipalities, using 3 regression approaches: classical linear model, robust linear model, and the linear model with cluster-robust standard errors. These results were compared in terms of standard errors, statistical significance, and trend direction. Overall, the direction and magnitude of estimated trends were consistent, while significance levels were appropriately adjusted for within-municipality correlation.

Among the tested waste types, plastics, beverage cartons, and textile waste demonstrated declining trends over time, suggesting improving sorting practices for these waste categories in municipalities. In contrast, biodegradable waste exhibited an increasing trend, indicating a growing share of this waste type in MMSW. Mixed municipal waste demonstrated only a minimal increase, resembling stable development (Fig. 5). These results confirm effective sorting of plastic waste, beverage cartons, and textile waste. However, attention must be focused on reducing biodegradable waste quantities, improving its sorting, or preferably preventing its generation through home composting initiatives.

Comparison of the robust and classical linear models indicated that estimates were generally similar. However, the robust model often yielded a lower residual standard error, confirming its resistance to the influence of outliers. A notable difference was observed for the plastic fraction, where the robust model estimated a slight decline over time, whereas the model with cluster-robust standard errors suggested almost no change. This discrepancy illustrates the potential impact of outliers on trend estimation.

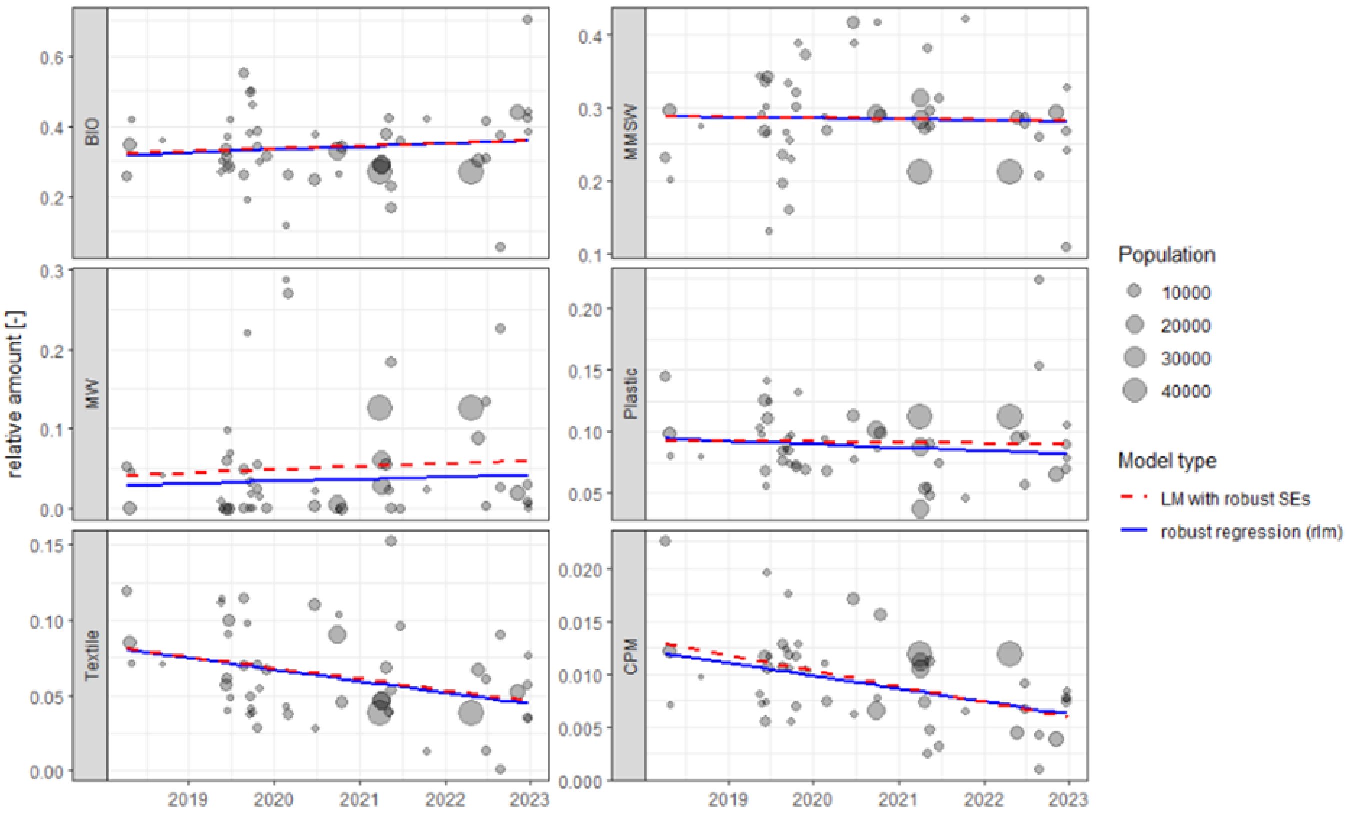

Figure 5: Temporal analysis of key MSW fractions across Czech municipalities (2018 – 2022), scaled by population size. Abbreviations: BIO: biodegradable waste; MMSW: Mixed municipal solid waste; MW: Miscellaneous waste; CPM: Composite packaging materials. 2025

An additional mixed-effects model was used to better account for the impact of repeated measurements from the same municipalities, with selected key results shown below:

Biodegradable waste (BIO): The analysis employed a linear mixed-effects model (lmer) with municipality-level random intercepts to account for variation between groups. The fixed effect for time (date) was positive but not statistically significant ($\beta = 2.07e{-5}$, $t = 0.66$). Most of the variance was captured by the residual component (SD = 0.0978), but the random intercept for municipality also showed notable variability (SD = 0.0464), suggesting differences in baseline levels across municipalities. The proportion of BIO in MMSW was additionally tested for temporal and seasonal patterns using a linear mixed-effects model because of its seasonal characteristics. Fixed effects included date (as a continuous time variable), season (categorical: Spring [ref], Summer, Autumn, Winter), and a random intercept for each municipality to account for between-group variability ($n = 38$). The fixed effect of time was small and not statistically significant ($\beta = 1.35e{-5}$, $t = 0.41$), indicating no consistent linear trend over time. Seasonal effects showed some variation: compared to spring (reference category), the share of biowaste was higher in autumn ($\beta = 0.075$, $t = 1.84$) and winter ($\beta = 0.088$, $t = 1.59$), though these estimates were not statistically significant at conventional thresholds. Random effects indicated modest between-municipality variability (SD = 0.043), with the majority of variance explained by residual variation (SD = 0.097). Overall, the model suggests a possible seasonal pattern, with higher proportions of BIO in autumn and winter, and no clear time trend. However, due to the limited sample size ($n = 50$) and uneven seasonal coverage, these results should be interpreted with caution.

Plastics: A slight negative trend over time was detected ($\beta = -5.29e{-6}$), accompanied by a small but non-zero municipality-level variance (SD = 0.0237). The residual variance (SD = 0.0212) was of similar magnitude, indicating that both individual- and group-level components contributed modestly to the overall variability.

Textile: The model estimated a negative time effect (β = −2.00e−5), suggesting a possible decline over time. Municipality-level variance was zero, indicating highly similar baseline levels across municipalities. Residual variation (SD = 0.0303) accounted for all observed differences.

Composite packaging materials: A slight negative time trend was observed (β = −4.49e−6), with minimal variation attributable to municipalities (SD = 0.0034). The residual component was also relatively small (SD = 0.0021), suggesting limited overall variability in this waste type.

MMSW: The model indicated a negligible positive time trend (β = 4.85e−7), suggesting virtually no change over time. Variability between municipalities was modest (SD = 0.0421), while the residual variance remained the dominant source of variation (SD = 0.0548). These results point to temporal stability in this waste type.

Miscellaneous waste: A small positive time effect was identified (β = 1.08e−5), while the municipality-level random effect variance was estimated at zero, indicating no detectable between-group variability. The residual standard deviation was 0.0734, implying that variation occurred primarily at the individual observation level.

Across all waste fractions, the effect of time was small and in many cases statistically non-significant, indicating relative stability in composition over small municipalities and the observed period. For recyclable fractions such as textiles and plastics, slight negative trends were observed, which indicates a reduction of these materials in the MMSW waste stream and suggest a gradual improvement in source separation, possibly influenced by policy measures such as the upcoming mandatory textile collection in 2025 and the expansion of multi-material collection systems. This is a positive development, as lower proportions of recyclable materials in MMSW reflect more effective diversion from disposal and better system performance. In contrast, biodegradable waste showed no statistically significant reduction, remaining the largest single component of residual waste, which points to persistent shortcomings in its separate collection. Variability between municipalities was notable for certain fractions, such as biodegradable waste, plastics, and MMSW, implying that local conditions, including settlement size, infrastructure availability, and collection systems (e.g. frequency) play a role in determining outcomes. In contrast, fractions with zero municipality-level variance (e.g., textiles and metals) appear more homogeneous nationwide, with observed changes driven primarily by temporal factors rather than local factors. Overall, the results indicate that while targeted municipalities with up to 49 999 inhabitants show modest signs of progress in certain material streams, substantial amounts of recyclable materials remain in MMSW, indicating that targeted, locally adapted interventions are still needed. Extending such analyses to larger municipalities will be essential to fully understand national waste composition dynamics and to design interventions that are effective across diverse settlement types.

4. Discussion

The physical analyses of MMSW conducted in 38 Czech municipalities up to 49 999 inhabitants between 2018 and 2022 reveal a surprisingly large quantity of recyclable materials still found in residual black-bin waste, with several key trends: a consistently high share of biodegradable waste and a modest decline in beverage cartons, textiles, and plastics. These findings underscore both systemic shortcomings and strategic opportunities for improvement.

The finding that 65.56% of MMSW consists of recyclable fractions requires interpretation that goes beyond a purely technical reading of the data. The substantial presence of high-value materials such as PET bottles, paper, and textiles in MMSW highlights systemic inefficiencies rather than solely methodological artefacts. The measured inefficiency of the system is not influenced by the methodology, as the adopted approach allows only minimal room for inaccuracies, unlike the methodology used by the Ministry of the Environment, which does not separate fine fractions and instead incorporates them into MMSW, despite the fact that fine fractions may contain a considerable share of biodegradable material.

Analyses were carried out in several municipalities with diverse waste management systems, taking into account factors such as the distance to collection points, the type of housing (multi-unit versus single-family dwellings), and other relevant variables. The reported outcomes represent a weighted average of all analyses conducted. The findings reveal a significant inefficiency within the current waste management system, which relies primarily on voluntary citizen participation and gradual public education. The presence of 65.6% recyclable components in residual waste may be interpreted as an approximate upper limit of the effectiveness of such a system. Further intensification of waste separation efforts, in the absence of additional motivational instruments, is unlikely to lead to substantial improvements.

The observed decline in beverage cartons and textiles over time can likely be attributed to intensified source separation efforts: in the case of textiles, as a preparatory response to the mandatory textile collection starting in 2025; and for beverage cartons, due to the increasing adoption of multi-material collection systems (e.g., plastics, metals, and cartons combined). This trend highlights that where concrete interventions combine **convenient infrastructure** with **systemic incentives**, behavioral shifts among residents are achievable.

However, the persistently high proportion of biodegradable waste — averaging 33.62% — remains a major concern. Although biodegradable waste constitutes the single largest waste fraction by both weight and volume, its separate collection is clearly insufficient. This situation has significant environmental implications, such as methane generation in landfills, and represents a missed opportunity for the production of biogas, compost, or digestate. The findings clearly indicate that the current system in small towns is ineffective: **most residents pay a flat-rate waste fee**, meaning their behavior has no impact on costs, and **collection containers for sorted waste are often farther away than residual bins**, reducing the convenience of source separation. In municipalities with maximum inhabitants up to 49 999, waste management services operate with limited budgets, which can result in less frequent collections, fewer container locations, and lower investment in public awareness campaigns. Seasonal fluctuations, such as increased population during holiday periods, can further strain existing collection systems and exacerbate inefficiencies in waste separation.

One of the key contributions of this study lies in its ability to quantify these patterns across time and location. Without adequate motivation — whether financial (e.g., discounts, PAYT schemes, deposit-return systems) or ergonomic (e.g., proximity and usability of bins) — behavioral change is unlikely. Moreover, according to annual reports from authorized packaging company EKO-KOM[29], about 20 – 30% of households still do not engage in waste sorting at all, or do so insufficiently, highlighting a significant untapped potential for improving source separation directly at the source. The fact that over 65% of residual waste still consists of recyclable materials indicates that existing measures in small municipalities are insufficient. There is an urgent need to redesign the system to be convenient, motivational, and economically fair.

Behavioural and social aspects further amplify these effects. Established disposal habits, limited awareness of the economic and environmental value of recyclables, and perceived inconvenience in transporting sorted materials to bring points all contribute to recyclable leakage into residual streams. Seasonal and situational factors – such as garden waste peaks, tourist influxes, or limited storage space in multi-unit housing – may also temporarily increase the share of recyclable fractions in black-bin waste.

These findings indicate that the high proportion of recyclable materials in residual waste is not simply a measure of technical recovery potential, but a reflection of the interplay between collection infrastructure, economic incentives, and household behaviour. Incorporating such behavioural and service-related parameters into future waste composition studies would enable a more accurate assessment of systemic efficiency and support the design of targeted interventions, such as improved container accessibility, PAYT implementation, or deposit-return systems for high-value packaging.

The data presented can be used not only to optimize local collection networks but also to inform **national policy interventions**. For instance, introducing deposit-return schemes for PET bottles and aluminum cans – materials with high market value and volumetric impal – would address key leakage points. Likewise, **door-to-door collection of biodegradable waste** should be prioritized, drawing inspiration from proven international practices. The study also notes that certain fractions (e.g., e-waste, composite materials) remain underrepresented, which may reflect not only analytical methodology but also low consumer engagement in specialized waste sorting.

Future research should delve deeper into the **motivational factors influencing household waste behavior**, the effect of container proximity, pricing models, and seasonal waste generation. Additionally, it would be beneficial to integrate physical waste composition data with **municipal sorting performance metrics**, thereby enabling a more holistic understanding of system efficiency. The results of physical waste analysis can be effectively used for several key purposes. They provide a basis for designing and optimising strategies aimed at increasing the rate of sorting recyclable and recoverable waste. Additionally, such data can support the adjustment of legislative measures related to waste management at the regional or national levels. Furthermore, the findings can help municipalities to set priorities for investment in local waste processing infrastructure.

5. Conclusion

This study presents a comprehensive analysis of the physical composition of mixed municipal solid waste (MMSW) in the Czech Republic, based on 50 standardized sampling campaigns conducted between 2018 and 2022 across 38 municipalities (inhabitants < 49 999). The results offer a detailed, data-driven insight into waste generation patterns and the efficiency of existing waste separation systems mainly in small Czech municipalities.

Key Findings:

The analysis reveals that **biodegradable waste constitutes the largest single component**, accounting on average for **33.62%** of total MMSW. This is followed by plastic waste (**8.84%**), textiles (**6.46%**), and paper (**5.93%**). Non-recyclable waste makes up **34.44%** of the total, a surprisingly low proportion given that the sampled waste represents residual streams after source separation. This suggests significant inefficiencies in waste sorting practices.

Temporal trend analysis identifies **statistically significant reductions** in the shares of **beverage cartons, textiles, and plastics** in the residual waste stream, indicating modest improvements in source separation for these categories. Conversely, the **share of biodegradable waste has slightly increased over time**, a finding that is both unexpected and concerning, given the availability of composting infrastructure in many municipalities. The composition of residual waste thus remains relatively stable in structure but suboptimal in performance, particularly with respect to organic waste management.

Interpretation and Implications:

These findings highlight critical systemic shortcomings in the Czech waste management over small up to medium-size areas. While improvements in the separation of some recyclable streams are observable, the persistent presence of biodegradable waste and other recoverable materials in MMSW suggests that **neither current infrastructure nor incentive structures are sufficient**. The flat-rate payment system, coupled with suboptimal accessibility of sorting infrastructure (i.e., containers located farther than residual bins), contributes to a lack of behavioral change among residents.

The study also confirms the **high material recovery potential** embedded within residual waste — 65.56 % of the analysed waste could be recovered or recycled. Particularly from a resource economics perspective, the presence of PET bottles and aluminum cans in residual waste represents a **significant loss of marketable materials**.

Recommendations for Practice and Policy:

The data advocate for a shift toward more **personalized and motivational waste management models**, such as:

- **PAYT (Pay-As-You-Throw) systems** to link behavior with cost;
- **Door-to-door collection schemes**, especially for bio-waste;
- **Deposit-return systems** for high-value packaging materials;
- Targeted communication strategies backed by behavioral insights and data.

From a policy perspective, these results reinforce the urgency of moving beyond infrastructural expansion and toward **systemic redesign that prioritizes motivation, convenience, and economic feedback loops**.

While this study provides valuable insights into waste composition across a wide geographic range in Czechia, the sampled municipalities all had populations below 49,999 inhabitants. Extending physical waste composition analyses to medium-sized towns and large municipalities is essential for building a comprehensive national dataset. Such an expansion would capture the influence of higher population density, diverse socio-economic conditions, and different waste management systems, enabling more accurate generalizations and the design of targeted, scalable policy interventions.

In conclusion, althoughthe Czech Republic has made measurable progress in waste separation, this analysis confirms that the **status quo is insufficient to meet EU circular economy targets** or to meaningfully reduce landfill rates. If biodegradable waste and high-value recyclables continue to leak into residual streams, both environmental and

Physical waste composition analyses – standardized, repeated, and scaled—should be embedded as a regular diagnostic tool for evidence-based municipal and national policy planning.

Acknowledgements

A special thanks to Professor Bedřich Moldan for his help with the formulation of research questions, as well as with focusing attention on the most essential aspects of the research in the field of circular economy, waste management focused specifically on textiles.

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Tajemství černých popelnic. Výsledky fyzických analýz směsného komunálního odpadu v letech 2018 – 2022

***Soňa Klepek JONÁŠOVÁ*[1], *Bedřich MOLDAN*[1], *Lukáš ZEDEK*[2], *Vratislav ŽABKA*[2], *Tereza VÁLKOVÁ*[3], *Shuran ZHAO*[4], *Petr NOVOTNÝ*[5]**

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Abstrakt

Tento článek představuje komplexní analýzu směsného komunálního odpadu (SKO) na základě fyzických rozborů jeho složení, které byly provedeny v českých obcích v letech 2018 až 2022. Studie identifikuje klíčové trendy v produkci odpadu, hodnotí efektivitu třídění a upozorňuje na potenciál zlepšení v oblasti nakládání s komunálním odpadem. Výsledky ukazují, že významnou část SKO tvoří biologicky rozložitelné a recyklovatelné materiály, což zdůrazňuje potřebu kvalitnějších systémů třídění a osvětových aktivit na podporu recyklace. Použitá metodika vychází ze standardizovaných postupů vzorkování a dat shromažďovaných po dobu deseti let.

Klíčová slova: *směsný komunální odpad, fyzická analýza odpadu, odpadové hospodářství, cirkulární ekonomika, efektivita třídění odpadu.*

Patron of the issue / Patron čísla: Symposium *ODPADOVÉ FORUM 2025 (12. – 14. 10. 2025, Hustopeče, Česká republika)*

Symposium
Výsledky výzkumu a vývoje pro průmyslovou a komunální ekologii
ODPADOVÉ FORUM 2025 (14. – 16. 10. 2025, Hustopeče)

Symposium se koná spolu s konferencí APROCHEM zaměřenou na rizikový management v rámci Týdne výzkumu a inovací pro praxi a životní prostředí TVIP 2025. Veškeré informace a aktuality na www.tvip.cz.

AVÍZO: Následující ročník, symposium ODPADOVÉ FORUM 2026 se bude konat 24. – 26. 3. 2026 opět v Hustopečích. Zvýrazněnými tématy budou: **Aktuální projekty: odpady – voda – ovduší; Vedlejší produkty z potravinářství; Odpady z recyklace a výroby automobilů; Radioaktivní a problémové odpady.**

PROGRAM *(stav k 11. 9. 2025)*

ÚTERÝ dopoledne 9:00 –13:20 hod. ODPADY ZE A PRO STAVEBNICTVÍ

Recyklace a reuse stavebních materiálů z demolic
Ing. Zuzana Vedralová, UCEEB ČVUT

Porovnanie vyhod optického a robotického triedenia s použitím AI
Ing. Robert Procházka, PhD., MBA, VÚMZ SK, s.r.o.

Možnosti využívání cihelných a betonových recyklátů jako náhrady přírodních kameniv pro výrobu betonů
Prof. Ing. Rudolf Hela, CSc. Ing. Klára Křížová, Ph.D., VUT v Brně, Fakulta stavební, Ústav technologie stavebních hmot a dílců

Využití mletého betonového recyklátu jako částečné náhrady cementu či jako mikroplniva v cementových kompozitech
Ing. Ivana Chromková, Lubomír Zavřel, Výzkumný ústav stavebních hmot, a.s., Brno

Efektivní využití odpadního skla v cementovém kompozitu
Ing. Zdeněk Prošek, Ph.D., prof. Pavel Tesárek, Ing. Aleš Palička, ČVUT v Praze, Fakulta stavební

Cirkulární využití nemrznoucích směsí v HVAC systémech a jeho dopad na uhlíkovou stopu
Ing. Olga Pleyer, Ph.D., Ing. Jan Skolil, Ph.D. CLASSIC OIL, s.r.o.

Vícesložkové směsné cementy a příměsi pro betonové konstrukce
Ing. Miroslav Procházka, Technický a zkušební ústav stavební Praha, s.p.

Sanační a výplňové malty na bázi metalurgických odpadů
Doc. Ing. Jana Daňková, Ph.D., Ing. Adéla Valentová, Mgr. Petr Běčák, prof. Ing. Jana Seidlerová, CSc., VŠB-TU Ostrava, Stavební fakulta

Popílky z odkaliště Elektrárny Třebovice v Ostravě pro použití v cementu, betonu a zemních pracích
Doc. RNDr. František Kresta, Ph.D., SG Geotechnika, a.s.

Případová studie využití recyklovaného stavebního sádrokartonuo
Prof. Ing. Pavel Tesárek, Ph.D. Ing. Zdeněk Prošek, Ph.D. Ing. Hana Fojtáchová, ČVUT v Praze, Fakulta stavební

Případová studie - konstrukce vozovky s maximalizovaným podílem recyklovaných materiálů
Doc. Ing. Jan Valentin, Ph.D., ČVUT v Praze, Fakulta stavební; Ing. Tomáš Baloch, Pražské služby a.s., ZEVO Malešice; Ing. Michal Šyc, Ph.D., Ústav chemických procesů AV ČR; Amira Ben Ameur, MSc., ČVUT v Praze, Fakulta stavební

ÚTERÝ odpoledne 14:00 – 18:40 hod. ODPADNÍ TEXTIL

Osud oděvů
Prof. Ing. Jakub Wiener, PhD., Technická univerzita v Liberci

Design for recycling: eko-koberec z lýkových vláken
Ing. Jana Šašková, PhD., Prof. Ing. Jakub Wiener, PhD., Technická univerzita v Liberci

Využití textilního odpadu
Ing. Roman Knížek, Ph.D., MBA, Technická univerzita v Liberci, Fakulta textilní, Katedra hodnocení textilií

Potenciál recyklace textilu v ČR
Ing. Robert Šimek, RETEX, a.s.

Jak nová legislativa EU změní podmínky recyklace textilu
Ing. Robert Šimek, RETEX, a.s.

Deadstock: odpad nebo surovina
Ing. Petra Koudelková, Ph.D., PhDr. Soňa Schneiderová, Ph.D., Univerzita Karlova, Fakulta sociálních věd, Institut komunikačních studií a žurnalistiky

Analýza chemických rizik v textilních výrobcích z pohledu evropské legislativy
Ing. Olga Chybová, INOTEX s.r.o., Dvůr Králové n.L.; Ing. Jakub Fojt, Ph.D., Textilní zkušební ústav, Brno

Cirkulárna ekonomika textilného odpadu z automobilového priemyslu ako účinný nástroj pre aplikácie, ktoré prispievajú k adaptácii stavieb na zmenu klímy
Juraj Plesník

Chemická recyklace pro textilní odpady
Ing. Radek Pjatkan, Svaz chemického průmyslu ČR

Zpracování textilního odpadu pomocí vysokoteplotního plazmatu pro energetické a materiálové využití
Dr. hab. Mgr. Maksym Buryi, Ph.D., Mgr. Alan Mašláni, Ph.D., Mgr. Michal Hlína, Ph.D., Dr. Shelja Sharma, Dr. Brenda Natalia Lopez Nino, Ing. Jafar Fathi, Ing. Jakub Pilař, Ústav fyziky plazmatu AV ČR, v. v. i.

Problematika mikroplastů při čištění průmyslových a komunálních odpadních vod
Ing. Lubor Laichman, Ph.D., Ing. Marek Holba, Ph.D., ASIO TECH, spol. s r.o.

Využití iontové výměny pro separaci kyselých azobarviv
Ing. Jonáš Malý, prof. Ing. Tomáš Weidlich Ph.D., Ústav environmentálního a chemického inženýrství, Univerzita Pardubice

STŘEDA 14. 10. 2025 dopoledne 9:00 – 12:00 hod. OEEZ a ELEKTROPRŮMYSL

Aktuální problémy při využití lithiových baterií
RNDr. Petr Kratochvíl, ECOBAT s.r.o.

Recyklační předpříprava lithium-iontových baterií - nové přístupy a udržitelná řešení
Ing. Anna Pražanová, Ing. Zbyněk Plachý, MSc. Václav Knap, Ph.D., ČVUT v Praze, Fakulta elektrotechnická, Katedra elektrotechnologie

Recyklace Li-ion akumulátorů
Ing. Jiří Báňa, VUT v Brně

Získávání cenných prvků z lithiových baterií - očekávání vs. praktické zkušenosti
prof. Ing. Pavel Janoš, CSc., Ing. Jiří Štojdl, Ing. Ladislav Bříza, Ing. Tadeáš R. Wangle, PhD, FŽP UJEP

Autorská prezentace vývěsek

Přestávka 10:20 – 11:00 hod.

Recyklace? Ještě počká. Co nám říkají data o životnosti trakčních akumulátorů
Ing. Jan Dedek, Ph.D. AURES Holdings

REMA Systém – kolektivní systém pro sběr, svoz, zpracování a využívání odpadních elektrozařízení
Ing. Vítězslav Páral, Ing. Kateřina Opletal Průchová, REMA Systém, a.s.

20 let zpětného odběru elektroodpadu v ČR
Daniel Šafář, ASEKOL, a.s.

Moderní technologie v recyklaci elektroodpadu
Mgr. Helena Nehasilová, Technoworld, a.s.

STŘEDA 14. 10. 2025 odpoledne 14:00 – 17:20 hod. OEEZ a ELEKTROPRŮMYSL

Chemická recyklace jako cesta pro zpracování elektroodpadu
Ing. Radek Pjatkan, Svaz chemického průmyslu ČR

Sustainable Electronic Waste Management via Thermal Plasma Processing: Opportunities and Challenges
Dr. hab. Mgr. Maksym Buryi, Ph.D., Mgr. Alan Mašláni, Ph.D., Mgr. Michal Hlína, Ph.D., Dr. Shelja Sharma, Dr. Brenda Natalia Lopez Nino, Ing. Jafar Fathi, Ing. Jakub Pilař, Ústav fyziky plazmatu AV ČR

Wolframový prach jako významný odpad z jaderného fúzního reaktoru
Ing. Jaroslav Stoklasa, Ph.D., Ing. Bc. Lucie Karásková Nenadálová, Ph.D., Centrum výzkumu Řež, s.r.o.

Aplikace solvolytických postupů pro purifikaci odpadních plastů z autobaterií
Ing. Ivana Barchánková, Ph.D., Fakulta životního prostředí Univerzita Jana Evangelisty Purkyně v Ústí nad Labem

Tonerové kazety – zdroj surovin i toxický odpad
Pavel Hrdlička, Česká zemědělská univerzita v Praze, Provozně ekonomická fakulta

Tonerový prášek – kam s ním?
Ing. Olga Šolcová, CSc., prof. Milan Čárský, Ing. Karel Soukup, Ph.D., Ing. Milena Rousková, Ph.D., Ing. Stanislav Šabata, Ústav chemických procesů AV ČR

Přítomnost plastových aditiv z elektroodpadu (OEEZ) v dětských výrobcích
Ing. Katarína Rusiňáková, Mgr. Simona Rozárka Jílková, Ph.D., Chijioke Olisah, Ph.D., Lisa Emily Melymuk, Ph.D., Mgr. Ondřej Audy, Ph.D., Mgr. Petr Kukučka, Ph.D., RNDr. Petra Přibylová, Ph.D., Recetox, Masarykova Univerzita v Brně; Martin Boudot, Premières Lignes Television, Brûlon, Paris, France

Problematika ekologie různých typů vozidel
Ing. Kamil Jaššo, Ph.D., VUT a UO; prof. Ing. Tomáš Kazda Ph.D. VUT; Ing. Martin Mačák Ph.D., VUT a AIT; Ing. Martin Šedina, Ing. Josef Máca, Ph.D. VUT; Gavin D.J. Harper,University of Birmingham

ČTVRTEK 16. 10. 2025 dopoledne 9:00 – 13:00 hod. EXKURZE

RETEX, a.s. *(výroba ekologických a technických netkaných textilií z recyklovaných materiálů)*

VÝVĚSKY

Porovnání asfaltových směsí s vysokým podílem R-materiálu a modifikací odpadními plasty
Amira Ben Ameur, MSc., ČVUT v Praze, Fakulta stavební; Joseph N. La Macchia, MSc., Politecnico di Torino; doc. Ing. Jan Valentin, Ph.D., ČVUT v Praze, Fakulta stavební

Využitie kukuričného oleja na produkciu bionafty a separáciu fytosterolov ako látok s vysokou pridanou hodnotou
Roksolana Fromel, Združenie Energy 21, Leopoldov, Slovensko; Ján Janošovský, Valentína Kafková, Centrum výskumu a vývoja, s.r.o., Leopoldov, Slovensko; Adriana Brisudová, ENVIRAL, a.s., Leopoldov

Utilisation of magnetic and non-magnetic ash fractions for the preparation of glazes from waste materials
Ing. Michaela Topinková, Ph.D., Ing. Filip Kovár, Ph.D., doc. Ing. Ovčačíková Hana, Ph.D., VŠB-TU Ostrava

Using magnetic separation to recover iron from steel slag
Ing. Filip Kovár, PhD., doc. Mgr. Lucie Bartoňová, Ph.D., prof. Ing. Vlastimil Matějka, Ph.D., VŠB-TU Ostrava

Možnosti racionalizace využití fermentačního zbytku z bioplynových stanic
Ing. Pavel Míchal, Ph.D., Ing. Pavel Švehla, Ph.D., Ing. Barbora Koubková, Bc. Jakub Tegel, prof. Ing. Pavel Tlustoš, CSc., dr. h. c., Česká zemědělská univerzita v Praze

Charakteristika produkované vody ze zpracování odpadů z fúze MSO technologiií
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Eco-Friendly Ceramic Glazes from Waste Pigments: A Sustainable Approach
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