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Book of Abstracts

Sanja POTRČ Miloš BOGATAJ Zdravko KRAVANJA Zorka NOVAK PINTARIČ
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Emerging Technologies and Innovative Approaches – from Development Environments to Practical Implementation

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Book of Abstracts

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KEYNOTE LECTURE

Fungal-Driven Lignocellulosic Biorefineries: Bridging Bioeconomy, Sustainability, and Climate Resilience

MARINA TIŠMA
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Lignocellulosic biorefineries are innovative systems designed to convert lignocellulosic residual biomass into a variety of bio-based products, including high-value chemicals, food supplements, animal feed, materials, and fuels, through sustainable and integrated processes. Fungi play an important role in these bioconversion pathways due to their exceptional enzymatic capabilities and metabolic versatility.

By integrating biotechnology, systems thinking, and principles of the circular bioeconomy, this lecture will explore how fungal-based bioprocesses can significantly reduce carbon footprints, valorize waste streams, and drive innovation across multiple sectors of the bioeconomy.

The presentation will also address current challenges and future directions for scaling up these technologies, as well as their policy and socio-economic implications within the broader bioeconomy framework. Special emphasis will be placed on interdisciplinary approaches and the importance of collaborative innovation in the transition toward more resilient and climate-smart industrial systems.

Keywords: lignocellulosic biorefineries, fungal bioprocesses, circular bioeconomy, biotechnology, waste valorisation

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PLENARY LECTURE

The Role of Lifecycle Engineering in Decarbonising Our Built Environment

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Decarbonising the built environment is essential for achieving global net-zero targets, as the construction, operation, and end-of-life phases of buildings account for over 35% of global energy use and approximately 40% of carbon emissions. This keynote explores the pivotal role of lifecycle engineering (LCE) in tackling these challenges by integrating environmental, economic, and social dimensions across the full lifecycle of built assets. Drawing on research across hard-to-abate sectors—including cement, steel, glass, ceramics, and food and beverage manufacturing—this presentation highlights how data-driven LCE can support low-carbon material choices, optimise industrial processes, and unlock circular economy solutions such as recycling, remanufacturing, and innovative business models.

Key enabling technologies, such as phase change materials, hydrogen integration, and advanced energy storage systems, are examined for their role in enhancing resource efficiency and reducing emissions across design, construction, use, and disposal. The presentation also emphasises the role of digital tools and Industry 4.0/5.0 approaches in delivering robust lifecycle sustainability assessments (LCSA). Crucially, it underscores the need to align policy, regulation, and market incentives to scale sustainable practices. Through case studies from foundation industries and transport, the talk advocates for whole-system thinking to address the interconnected water-energy-materials nexus and progress toward meaningful sustainability in the built environment.

Keywords: lifecycle engineering, built environment, lifecycle sustainability assessment, industry 4.0, low-carbon materials

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Cost Analysis of Future Defence Camps With a High Share of Renewable Energy Sources

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Ensuring energy independence in deployable military camps is a growing strategic priority, particularly in light of limited and unreliable local fuel availability and logistic constraints. This study presents a comparative analysis of various energy system configurations for such defence camps, focusing on capital expenditure (CAPEX), operational expenditure (OPEX), fuel costs, and transport logistics. The cost-effectiveness of four system scenarios was evaluated: a diesel-based legacy scenario, a 2030 scenario with an increased share of renewable energy sources, and two advanced 2050 scenarios based on full electrification and hydrogen related technologies.

The main goal of the study was to perform techno-economic optimisation of microgrid components intended for deployment periods of up to ten years, while accounting for various energy-related constraints such as energy autonomy, logistics, and sustainability. System components ranged from diesel generators to renewable energy sources related technologies including storage solutions. Annual costs were broken down into amortised CAPEX, OPEX, fuel consumption, and transport of equipment.

Results show that while the legacy system maintains the lowest total annual cost for up to one-year deployments, it is rapidly surpassed in cost-effectiveness by alternative systems over extended durations. Over a 10-year camp deployment duration, the 2030 scenario system achieves the lowest total cost. This is primarily due to reduced fuel dependency leading to lower fuel costs and a minimal CAPEX increase. The 2050 electrification scenario exhibits a steep upfront CAPEX, with energy storage (mainly batteries) contributing the biggest share of the total cost. Similarly, the 2050 hydrogen system shows the highest cost under a one-year deployment, driven by the significant CAPEX associated with hydrogen storage infrastructure. Despite these initial expenses, both 2050 systems become relatively more competitive when evaluated over a ten-year operational timeframe.

Overall, findings indicate that the cost-optimal solution is time-dependent. For short-term deployments, the legacy scenario remains financially favourable. In contrast, the 2030 scenario achieves significant cost savings over longer deployments due to moderate investment and fuel use reduction. Fully renewable strategies for 2050, while aligned with minimal fuel logistics and maximum energy independence, currently face major financial barriers due to high CAPEX in storage technologies.

This analysis shows that financial viability must be evaluated alongside mission duration and logistical considerations, particularly in defence applications where energy autonomy is essential. Decision-makers should consider hybrid or phased investment approaches to balance short-term cost constraints with long-term strategic resilience.

Keywords: microgrid topology optimization, economic analysis, renewable energy systems, energy autonomy, deployable defence camps

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Concept of and Proposal for International Distributed Laboratory for Hydrogen Technologies in Energy Supply (DLHTE)

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DLHTE - **D**istributed **L**aboratory for **H**ydrogen **T**echnologies in **E**nergy Supply

The concept of distributed laboratory as a virtual laboratory for the target Use case of the Local Energy Community ecosystem. An energy community of the Renewable Energy Community type (Energy Communities, 2025) is a vertically nested system in the energy supply system. It contains all the processes and roles that participate in a segment of the electricity supply system, and it interacts with other parts of the electricity system:

- It contains electricity production, consumption and storage
- It exchanges flexible energy products – energy flexibilities internally and externally

With integrated hydrogen systems to provide balancing between consumption and local renewables production, it can optimize its operation on a sustainable basis at high level of self-supply. The Important functional building blocks of the system are:

- Hydrogen prosumers or functional parts thereof: electrolyser, storage tank, fuel cell
- Producers and prosumers of renewables
- Platform for Automated Trading of prosumers with energy flexibilities

A more detailed description of the Local energy community with integrated hydrogen systems (termed H2LEC) can be found in (Marinšek et al., 2024a) . H2LEC represents a type of Small Hydrogen valley (Hydrogen Europe, 2023).

With DLHTE, we want to establish a developmental testing environment for building blocks that constitute H2LEC - Local energy community with integrated hydrogen systems, and RES producers and prosumers, e.g. photovoltaics and wind turbines, biomass etc., depending on the specifics of the LEC to be tested.

DLHTE encompasses hydrogen and RES building blocks embedded in the ecosystem of the energy community. The missing building blocks in the community and, in particular, the buyers of energy flexibility outside LEC are simulated.

<u>Target Use cases tested in DLHTE</u>. The H2LEC is a connected subsystem in energy supply system. The positive and the negative energy flexibilities, not exchanged in peer-to-peer trading between the energy community members, are offered and traded on external markets. The basic targeted use cares are the local and regional flexibility markets, c.f. (Marinšek et al., 2024b).

Extension of DLHTE to regional and multi-LEC environment. There are two basic concepts in extending the DLHTE from one H2LEC system to more LEC demonstration locations: i) Adding individual building blocks from other laboratories to the Use case testing constructed from the building blocks in the "domestic" DLHTE site; and ii) Structuring the Use case tested in the DLHTE as a regional multi-LEC Use case, consisting of two H2LECs, participating in the regional market for DSOs. Both national regional and cross-border cases are possible to construct and emulate.

The initial DLHTE was developed and set up by CC ACT (Zavod KC STV) and its partners in Slovenia: OFFSET Energy, J.Stefan Institute (JSI) and National Institute of Chemistry (NIC), with the building blocks Electrolyser, Hydrogen Fuel Cell, Hydrogen prosumer (simulated), Automated Trading Platform (Aurora), and centre for monitoring (emulation of business operator of the H2LEC). It is planned to extend it to other locations internationally, as a first step to a partnering lab in Germany. The ultimate goal is to set up a multi-LEC regional or cross-border Use case testing environment, with several centres.

Keywords: local energy community; hydrogen valley; ecosystem; vertically nested system; prosumer; hydrogen system; flexibility trading; renewable energy; distributed laboratory; use case

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The Usage of the Hybrid Raw Materials for Ethanol Production

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The fossil must be replace with renewable raw materials for different products production. The choice of renewable raw materials is very crucial for ethanol production from syngas. A hybrid renewable raw materials for syngas production includes at least three different sources, such as municipal solid waste (MSW), biogas, and the use of carbon dioxide from flue gases generated during waste incineration. This triangular hybrid combination of raw materials study presents the technique, which is supported by the mathematical model and the Aspen Plus® simulator for syngas converted into ethanol. The mathematical model includes real-simulated results. Gassed MSW, biogas, and the purified circulated flue gas can enter as complete circular economy systems into reforming for syngas (as components of CO, CO_2, H_2, H_2O) production for further ethanol product, which is depending on the critical molar flow rate of CO and CO_2. The molar flow rate of hydrogen is generated in surplus, therefore hydrogen can be cleaned and produced as co-product.

Keywords: waste flue gas, biogas, syngas, ethanol, hydrogen

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Heat Transfer Enhancement Methods for Compact Heat Exchangers with Mini and Micro Channels

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Increased heat recuperation is the main prerequisite for efficient energy use in thermal systems in chemical and many other industrial applications. The main components responsible for this and for the total size and weight of such a system are heat exchangers. With a further rise in demand for energy, limited space and material resources necessitate further developments in heat exchangers' construction and design principles. In that view, compact heat exchangers with mini and micro channels can be regarded as the next generation of heat transfer equipment, accounting for enhanced heat transfer and reduction of weight, volume and materials for their construction.

According to (Kandlikar and Grande, 2003) minichannels can be classified by hydraulic diameters Dh from 3 mm to 0.2 mm, and microchannels as having Dh from 0.2 mm to 0.01 mm. The hydraulic diameters outside these ranges characterise conventional channels with Dh exceeding 3 mm and transitional microchannels and nanochannels with Dh smaller than 0.01 mm.

Mini and microchannel heat exchangers have found a wide range of applications in microelectronics, micro process systems, waste heat utilisation involving supercritical CO_2 and Micro-Electromechanical Systems (MEMS) technology, air conditioning systems, communal sector and pasteurisation, solar thermal energy and nuclear power, recuperators for micro gas turbines, refrigeration, aerospace and defense aviation applications. It stipulated a large number of studies in this field.

With such a large number of experimental studies on heat transfer and friction in minichannels and microchannels, there are considerable differences in the results of experiments. It was observed more than two decades ago by (Sobhan and Garimella, 2001), and not much changed later with the appearance of newer research results surveyed by (Morini, 2004) and later by (Singh et al., 2019). It creates uncertainties in choosing the geometry of minichannels and microchannels while designing efficient heat exchangers for specific conditions of heat transfer processes.

This paper aims to present the method of comparing heat exchangers' efficiency with different minichannels and microchannels, based on the developed equation for optimal fluid velocity inside the channels. The heat transfer and friction factor correlations published by different authors are analysed with recommendations for their application in designing the heat exchangers for specific applications.

A method to estimate the performance of a heat exchanger with different mini and micro channels is proposed. It is based on a developed equation for the estimation of fluid velocity in the channel that allows strict satisfaction of the specific conditions of the temperature program and pressure losses in a heat exchanger with channels of different hydraulic diameters. To get a monotonic decrease in heat transfer surface area with the diminishing hydraulic diameter, it is better to use channels with enhanced heat transfer. It is shown by an example of the crisscross flow channel, typically used in plate heat exchangers and primary surface recuperators of gas turbines. In future research, other methods of heat transfer enhancement in microchannels should be investigated and estimated with the proposed methodology.

Keywords: minichannel, microchannel, heat exchanger, heat transfer, pressure loss

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Modeling Convective Drying Processes with Python: A Case Study on Municipal Sewage Sludge

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The removal of moisture from municipal sewage sludge (MSS) is a key step in ensuring efficient and sustainable sludge management. With an initial moisture content of 81.6% (corresponding to 18.4% dry matter), MSS requires significant dewatering to reduce volume and facilitate further treatment or disposal. Accurate modeling and analysis of its drying are essential for optimizing this process. This study highlights the use of Python programming for modeling, analyzing, and visualizing the drying behavior of MSS under controlled conditions.

MSS samples were collected from the centrifuge unit of the wastewater treatment plant in Ptuj, Slovenia. Four drying tests were conducted at constant temperatures of 25, 30, 35, and 40°C, with mass loss monitored continuously using a digital scale. The distinction between the first and second drying periods was achieved by applying linear and exponential regression models, respectively, to determine the

critical drying point. Python scripts facilitated systematic data processing, smoothing, derivative computation, and parameter calculation.

Key drying parameters, including drying rate, molar flux, heat flux, and heat and mass transfer coefficients, were successfully computed using Python-based calculations. The utilization of libraries such as NumPy, Pandas, SciPy, and Matplotlib has been demonstrated to enhance the precision of analyses and enable complete visualizations. The utilization of master drying curves yielded comparative insights, highlighting the impact of varying temperature conditions on the drying processes.

The Python modeling approach effectively optimized the MSS drying analysis. This approach offered three key advantages: it enabled precise determination of the critical drying point and distinction between the first and second drying periods, facilitated accurate calculation of drying parameters, and perfomed data visualizations This study demonstrates Python's significant potential as a usefull tool for controlling and optimizing the MSS drying process.

Keywords: municipal sewage sludge, convective drying, Python modeling, sludge management, drying parameters

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The Impact of Plastic Waste Import on the Environmental Degradation and Health Issues? Evidence From Network and Panel Data Analyses

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Plastic waste generation, which was manageable from the 1950s to the 1970s, has experienced a significant increase since the 1970s. The United Nations reports that we currently produce nearly 400 million tonnes of plastic waste each year (UNEP, 2025a). Additionally, approximately 19 to 23 million tonnes of plastic waste enter aquatic ecosystems each year (UNEP, 2025b). Addressing plastic waste is crucial, as plastic pollution can harm habitats, diminish ecosystems' resilience to climate change, and negatively impact the lives of millions by reducing food production capabilities and overall social well-being.

To achieve this, the study examines the plastic waste trade and its impact on pollution and health issues in importing countries. The methodology consists of two main components. First, we analyzed the evolution of the plastic waste trade dynamically through the lens of network analysis from 1990 to 2023. A substantial body of literature includes studies that utilize network tools (Wang et al., 2020; Zhao et al., 2021; Shi et al., 2021; Pacini et al., 2021; Li et al., 2021; Liu et al., 2023) to reveal the topology of the global plastic trade. In this study, we employed network analysis and panel data analysis as complementary methods. Initially, we identified the most central importing countries within this network, and subsequently, we tested the effect of plastic imports on environmental degradation in these central importers. Network analysis revealed a two-fold increase in density within this trade network over the study period, indicating a significant rise in plastic waste trade. Additionally, we identified the most prominent developing importing countries: Malaysia, Vietnam, Türkiye, Indonesia, Thailand, S. Korea and India. In the second phase, we applied panel data analysis to examine the long-term relationship between plastic waste imports and ecological footprint breakdowns in these countries, highlighting the environmental degradation caused by these imports. We also searched for the long-term relationship between plastic waste import and share of lung cancer deaths attributed to air pollution. The findings revealed that plastic import has a negative effect on lung cancer in India and has a negative effect on cropland footprint in Vietnam. This study offers significant policy implications for policymakers in these nations.

Keywords: plastic waste, environmental degradation, ecological footprint, network analysis, panel data analysis

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Assessment of the Technological Feasibility and Economic Viability of Residue Valorisation in Apple Processing

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Apple processing generates large quantities of apple pomace, which is usually processed into animal feed or disposed of in the environment. Apple pomace contains various high-value components, such as phenolic compounds, dietary fibre and abundant pectin and cellulose, making apple pomace a potential source of pectin and cellulose (Bhushan, et al., 2008; Barreira, et al., 2019; Costa, et al., 2022; Ma, et al., 2019).

The material flow balance carried out as part of the project "Circular technological concepts and business models in Slovenian agriculture (CircAgro)" confirmed the prospects of apple pomace as a source of raw materials for further utilisation. The cascading utilisation of apple pomace has proven to be a showcase for the circular economy at the agricultural level, while reducing disposal costs and opening up new revenue streams. Two prototypes were developed to assess the economic potential of apple pomace in Slovenia. The first prototype involved the extraction of pectin and the use of the residue for the production of speciality paper. The second prototype focussed on the production of fruit leather as a plant-based alternative to conventional animal-based leather. Technological prototypes were then translated into business models that can be transferred to professional fruit farms or micro-enterprises operating in this sector. Both concepts – pectin extraction and fruit leather production - intentionally target higher value market segments where eco-design and local origin create a particular added value that can compensate for the limited raw material base and higher unit costs typical of family farms.

In presnet contribution we focus on the process of transforming technological prototypes of agricultural by-product utilization into functioning business models, following the principle that business models can be used as supplementary activities on farms or small-scale processing plants in rural areas.

The technological prototypes, translated by the proposed technological solutions were transformed into a business model that describes the organization of the business process, the technological parameters of production and the form of the economic entity. The analytical framework mirrors the stepwise approach described by (Fatur et al., 2025), in which prototype mass balances are first translated into cost items and thereafter into discounted-cash-flow indicators.

For pectin extraction two capacity scenarios were evaluated 6.6 tonnes annually (single farm) versus 30 tonnes (cluster of farms), where 6.6 tonnes of apple pomace per year for fruit leather production were evaluated. Economic viability is gauged over ten years at a real 6% discount rate, using straight-line depreciation for the resulting Net Present Value (NPV) and Internal Rate of Return (IRR). Qualitative discussion of loop-closing options – either outsourcing the cellulose-rich residue to a niche paper mill or fermenting it to regenerate extraction ethanol – follows the sustainability reasoning advanced in the second stage of the cascade.

The study confirms that economic resilience hinges on premium positioning. Clustered pectin extraction leverages economies of scale to deliver IRR above 100%, whereas single-farm installations remain borderline profitable unless backed by strong branding. Fruit leather, though more speculative technologically, achieves attractive returns owing to favourable price–cost differentials and modest capital needs. In both cases, loop-closing options – be it cellulose-based paper for promotional use or in-house ethanol regeneration – enhance circular performance and reinforce the storytelling potential that underpins market acceptance. The evidence thus supports the broader claim that circular products from agri-food by-products can succeed commercially when embedded in well-crafted, sustainability-oriented business narratives.

Keywords: apple pomace, pectin, paper, fruit leather, economic evaluation of the prototype, valorization of biomass side-streams

Acknowledgement

This work largely builds on findings, developed within the project »Circular technological concepts and business models in Slovenian agriculture« (V4-2208), financed jointly by the Slovenian Research and Innovation Agency, and Ministry for Agriculture, Forestry and Food.

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A Business Model for Recycling Agricultural Plastic Waste

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Discarded agricultural film left over after primary use (silage bales, weed control films) represents a significant environmental challenge. The annual consumption of these materials is estimated at around 2,000 tonnes, of which 30% is recycled and the remaining 70% is (ideally) destined for energy use. The study tackles this challenge by (i) developing the technological prototype of upcycling discarded agricultural film into innovative thermoplastic composite and (ii) developing a business model built on this propotype that could use as a blueprint of a network of small-scale processing facilities throughout the country.

This business model focuses on the sustainable recycling of discarded plastic film form agricultural use, and harvest residues (in our case, corn stalks). The plastic film, commonly used in farming, is collected, cleaned, and processed into plastic pellets that can be reused in manufacturing. At the same time, corn stalks left after harvest are converted into biomass products such as pellets for energy, compost, or even bioplastics. The model generates revenue through the sale of these recycled materials and may benefit from targeted public policies. It supports a circular economy by reducing plastic pollution and agricultural waste, while offering eco-friendly alternatives to virgin materials. The primary customers include plastic manufacturers, biomass energy producers, and sustainability-oriented agricultural organizations.

The innovation of the product lies in the reuse of waste materials from farms (agricultural film), which are currently not separately collected or processed. This approach reduces the carbon footprint and increases the sustainable use of resources, adding value after use. The granulate contains 96.5% of its own waste material (76.5% agricultural waste film and 20% corn husks) and 3.5% additives (compatibiliser and plant extracts). On an annual basis, the production of a typical small processing company would be approximately 250 tonnes of granulate, requiring 191.25 tonnes of agricultural waste film and 50 tonnes of corn husks, 7.5 tonnes of compatibiliser and 1.25 tonnes of plant extract.

Based on the estimated production costs, the cost price of the innovative thermoplastic biocomposite is estimated at competitive level of € 1.02/kg. In calculating the economic viability of setting up the production of the innovative thermoplastic composite, the most expensive possible investment was taken as a starting point, namely the investment in setting up a completely new processing plant. In this case, the net present value is low in relation to the amount of the initial investment (€765,000) and, over a 15-year period, at a discount rate of 6%, is close to €70,000. Both indicators suggest that the investment is at the limit of acceptability. Economic viability of the business model would significantly improve in the case of a diverrsification of the existing enterprises active in the plastics manufacturing sector, as well as in the case of relevant public schemes incentivising closing the material loops and long-term storage of carbon (e.g. in durable plastic products, such as thermoplastic composite products).

Keywords: upcycling, discarded agricultural film, harvest residues, closing material loops, carbon sequestration, agriculture

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Surface Activation of Cotton with Plasma for Improved Chitosan Adsorption

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Cotton fabrics are widely used in medical environments, but their lack of inherent antimicrobial properties limits their functionality. Chitosan, a natural biopolymer with antimicrobial activity, can be applied as a coating to impart antibacterial functionality to cotton textiles, yet its binding stability on cellulosic substrates remains a challenge (Staneva et al., 2023). Plasma treatment of textile surfaces presents an eco-friendly alternative to chemical modifications by introducing reactive functional groups that enhance polymer adhesion.

In this study, oxygen plasma was used to activate the cotton surface prior to chitosan impregnation. Cotton fabrics were first alkaline-washed and then treated with low-pressure oxygen plasma (60 s) using a laboratory plasma reactor. Chitosan solutions of various molecular weights (high, medium, and low) and concentrations (1%, 0.5%, 0.1%, 0.05%, 0.01%) were prepared and characterized using UV-VIS spectroscopy to identify the optimal type and concentration for application. High molecular weight chitosan at a concentration of 0.5 wt.% was selected as optimal based on the highest UV-VIS absorbance (0.2 at 290 nm) and literature-supported stability (Szymańska & Winnicka, 2015).

FT-IR and XPS analyses confirmed partial functionalization, though spectral evidence of chitosan was limited due to low surface coverage. Potentiometric titration quantified amino group concentrations, with plasma-treated samples showing increased adsorption (52.7 mmol/kg) compared to untreated ones (40.6 mmol/kg). Compared to untreated cotton, plasma activation followed by chitosan coating resulted in a measurable increase in the contact angle, indicating a shift toward lower surface wettability due to the coating.

The results confirm that plasma pre-treatment significantly enhances the adsorption capacity of cotton for chitosan without chemical reagents, offering a sustainable strategy for functional textile development and supports its application in the development of sustainable biofunctional materials.

Keywords: plasma treatment, cotton fabric, chitosan adsorption, sustainable textile finishing, biofunctional materials

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Regulatory and Strategic Review of Circular Economy Implementation in Adriatic-Ionian Region with Focus on Local Challenges and Upcycling Opportunities

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Introduction

The Adriatic-Ionian region has increasingly embraced the circular economy (CE) to address environmental challenges, support sustainable growth, and align with EU policy. Individual countries of the region have developed CE strategies based on their socio-economic conditions and institutional capacity. However, small and rural municipalities often lag in implementing EU targets for waste reduction, recycling, and sustainable resource use (Brinsi and Koloszár, 2024). A notable gap remains between EU directives and their national and local execution. To ensure effective CE adoption, it is essential to understand regulatory landscapes, local challenges, and coordination opportunities (Michalun and Nicita, 2019).

Methods

As part of the Interreg ADRION project CAROUSEL, a structured two-part questionnaire was designed and distributed among project partners in Italy, Slovenia, Greece, North Macedonia, Serbia, and Montenegro. The first part focused on national policy frameworks, stakeholder mapping, municipal-level practices, and innovative waste management approaches. The second part addressed local availability of materials for upcycling, the prevalence of upcycling practices, relevant EU experiences, and current market conditions. For countries not directly involved in the questionnaire, strategic documents and scientific literature were reviewed to ensure consistent coverage. Desk research was used to supplement empirical data, especially in terms of EU and national legal and policy documents.

Results

The analysis revealed significant regulatory differences across Adriatic-Ionian countries. Italy has a strong legal framework and CE policies aligned with EU directives, though regional gaps and inconsistent implementation persist (Michalun and Nicita, 2019). Slovenia also shows strong alignment with EU regulations but lacks specific upcycling legislation (Tsatsou et al., 2023). Serbia has comprehensive national strategies, including the Law on Waste Management and the Circular Economy Roadmap, but faces challenges in regional and municipal implementation due to infrastructure gaps. Greece offers regulatory incentives for municipalities to adopt green technologies but lacks clear certifications, hindering the upcycled product market. Montenegro (Spalević, Škatarić and Dudić, 2024) and North Macedonia (OECD, 2024a) have basic policy frameworks but experience gaps in local-level enforcement, clarity, and infrastructure support. Croatia has implemented a comprehensive CE policy framework (Svarc, 2022), while Slovenia innovated with tools like the e-Simbioza platform (Fric and Rončević, 2018). Greece applies a quintuple-helix approach, emphasizing SME engagement (Arsova et al., 2021), and

Montenegro explores CE through green economy initiatives and cross-border cooperation (Sumpor, 2011). Albania and Bosnia and Herzegovina are less advanced but participate in regional programs like ASEP to enhance sustainability (Marino et al., 2013). North Macedonia is distinguished by its OECD-based CE roadmap OECD, 2024a). Despite strong alignment with EU objectives, significant implementation gaps remain.

Conclusions

Common challenges include insufficient infrastructure, inconsistent local regulations, limited financial incentives, and low public awareness. To address these issues, policy harmonization, standardized certifications, regional cooperation, targeted infrastructure investments, and capacity-building programs are essential. EU funding and strategic guidance are crucial, but local capacities and stakeholder engagement will ultimately determine success. These findings lay the foundation for a transnational modular action plan and provide a baseline for regional authorities and decision-makers aiming to improve CE implementation.

Keywords: circular economy, Adriatic-Ionian region, waste management, policy implementation, upcycling

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Assessment of Analytical Methods for Palladium Detection in Pharmaceutical Waste Streams

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Palladium-catalyzed reactions play a central role in modern pharmaceutical industry, enabling highly efficient and selective transformations such as cross-coupling (Dana A. Kader et al., 2025) and asymmetric hydrogenation (Wang et al., 2024). These reactions are crucial for the synthesis of complex active pharmaceutical ingredients (APIs) (Emadi et al., 2023). However, the use of palladium brings dual challenges: potential contamination of final products with metal impurities and the economic and environmental impact of palladium losses (Chatzopoulou et al., 2022). Monitoring and recovering residual palladium are therefore essential not only for meeting stringent quality and regulatory standards, but also for optimizing resource use and reducing production costs.

According to the PW Consulting Chemical & Energy Research Center, palladium recovery rates in the pharmaceutical sector remain low-rarely exceeding 30%, in contrast to recovery rates of up to 95% reported in the automotive sector. Given palladium's high cost, limited natural availability, and growing demand, improving recovery from pharmaceutical waste streams is vital for enhancing sustainability and supporting circular economy objectives.

As part of the GreenChemForCE project, funded by Interreg Central Europe and aimed at promoting greener chemical production and sustainable resource use, we investigated the effectiveness of four analytical methods-Atomic Absorption Spectroscopy (AAS), Inductively Coupled Plasma Mass Spectrometry (ICP-MS), Ultraviolet (UV) Spectrophotometry, and Fluorescence (FL) Spectrophotometry-for quantifying spent palladium in pharmaceutical waste. Our study examined the precision, reliability, and suitability of each method for both aqueous and organic waste fractions. Furthermore, we examined the potential of UV spectrophotometry for rapid, on-site screening of palladium content in real industrial samples, estimating its value as a cost-effective and scalable solution for pharmaceutical waste monitoring.

These findings contribute to the development of practical, scalable monitoring tools that support improved palladium recovery.

Keywords: Palladium detection, Pharmaceutical waste, ICP-MS, AAS, Spectrophotometry (UV, FL), Circular economy

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Urban Circularity – Business Model Framework

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The transition to a circular economy (CE) is widely recognized as a process that requires engagement from governments, municipalities, businesses, and citizens (Korsunova et al., 2021). The European Commission forecasts that by 2050, the urbanization rate in Europe will reach approximately 83.7%. Given that urban environments are major centers for the consumption of goods and services, they are uniquely positioned to accelerate the shift toward circularity in both production and consumption patterns. The proliferation of circular businesses is a positive development; however, this alone is insufficient to drive the transition to a circular economy (Borrello et al., 2022). This paper presents a framework for circular business models that support circular lifestyles in cities developed within the NiCE project. The framework offers a comprehensive, evidence-based guide for local and regional authorities to foster circular lifestyles in urban environments. Synthesizing policy analysis, stakeholder engagement, needs assessments, and pilot activities across eight Central European countries, the framework addresses the critical role of urban centers in resource consumption and the transition to circular economy

models. The study identifies persistent barriers – including funding and regulatory gaps, fragmented policy landscapes, limited public awareness, and infrastructural constraints – as well as key opportunities such as political support, economic incentives, and innovative local solutions. The conceptual model is grounded in a value retention hierarchy and introduces the dual concepts of ecological footprint and handprint to frame behavioral and systemic change. Pilot implementations in cities such as Bologna, Graz, Budapest, and Ptuj provide empirical insights into effective interventions, including the reuse of urban spaces, resource centers, and citizen engagement strategies. This work contributes a multidimensional approach to operationalizing circularity in cities and serves as a reference for future research and policy development in urban sustainability and the circular economy.

Keywords: circular economy, urban sustainability, circular lifestyles, ecological footprint, handprint

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Technology Acceptance Model Analysis for a Potential Smart Waste Segregation System in Mashhad City

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Technology acceptance model introduced by Davis in 1989, have been used in many researches to analyze and develop new technologies since then, smart waste segregation at source, nowadays, is developing to improve solid waste segregation at source procedures, and mobile app based, solid waste picker companies are expanding their customers across city of Mashhad. The aim of this research was analyzing technology acceptance model for a potential smart waste segregation system in Mashhad city, first by introducing integrated smart waste segregation systems based on smart identification then analyzing the technology acceptance and effective components. Data gathered from 210 questionnaires, including hard copy and online, from 3 districts of the city due to their developing levels, consist of 17 questions from citizens' interest to waste segregation at source, external variables of perceived usefulness and perceived ease of use, further their behavioral intention to use points. Structural Equation Model (SEM) is served to analyze by Spss-Amos software, out puts in 95% level of significance, demonstrates, governance component has significant effect on behavioral intention to use of some citizens via existed perceived usefulness. Economical component has significant effect on behavioral intention to use of some citizens via both existed perceived usefulness and perceived ease of use. In results, incentives and disincentives could affect behavioral intention to use of smart waste segregation system further commitment to use could create positive attitude for some citizens to their behavioral intention to use due to the usefulness perceived by them. Noticed from descriptive statistic 70% of citizens don't use smart application systems in the city, thus we recommend developing engagement by marketing tools strengthen by incentives and guidelines till reaching significant participation rate, then commitment could be employed and finally disincentives could be applied

Keywords: smart waste segregation, perceived usefulness, perceived ease of use, behavioral intention to use, incentives, disincentives

Acknowledgement

Hereby writers declare Thesis properties belog to Ferdowsi University of Mashhad.

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Restoration of 80-Year-Old Timber Structure with Hempcrete: Ensuring Healthy Standards of Living

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This study presents the restoration of an 80-year-old timber structure using hempcrete as a sustainable insulating material. As a bio-composite with notable hygrothermal and carbon sequestration benefits, hempcrete represents a regenerative approach to building conservation. The restoration process, conducted by CoGreen d.o.o. in Novo Mesto, Slovenia, involved two key phases: material characterization and optimization of the hempcrete mix for structural durability and thermal performance.

Tradical Thermo Lime, a binder composed of 70% aerial lime, 15% hydraulic lime, and 10% pozzolanic additives, was combined with 15–20 mm hemp shives to formulate lightweight, breathable, and low-impact construction elements. The adopted mix ratios achieved a density range of 305 kg/m³, producing thermal conductivity as low as 0.085 W/mK and compressive strengths between 0.25–0.40

MPa for the adopted hempcrete spray method. 90 days of curing, making it suitable for wall infill and roofing insulation (Hirst et al., 2012; Shareef & Rauf, 2022).

The construction applied a uniform mix ratio across walls, flooring, and roofing, with 30 cm thick hempcrete walls, 20 cm floors, and roofing insulated using 14–16 cm thick Combi Jute and hemp layers. These choices not only enhanced the thermal envelope but also preserved the breathable characteristics of the structure. The materials were subjected to X-ray diffraction and SEM-EDS analysis, confirming the mineralogical presence of portlandite, alite, and calcite—contributing to improved thermal inertia and long-term durability (Pietruszka et al., 2019; Eddy, 2015).

Experimental trials followed standardized procedures (SIST EN 12664:2002 and ZWICK Z030), ensuring that the thermal and mechanical results were accurately validated. Findings showed that thermal conductivity decreased with reduced material density, while mechanical strength increased with denser compositions. The results confirmed that higher hemp shiv content improved insulation but reduced compressive strength due to increased porosity—an essential trade-off in restoration applications (Poletanović et al., 2019; Barnat-Hunek et al., 2015).

From a sustainability standpoint, the project aligns with the United Nations Sustainable Development Goals (SDG 11 and 13), supporting climate action and healthy living environments. Life Cycle Assessment (LCA) data revealed a carbon dioxide uptake of –86.5 kg/m², marking hempcrete as a carbon-negative material. This performance is further enhanced when considering hemp's local sourcing and minimal embodied energy, especially compared to conventional materials such as concrete, which exhibits a thermal conductivity of 2.25 W/mK (Ip & Miller, 2012; Florentin et al., 2017).

The project exemplifies a shift toward regenerative construction, wherein agricultural by-products like hemp are valorized into high-performance building materials. Hempcrete's use in this historic Slovenian structure demonstrates not only ecological advantages but also the feasibility of integrating traditional materials into modern construction practices with minimal environmental disruption (Lupu et al., 2022; Stanwix & Sparrow, 2014).

Keywords: hempcrete restoration, material characterization, thermal conductivity, carbon sequestration, life cycle assessment

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Exploring Renewable Biopolymers as Sustainable Alternatives for Functional Hydrophobic Materials

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Traditional hydrophobic coatings, which are widely used in various industries, heavily rely on per- and polyfluoroalkyl substances (PFAS). Although effective, PFAS raise significant environmental and human health concerns due to their persistence and toxicity (Fenton et al., 2021). This has prompted a great interest among researchers and industry in developing safer yet equally effective alternatives applicable in diverse industrial settings. This study explores the development of hydrophobic coatings based on natural biopolymers derived from renewable resources. These biopolymers can be chemically modified or combined into complex mixtures to achieve hydrophobic properties comparable to traditional PFAS-based coatings (Verbič et al., 2025). Additionally, the compounds can act synergistically to provide new functionalities. By employing materials such as chitosan, cellulose, starch and other non-toxic biopolymers that are renewable and abundant in nature,

we aim to create sustainable alternatives to conventional chemical treatments. These biopolymer coatings not only provide effective water-repellency but also offer significant advantages such as biodegradability and non-toxicity. This addresses critical issues of environmental persistence and health risks associated with fluorinated substances. Moreover, the developed coatings maintain their functional performance during typical use, such as washing and abrasion, while degrading efficiently after disposal. This aligns with the principles of the circular economy and sustainable industrial practices. This research highlights the potential of biopolymers to provide sustainable, multifunctional materials that combine effective performance with human safety and reduced environmental impact.

Keywords: biopolymers, hydrophobic, functional materials, coatings, PFAS, biodegradable

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Biotechnological Approach in Critical Metals Recovery from Electronic Waste: Bioleaching of E-Waste and Lithium-Ion Battery Black Mass

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The increasing amount of electronic waste (e-waste), including LCD and LED components, printed circuit boards (PCBs) and lithium-ion batteries (LIBs), poses significant environmental and strategic resource challenges. These complex waste types contain critical raw materials (CRMs), such as indium (In), gallium (Ga), lithium (Li), and cobalt (Co), which are vital for the European Union's green and digital transition. Environmentally friendly and selective recovery of these metals is a key objective of circular economy initiatives.

Our research group, University of Miskolc has carried out systematic bioleaching experiments using *Acidithiobacillus ferrooxidans* and *Acidithiobacillus ferridurans* strains on various e-waste fractions and black mass from LFP ($LiFePO_4$) and NMC

($LiNiMnCoO_2$) type LIBs. The aim was to assess microbial metal solubilization efficiency, process limitations, and the impact of waste composition.

A critical precondition for effective bioleaching is a proper mechanical pretreatment of the wastes. It includes the sequence of comminution, classification, thermal conditioning, magnetic and eddy current separation,etc. to remove plastics and bulky common metals, depends on the given substrate. The mechanical pretreatment not only highly contributes the recycling rates, but also improves the surface availability, reduces diffusion limitations, removes inhibitory components, and allows better interaction between microorganisms and the target metals (Bokányi L., 2014).

In case of LCD panel waste, indium was effectively solubilized from ITO-coated glass substrates after mechanical pretreatment. The tested *A. ferridurans* outperformed both the *A. ferrooxidans* and chemical controls, with up to 4 times higher indium concentrations in solutions, with up to 75% recovery. In LED-derived waste, gallium leaching efficiencies of 100% were achieved under optimal conditions (Bokányi et al, 2018; Simon K, 2019).

In LIB black mass, growth inhibition analysis using a Hamilton Incyte real-time monitoring system revealed that LFP-type material promotes bacterial growth up to 10 g/L solid concentration, while NMC-type black mass strongly inhibits bacterial activity above 5 g/L, mainly due to metal toxicity (Co, Ni, Mn). Lithium recovery from LFP black mass exceeded 70% at 10 g/L pulp density, whereas recovery from NMC sharply decreased at higher solid concentrations (Mádainé-Üveges et al, 2024).

One of the major challenges across all investigated systems was jarosite precipitation, which consumes Fe^{3+} ions and forms surface coatings hindering metal dissolution, and can also uptake valuable metals from the solution. This confirms the need for strict pH- and redox control and highlights the added complexity in scaling up.

Our results confirm that bioleaching, when combined with adequate mechanical pretreatment, is a promising and sustainable approach for recovering valuable and critical metals from e-waste and LIB residues. However, further research is required to enhance kinetics, manage inhibitory effects, and design scalable reactor systems suitable for industrial implementation.

Keywords: CRMs, bioleaching, e-waste, LIBs, critical metals recovery

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Prediction of Hydrophobic Properties in Biopolymer-Based Coatings via Formulation Data Modelling

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The urgent need to replace environmentally persistent and toxic per- and polyfluoroalkyl substances (PFAS) in hydrophobic coatings, has driven the exploration of renewable biopolymers as sustainable alternatives. While biopolymer coatings, such as those based on chitosan, cellulose, starch, demonstrate a promising alternative (Verbič et al. 2025, Golja et al. 2025, Calvo et al. 2024), optimizing these formulations to achieve targeted properties remains challenging due to complex

interactions between the compounds. Furthermore, development of a large number of formulations in the laboratory is both time- and materials-consuming, as each coating candidate must be prepared, applied and analysed, which limits the speed of innovation and increases resource consumption. This study integrated machine learning (ML) techniques to model the relationship between formulations composition and resultant water contact angles (WCA) which is achieved when the coatings are applied on textiles. Using experimental data from diverse biopolymer mixtures we apply linear regression to predict WCA, based on the presence and ratios of biopolymer components in the coating. The results demonstrate that using data modelling, WCA can be accurately predicted, proving the potential for guiding the design of multifunctional coatings, by enabling rapid screening and optimization of formulations, reducing reliance on extensive laboratory experimentation and consumption of chemicals.

Keywords: biopolymers, functional materials, coatings, PFAS, machine learning, data modelling

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Gold-Modified Magnetic Biopolymer Nanohybrid Coatings as Electrochemical Sensors for Chloramphenicol Determination

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The growing global concern about antimicrobial resistance (AMR) is mainly due to the widespread and uncontrolled spread of antibiotics in the environment. This situation poses a significant threat to both public health and ecological integrity. Antibiotics, even in low concentrations, can have harmful effects on aquatic ecosystems, bioaccumulate and facilitate the spread of resistance genes. Chloramphenicol (CAP), a broad-spectrum antibiotic, is used in human and veterinary medicine as well as in aquaculture and livestock farming due to its effectiveness against a wide range of bacterial infections. However, its persistence in the environment and its potential toxicity, including negative effects on public health, have raised significant concerns. Given its hazardous profile and its determination in environmental matrices at trace levels, monitoring and control of CAP contamination is therefore crucial. This requires the development of a selective analytical method with low limits of detection tailored to complex environmental conditions. Electrochemical sensors offer advantages such as portability, cost efficiency and rapid analysis time. By appropriately modifying the surface of the working electrode, the performance of an electrochemical sensor can be significantly improved in terms of low limits of detection and higher selectivity for a given analyte. In this context, the integration of nanomaterials represents a highly innovative strategy, as these materials can significantly lower the limits of detection, improve the selectivity and the overall performance of the sensors due to their unique physicochemical properties. In this study, we report the preparation of nanohybrids (NHs) of magnetic iron oxide nanoparticles (MNPs) coated with carboxymethyl cellulose and functionalized with gold nanoparticles (MNPs@CMC-Au) in combination with MNPs immobilized on phosphorated nanocellulose (MNPs@pCNF). A comprehensive physicochemical characterization of the NHs was performed, including transmission electron microscopy (TEM) for morphological analysis, X-ray diffraction (XRD) for crystallographic structure, Fourier transform infrared spectroscopy (ATR-FTIR) for functional group identification, zeta potential for surface charge evaluation, and magnetic measurements to assess their magnetic properties. The NHs were then drop-casted onto the working electrode of glassy carbon electrodes (GCEs) and the limit of detection, limit of quantification and linear concentration range for CAP were determined. The results showed the successful preparation of multifunctional NHs, whose synergistic structural and conductivity features significantly improved the limit of detection and limit of quantification for CAP compared to unmodified GCEs.

Keywords: electrochemical sensor, chloramphenicol, magnetic nanohybrids, gold nanoparticles, polysaccharides

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Development of a Carbon Footprint Evaluation Tool for the Slovenian Healthcare Sector

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Introduction

The healthcare sector contributes approximately 5% of global greenhouse gas (GHG) emissions, making it an important but often overlooked area for decarbonisation. As the European Union moves towards its 2050 net-zero target, healthcare systems need to adopt robust sustainability strategies. A prerequisite for this transformation is the ability to accurately quantify emissions. To address this, an initiative has been launched to develop a specialised carbon footprint calculator for the Slovenian healthcare sector.

Methods

A benchmarking analysis of international approaches to healthcare carbon footprint assessment was conducted, evaluating the tools, methods and data sources utilised across various countries. Additionally, existing calculators were reviewed, revealing common limitations including low sector specificity, restricted public accessibility and limited adaptability to national contexts.

For the Slovenian context, EXIOBASE (Stadler et al., 2025) and Ecoinvent (Ecoinvent, 2021) were selected as the primary databases for emission factors, due to their compatibility with input-output and life cycle assessment (LCA) methodologies. These were supplemented with national datasets covering electricity consumption, thermal energy use, transportation, procurement, and waste management.

A prototype of the calculator was implemented in Microsoft Excel to validate the logic, data structure and calculation processes. The emissions were categorised according to the Greenhouse Gas Protocol (2024) and included Scope 1 (direct emissions), Scope 2 (indirect emissions from purchased energy) and Scope 3 (other indirect emissions in the supply chain).

Results

The Excel-based prototype demonstrated the feasibility of sector-specific carbon accounting and enabled initial testing. However, challenges related to data protection, update automation, and user interface limitations highlighted the need for a more robust platform. Therefore, a Microsoft Power BI-based version of the calculator is currently under development. This new platform will offer enhanced interactivity, improved visualisations, integration with institutional data systems, and secure data management.

The tool is designed for use across diverse healthcare settings, from hospitals to primary care providers, and provides a standardised yet adaptable approach to carbon footprint assessment.

Conclusions

The Carbon Footprint Calculator serves as a tool for systematic and consistent GHG accounting within the Slovenian healthcare sector. It facilitates evidence-based sustainability planning and aligns with evolving EU regulations and reporting frameworks. The integration of national data sources, adherence to established protocols, and close collaboration with institutional stakeholders are key factors to ensuring the technical accuracy, usability and long-term relevance of the tool.

This initiative is a strategic step towards integrating environmental responsibility into public health management and policy and enabling institutions to track, report and ultimately reduce their climate impact.

Keywords: carbon footprint, healthcare system, GHG emissions, carbon footprint calculator, carbon footprint evaluation tool

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Polyolefins from Landfill Mining – Energetic Valorization

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As the transition to a circular economy accelerates, the untapped energetic and material potential of legacy landfills emerges as a critical opportunity. (Chioatto et. al., 2023) The CERO Gajke landfill, located in Ptuj, Slovenia, contains large volumes of baled municipal waste deposited between 2002 and 2015, with sorting analyses confirming that over 25–40% of the excavated mass consists of stable plastic fractions—primarily polyolefins such as HDPE, LDPE, and PP. These long-lived polymers, resistant to biological degradation, represent a viable energy source via thermal valorisation technologies. (Sharma et. al., 2024)

This contribution explores the potential of mining polyolefin-rich waste from the Gajke landfill for pyrolysis-based energy recovery. A key focus is on the mechanisms of thermal degradation (pyrolysis), whereby long-chain hydrocarbons are thermally broken down into valuable gas-phase products. (Avolio et. al., 2019) The pyrolysis of polyolefins yields a mix of non- condensable short-chain alkanes and mostly alkenes (C_1–C_5), minor parts present also hydrogen, methane, and carbon monoxide. (Tan et. al., 2023) These gases can be partially recirculated to sustain the pyrolysis process selfsufficient, increasing system efficiency and minimizing the need for external energy inputs. (Larrain et. al., 2020)

To maximize energetic recovery, the generated gas stream is directed into a high-efficiency gas turbine. In this configuration, approximately 30% of the energy content is converted into electricity, while the remaining 70% manifests as useful thermal energy. (Klinar et. al., 2021) This cogeneration (CHP) model provides a more favourable energy yield than simple incineration or mechanical recycling, particularly for heterogeneous, contaminated, or aged plastic fractions from landfills. (Zou et. al., 2023)

The study also discusses the feasibility of deploying such a pyrolysis and energy recovery unit at or near the CERO Gajke site. The local potential for energy self-sufficiency (1–10 MW total energy processed scale), reduction of landfill mass, and creation of high-value outputs such as paraffin waxes or pyrolytic gases makes this a highly relevant case for circular economy strategies in regional waste management. (Bridgwater et. al., 2007)

Furthermore, the paper situates this technical approach within the broader framework of technospheric mining, where landfills are re-evaluated as secondary raw material reserves. This pilot model aligns with EU Green Deal goals by reducing landfill dependency, recovering embedded energy, and contributing to regional resilience. (Almeida et. al., 2023) The possibility of integrating permanent gases back into the pyrolysis process itself (auto-thermal operation) and valorising waxes as phase-change materials (PCMs) opens additional innovation pathways. (Bharathiraja et. al. 2024)

In conclusion, energetic valorisation of mined polyolefins from the landfill exemplifies a pragmatic and scalable approach to closing material loops and decarbonising local energy systems. A schematic diagram of the process will be presented, illustrating the flow from landfill excavation to gas turbine energy production. This model offers a replicable template for similar landfills across Europe regions, enabling the transformation of environmental burdens into energy assets. A schematic diagram of the process will be presented, illustrating the flow from landfill excavation to gas turbine energy production, as shown in Figure 1.

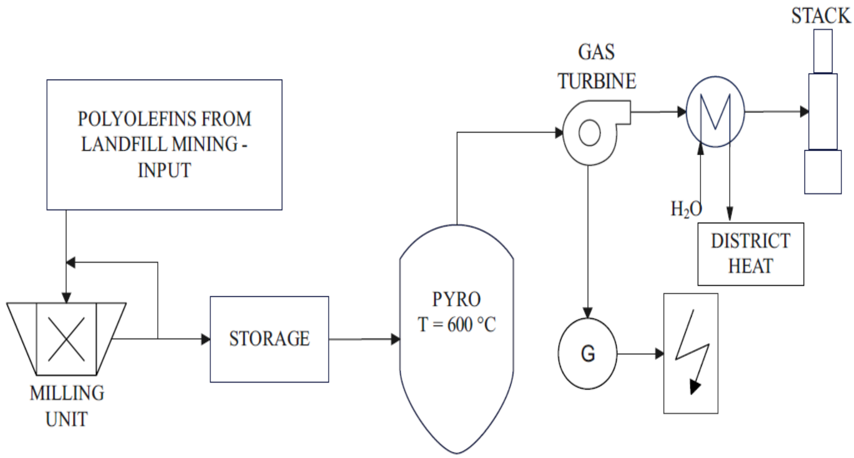

Figure 1: Schematic diagram of the integrated process, showing the progression from landfill excavation and plastic waste recovery to polyolefin pyrolysis and subsequent energy production using gas turbines.

Keywords: landfill mining, polyolefins, pyrolysis, energy valorization, circular economy

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Optimisation of Radioactive Fly Ash Processing With Focus on Mechanical Strength and Radwaste Safety of Microwave-Irradiated Alkali-Activated Material

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The building and civil engineering industry has a significant impact on the environment, by contributing over 40% of human-made carbon emissions. This is a consequence of the use of large quantities of raw materials (almost two-thirds of the mass of Mount Everest per year) and processing at high temperatures (over 1000 °C). To reduce environmental concerns, the building industry is exploring alternative materials such as alkali-activated materials (AAMs) with synthesis temperatures below 100 °C and secondary raw materials as reagents, which can even transform the built environment from a net carbon emitter into a carbon sink.

Potential precursors for alkali activation are inorganic materials rich in amorphous Al and Si, such as fly ash (FA). Although FA is one of the most researched materials for alkali activation, its main disadvantages have not yet been sufficiently explored:

(i) Cellulose content (incomplete combustion): The presence of cellulose poses a risk to long-term durability in construction applications due to the natural degradation of organic material over time.
(ii) Radioactivity: FA contains concentrated naturally occurring radioactive material (NORM) present in coal as a byproduct of coal combustion in power plants. While alkali activation offers a promising solution for immobilising NORM by entrapping it in a stable aluminosilicate network, immobilisation in AAM may not be sufficient for the highly radioactive NORM (among the FAs) used in this study.

Therefore, different processing methods were applied to FA before it was alkali-activated: (i) sieving, (ii) milling and sieving, or (iii) exposure to elevated temperatures before mixing with an alkali silicate solution. FA was analysed by X-ray fluorescence (XRF) and X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR) and Thermogravimetric analysis (TGA/DTG). The mixture of FA and alkali solution was precalculated using the XRF and XRD results of the original FA, while excluding the organic content. The precalculation was performed under boundary conditions aiming for the molar ratio of amorphous:

(i) Si to Al to be 1.9 to 1 to achieve the highest compressive strength,
(ii) Al to the sum of the chemical elements from the 1st group of the periodic table to be 1 to 1 or even 1 to <1 to avoid efflorescence and degradation of the AAM.

To maximise the compressive strength of the AAMs, freshly mixed and moulded samples were exposed to low-power microwave irradiation for a short time to volumetrically increase the temperature and dissolution, and improve the reaction kinetics throughout the slurry, using a non-irradiated AAM as a reference.

Experimental results demonstrate that the addition of low electrical energy by microwave irradiation significantly improves the mechanical properties of AAMs. However, the removal of cellulose from FA by sieving below 200 μm, which also resulted in the removal of radioactive nuclides, exhibited no microwave irradiation effects on compressive strength. Furthermore, the radionuclide-free sample resulted in the highest compressive strength (exceeding 60 MPa).

While further validation of radionuclide separation in naturally radioactive FA is required, the addition of sieving presents a viable pathway for the development of high-performance, environmentally sustainable and radwaste-safe construction materials.

Keywords: alkali-activated material, radioactive fly ash, naturally occurring radioactive material, radionuclide separation, microwave irradiation, circular economy

Acknowledgement

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Utilization of Industrial Red Gypsum for Sustainable Cementitious and Geopolymer Composites

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Red gypsum (RG) is an industrial by-product generated during titanium dioxide production via the sulphate process and is typically landfilled, raising both environmental and spatial concerns. Given its mineralogical composition – predominantly calcium sulphate with residual titanium dioxide and iron oxides – RG has been increasingly explored as a potential resource in sustainable construction materials. Recent studies have demonstrated its suitability in cementitious and gypsum-based binders, including applications with photocatalytic and self-cleaning functionalities (Sotiriadis et al., 2024; Ju et al., 2023). In addition, broader evaluations of red gypsum and similar industrial residues have identified their potential for integration into green construction materials under circular economy principles (Xie et al., 2024). Building on this context, the present work investigates the valorization of RG produced at Cinkarna Celje d.d. through its incorporation into cementitious and geopolymer materials, with the aim of evaluating its feasibility as a functional, low-carbon additive in green construction.

The aim was to assess the feasibility of its incorporation into sustainable construction materials. Comprehensive chemical, mechanical and physical characterization of RG was performed, followed by multiple tests involving its use in Portland cement mortars, cement pastes, and geopolymer composites.

For cementitious systems, RG was dried, milled, and sieved to <90 μm. Blends with 5–20 wt% RG were evaluated for workability, setting time, porosity, dimensional stability, and strength. Results showed that lower RG contents (5–10%) modestly delayed initial setting but preserved mechanical integrity, while higher contents reduced workability and compressive strength. Response Surface Methodology (RSM) revealed that 5% RG offers an optimal trade-off between porosity reduction and adequate workability. Le Chatelier expansion tests and FTIR-ATR spectra confirmed dimensional and chemical compatibility.

In addition to use as a binder supplement, RG was tested as a partial sand replacement (5–15%) in mortars. However, this significantly reduced both compressive and flexural strength, indicating limited suitability in this role. Further, feasibility of granulating RG was explored, but due to its low structural resistance and high water absorption, it requires plasticizer additives for adequate processing.

Finally, RG was incorporated into metakaolin-based geopolymer matrices as a filler. While partial replacement of metakaolin up to 10% maintained acceptable compressive strength (~13–19 MPa after 7 days), higher dosages impaired polymerization and mechanical properties.

The study concludes that red gypsum holds promise as a low-carbon additive in green concrete and geopolymer production when used in optimized proportions, particularly below 10% (Kravanja, 2025).

Keywords: red gypsum, sustainability, circular economy, concrete, geopolymers

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Mobility of Selected Elements in Different Recycled Materials

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The importance of using recycled materials is promoted by EU Waste Framework Directive (Directive 2008/98/EC) and the EU Landfill Directive (Directive 1999/31/EC), both of which were updated by Directive (EU) 2018/850. These regulations aim to promote recycling and reuse, while limiting the landfilling, by 2030. The use of such materials also contributes to reducing CO_2 emissions and supports the transition to a greener and more sustainable economy (Ahmad et al., 2019; Freitas et al., 2021). In order to use recycled materials efficiently, various standardized tests are used to assess the leaching and environmental risk of such materials (Russel et al., 2007). In this study, three different incineration ashes, and one steel slag were investigated. To assess the mobility of potentially toxic elements (PTEs), a batch leaching test, Tessier sequential extraction and a leaching test in a synthetic cement pore solution were performed. The samples were analysed by ICP-MS and ICP-OES. Complementary analytical techniques such as SEM-EDS and XRD were used to determine the phase composition and origin of PTEs. Results of Tessier's sequential extraction showed that, among the PTEs determined, Mo was the most mobile in the fly coal ash, Ba was identified as the most mobile PTE in paper sludge ash, while in biomass ash, the most mobile were Cr and Mo. In steel slag, most of the elements were found in the residual phase; bound to silicate and aluminosilicate matrices, indicating their high stability. To further determine the origin and study different immobilization strategies for PTEs, additional studies will be carried out where ICP-MS based analytical methods, including the speciation analysis and laser ablation-ICP-MS will be applied.

Keywords: recycled materials, potentially toxic elements, leaching tests, extraction tests, phase composition

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Energy-Efficient Coatings: The Role of Heat-Reflecting Pigments

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In view of the increasing global demand for energy and the growing climate problem, the development of energy-efficient materials has become ever more important. Heat-reflecting pigments play an important role in the formulation of coatings that reduce solar heat gain and thus contribute to passive cooling strategies in buildings, vehicles and infrastructure. By reflecting infrared light and reducing heat, infrared reflective coatings can keep objects cooler and offer significant benefits for a variety of applications. The main objective of our research was to investigate the applications of heat-reflective pigments (especially mica-based pigments) on transparent materials with different surface topography. The chromatic properties as well as infrared reflectance and transparency were examined as a function of the pigment concentration and the material used.

Keywords: heat-reflecting pigments, energy efficiency, solar heat, coatings, transparent materials

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Open Aqeous Loop Plastics Litter Utilization in Circular Business Models

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The accumulation of plastic litter in open water streams like rivers and oceans is the result of overconsumption, lack of collection regulations, waste management infrastructure and human behavioural problem, where the right business models could decrease the overall pollution. While the right approach is the reduction of overall litter at the source (shops, markets and trading places), the complexity and vested interest of several market stakeholders framed in growth-oriented consumption business models makes that goal harder, especially in Global South countries where the waste problems are more systemic and externalized by Global North (imports of plastic waste). Currently there are several mitigation strategies and some business model initiatives which have been tested with mixed results. In this overview paper we shall concentrate on the possibilities of making a circular business model from plastic litter which originated from aqueous environments. While open loop litter collection has its negative aspects regarding current economic viability (due to mixed types and contamination) the resourced materials cannot be circled back in high quality grade recycled content which leads to "downcycling" (production of lower-value products). While these products have maybe lower potential market value for commodities, they are excluded from the upcoming plastic taxes which require recycled content inclusion (as they are above the taxable threshold). The potential of such business models which shall be presented lies in wider aspects of value proposition. By directly addressing a critical global environmental problem, cleaning up ecosystems and protecting biodiversity, provides a compelling narrative which can be attractive for companies. For example, proactive collection in key riverine and coastal hotspots using advanced capture technologies (e.g., specialized vessels, AI-monitored booms) or wastewater treatment plants could harvest these material resources (like hydro plant reusing wood debris). Or initial pre-sorting to maximize recovery of higher-value plastics, with residual, degraded plastics earmarked for potential chemical recycling partnerships. All these initiatives must function either by market or state backed systems to be viables in the current economic setups. The presented cases will be risk assessed to market price volatility, supply chain consistency, regulatory changes, as well public perception changes with our perspective which gaps are need for upscaling successful circular models.

Keywords: plastic litter, business models, downcycling, aqueous enviroments, open loop

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Unlocking the Potential of Corn Cobs Biomass for Biorefinery Valorization

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Corn (*Zea mays L.*) is one of the world's most important agricultural crops, with a production of around 44 billion tonnes of grain in 2022 – 2023. The world's major producers, the United States of America, Brazil, China, Ukraine, Argentina, India, Mexico and Indonesia, produce more than 75% of global corn production (Swati et al., 2024). Corn is also an important agricultural crop in Slovenia, where corn is grown partly for the production of corn grain and partly for the production of fermented corn silage for animal feed. The production of corn grains generates a lot of corn plant residues. Corn cobs, the second largest by-product of corn biomass, account for almost 19% of the mass of the corn grains and produce about 3.0 tonnes of wet cobs per hectare of cultivated corn (Blandino et al., 2016). Corn cobs consist mainly of cellulose (between 35 and 45%), hemicellulose (30 – 40%) and lignin (8 – 18%) and contain some ash (2 – 5%) (Jansen et al., 2012; Bae et al., 2022; Fu et al, 2022).

Besides the traditional application for the production of heating energy, corn cobs have proven to be an excellent potential source for the production of biofuels such as methane (Blandino et al., 2016; Wojcieszak et al., 2020) and bioethanol (Garai et al, 2024; Antunes et al, 2023; Elegbede et al, 2021). Corn cobs have a high nutritional value with 74.5% carbohydrates, 3.4% proteins, 9.5% fat, 7.3% fibres and up to 4.4% ash (Swati, 2024) and represent a potential ingredient for animal feed or a feed additive (Keller et al., 2023). Due to the excellent carbohydrate source, corn cobs can be used as a substrate in biotechnological processes for the production of various components such as xylitol, lactic, citric and oxalic acid and also enzymes (Elegbede et al, 2021). Corn cobs are also interesting for sustainable building and insulation materials (Okeke et al, 2024) and also as an adsorbent to remove pollutants from water (Iwuozor et al., 2023). In addition, corn cob ash has shown promising applications in building materials (Sathiparan et al., 2025) and as a removable source of silica nanoparticles (Sarkar et al, 2021). Corn cob biomass serves as a wild scarecrow for potential applications in various fields and is therefore a good showcase for potential applications of similar agricultural biomass by-products.

The potential of corn cobs was assessed as part of the Interreg Central Europe project TeBiCE (Territorial Biorefineries for the Circular Economy), in which a new value chain for corn cobs was developed and evaluated. Our paper summarizes the potential use of corn cobs biomass in the context of biorefineries. In the second part of our sequel, the evaluation of corn cobs was carried out by applying the Value Chain Generator Artificial Intelligence Tool (VCG.AI Tool).

Keywords: corn by-product, corn cob, biomass valorization, value chain, TeBiCE project, biorefinery, Value Cain Generator ®.

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The High-Resolution Spark-OES Chemical Composition Measurements for Ensuring the Quality of Recycled Aluminium Alloys

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The common obstacles in ensuring the quality of wrought aluminium alloys produced from end-of-life products include difficulties in achieving the required chemical composition of the melt. The melt composition significantly influences microstructure development and the properties of semi-finished and finished products (Raabe et al., 2022). Imperfections in melt composition, caused by trace elements introduced by scrap, are among the most challenging to overcome. Typically, these elements appear in concentrations below 500 ppm, making their accurate, precise, repeatable, and reproducible quantitative determination a considerable challenge.

The objective of the research presented in this paper is to develop industrial tools for high-resolution and highly accurate determination of the chemical composition of aluminium alloys, as well as semi-finished and finished products derived from them. Such advancements would facilitate an increased share of post-consumer scrap in wrought aluminium alloys and accelerate the green transformation of the aluminium industry.

In the aluminium industry, the most widely used method for determining the chemical composition of alloys and scrap is spark optical emission spectroscopy (spark-OES). However, most commercial instruments used in industrial laboratories exhibit excellent Limits of Detection (LOD) for alloying and trace elements but insufficient Limits of Quantification (LOQ) due to inadequate instrument calibration.

This work describes a precise, high-resolution spark-OES calibration procedure suitable for accurate monitoring of alloying and trace elements in wrought aluminium alloys. The calibration was performed using a commercial spark-OES (Spectrolab S), which is currently in use in our industrial laboratory. The achieved calibration quality was documented by LOD and LOQ values (<< 1 ppm) for the set of elements routinely analysed, as will be presented.

Due to the complexity of our production program and the need to overcome matrix effects in element analysis, we implemented various calibration methods for different alloy matrices. Specifically, one calibration method was designed for the 1xxx, 3xxx, 6xxx, and 8xxx alloy groups, while individual calibrations were established for the 2xxx, 4xxx, 5xxx, and 7xxx alloy series. Special attention was also given to determining calibration curves for more than 30 elements, particularly at very low concentration ranges. The required precision was achieved using custom-made, certified reference standards of the highest quality class. The entire calibration setup was established in accordance with the requirements of ISO/IEC 17025:2017.

Accurate calibration of spark-OES with high resolution was found to offer significant advantages in ensuring the required quality of alloys and finished products. The achieved accuracy enables the correlation of chemical composition, microstructural characteristics, and the desired properties of finished products. This tool is particularly valuable for tailoring the properties of semi-finished and finished products ordered by customers in the aerospace and military sectors.

Customers in these demanding market segments have already recognized the benefits of this approach, identifying it as a key comparative advantage in the further development of high-value-added programs based on circular aluminium management.

Keywords: aluminium, wrough, alloys, chemical composition, trace elements, optical emission spectroscopy, calibration methods, circular economy

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Conversion of Solid-State Fermentation Residues Into Solid Biofuel

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Solid-state fermentation (SSF) using fungi offers significant environmental and economic advantages. It allows waste materials from agriculture and the food industry to be utilised as substrates, thereby reducing costs and environmental impact. SSF requires less water and energy compared to conventional fermentation methods, aligning with circular bioeconomy principles (Šelo, 2021). The potential of SSF to produce valuable compounds with a lower environmental impact makes it an attractive option for sustainable bioprocessing. The process is robust and can produce a wide range of high-value products, including enzymes, organic acids, bioactive compounds (antioxidants, vitamins and secondary metabolites) and functional foods. However, there are still problems with scale-up, process control and purification of the products generated during fermentation (Bamidele, 2025). Another challenge is the handling and disposal of biomass residues and waste generated during SSF treatment, although few studies have addressed this issue using methods such as anaerobic digestion and pyrolysis to treat SSF residues (Xu, 2024).

In this study, the hydrothermal treatment (HT) method was used to convert waste from SSF into value-added products, i.e. hydrochar. The laboratory experiments were carried out for hydrothermal treatment of SSF waste at selected temperature and reaction time. The influence of SSF pre-treatment on the HT products was investigated by analysing the chemical properties of the hydrochars, which were compared with those of the untreated biomass. The hydrochar yield, energy yield, ash content, carbon content and calorific value served as the main indicators to assess the potential of the obtained hydrochar for use as a solid biofuel in thermal applications.

Keywords: solid-state fermentation, residues, valorization, hydrothermal treatment, hydrochar production

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Extractives Content in Differently Stored Bark of Silver Fir (Abies Alba Mill.)

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The bark of coniferous trees has been shown to contain large amounts of phenolic compounds with antimicrobial, antifungal and antioxidant properties. The highest concentrations of bioactive polyphenols are found in the parts of the tree that remain as residues when logs are processed in wood processing plants. The bark of silver fir (Abies alba Mill.) is a natural source of bioactive polyphenols that are already used in commercially available dietary supplements. In order to obtain a high- quality extract, the bark must be properly treated and stored before extraction.

Several mature and undamaged silver fir trees were included. The trees were felled in the forests of Kočevska Reka at the coordinates 45°34’31.5” N, 14°46’27.8” E. The bark samples were obtained from the log slices in the laboratory of the

Department of Wood Science and Technology at the Biotechnical Faculty in Ljubljana. In addition, bark collected using an industrial debarker from the Poganci sawmill was used.

The field trial was used to investigate changes in the extract content of silver fir bark stored under different conditions. The effects of the storage conditions of the bark on the content of extractives, polyphenols and condensed tannins were analyzed. Monitoring was carried out over the course of a year with monthly sampling and measurements. The silver fir bark samples were extracted in an inert atmosphere using an accelerated extraction system (Thermo Scientific™ Dionex™ ASE™ 350). Water was used as the extraction solvent. The resulting extracts were chemically analyzed using the gravimetric method, UV-Vis spectrophotometry and chromatographic techniques (HPLC-PDA and GC-MSD).

The results of the chemical analyzes showed that both the mechanical processing of the biomass prior to extraction and the storage conditions significantly influence the content of extractives and polyphenols in the silver fir bark. In order to preserve the quality of the silver fir bark for efficient extraction with a high yield, the material should be stored uncrushed in a dark and covered place.

Figure 1: The samples of silver fir bark (Abies alba Mill.) for chemical analysis were prepared in the laboratory of the Department of Wood Science and Technology at the Biotechnical Faculty. Additional bark samples were taken from logs that had been debarked using an industrial debarker.

Keywords: silver fir, wood, bark, storage, extractives, polyphenols

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Hydrothermal Degradation of Glass Reinforced Polycarbonate Plastic

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Plastic pollution is one of the most important environmental problems we face today. The degradation of plastic is a slow process that can take decades to centuries. To reduce plastic waste, we use mechanical, thermal or chemical recycling. Polycarbonates with glass fibres are composite materials that combine polycarbonates composed of bisphenol A (BPA) with glass fibres. The fibre phase is dispersed or structurally integrated into a continuous polymer phase. The fusion gives us higher mechanical strength, greater durability of the material and good impact resistance of the material. It is used in a variety of technical applications in the aerospace, automotive, energy, construction and medical sectors (Karuppannan Gopalraj & Kärki, 2020).

Subcritical water is liquid water at temperatures between 100 °C and 370 °C and a pressure above the saturation pressure. In the subcritical state, water has a higher density, can dissolve organic substances and has a higher ionization constant, which increases its reactivity. It acts as a reaction medium that catalyses the

depolymerisation of the polycarbonate bonds and enables degradation without affecting the glass fibres. The use of subcritical water is a more environmentally friendly and cost-effective alternative, as it allows easy control of the process parameters without the need for additional chemicals and solvents (Goto, 2016).

In this study, the decomposition of glass fibre reinforced polycarbonate (30% glass fibres) in subcritical water was carried out to determine the optimal reaction conditions (temperature and time) for the recovery of valuable products. The experiments were carried out in a batch reactor at temperatures between 250 °C and 350 °C and a duration between 5 min and 120 min. The decomposition of PC into valuable products such as bisphenol A (BPA) monomer, various alkylphenols and phenol was successfully carried out in subcritical water. Investigation of the influence of the process parameters (temperature and time) showed that the maximum yield of the product (66.8%) was achieved at a reaction temperature of 350 °C and a reaction time of 5 minutes. The results of the study show that the choice of process parameters is of decisive importance, as they influence the course of the reactions and thus the type of degradation products and their yields.

Keywords: glass reinforced plastic, subcritical water, chemical recycling, hydrothermal process, bisphenol A

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Industry 4.0 Key Technologies as Technological Enablers of Circular Economy

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Introduction

The escalating global environmental crisis and dwindling natural resources necessitate a paradigm shift from the conventional linear "take-make-dispose" economic model to a regenerative Circular Economy (CE). Industry 4.0 (I4.0) technologies, characterized by interconnectedness, real-time data exchange, and intelligent automation, are increasingly recognized as pivotal enablers for accelerating and optimizing the transition towards a CE. This abstract explores the synergistic relationship between I4.0 and CE, highlighting how various I4.0 components can facilitate circular practices across product lifecycles.

Methods

Key I4.0 technologies such as the Internet of Things (IoT), Big Data Analytics, Artificial Intelligence (AI), Additive Manufacturing (3D Printing), Blockchain, Robotics, Control Technologies, and Cyber-Physical Systems (CPS) offer unprecedented capabilities for enhanced resource efficiency, waste reduction, and closed-loop material flows. IoT sensors provide real-time data on product usage, condition, and location, enabling optimized maintenance, extended product lifespans through repair and refurbishment, and efficient collection of end-of-life products for recycling or remanufacturing. Big Data Analytics and AI leverage this information to identify patterns, predict material flows, optimize production processes for minimal waste, and inform circular design strategies from the outset. Additive Manufacturing supports the creation of customized products with reduced material waste and facilitates on-demand production of spare parts, thereby extending product utility. Blockchain technology offers transparency and traceability across the entire supply chain, crucial for verifying material origin, tracking product journeys, and building trust in circular ecosystems. CPS enable smart factories that can autonomously adapt production based on real-time demand and resource availability, significantly reducing overproduction and waste.

Conclusion

The integration of these technologies allows for a more comprehensive approach to circularity, moving beyond mere recycling to encompass higher-value retention strategies such as reuse, repair, remanufacturing, and repurposing. This digital and technological transformation enables companies to implement new circular business models, including product-as-a-service, leasing, and collaborative consumption, fostering a shift from product ownership to access. While the potential benefits are substantial, including reduced operational costs, enhanced resource security, and improved environmental performance, challenges remain. These include significant initial investment costs, the need for new skill sets, data security concerns, and the complexity of integrating diverse technologies across fragmented value chains. Despite these hurdles, the synergistic application of Industry 4.0 technologies presents a transformative opportunity to operationalize the circular economy, fostering sustainable industrial development and contributing to a more resilient and resource-efficient future.

Keywords: industry 4.0, sustainable manufacturing, circular economy, digital technologies, resource efficiency

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Hydrothermal Conversion of Pumpkin Cake Into Reusable Secondary Products

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The agricultural and food industries produce large quantities of biological residues every year, which are often rich in carbohydrates, proteins, fibres, fats and minerals. Despite their potential for conversion into value-added products, these materials are still hardly utilised. Vegetable oils (pumpkin oil) are an important component of agricultural production and generate by-products such as oil cake. These are mostly used as animal feed or compost, although they can contain up to 50% crude protein, up to 60% fibre and significant amounts of minerals (N, P, K, Ca). These properties make them suitable for processing into food supplements, protein isolates, fertilisers or as a raw material for bioenergy production (Petrovič et al., 2024). Hydrothermal processes, which use subcritical and supercritical water as a process medium

represent a green technology for converting this type of biowaste into a wide range of value-added products (Knez et al., 2018) .

In this work, the hydrothermal conversion of pumpkin cake with sub- and supercritical water into secondary products was studied. The experiments were carried out in a high-temperature and high-pressure reactor at temperatures of 300 °C to 400 °C and reaction times of 30 to 120 min. The hydrothermal conversion resulted in four product phases (biogas, bio-oil, aqueous and solid). The biogas and bio-oil phases were analysed by GC-MS and the HHV of the bio-oil phases was also determined. The solid residues were analysed by FTIR and the aqueous phases were analysed for total carbon and furfural content by HPLC.

The results show that after hydrothermal conversion of pumpkin cake, the bio-oil phase dominated in all cases, with the maximum yield being achieved at 300 °C and 30 min (73%) and decreasing with increasing temperature and reaction time. The yield of the aqueous phase also decreased (from 16% to 10%), while the yield of the biogas phase increased with increasing temperature and reaction time, reaching the highest yield (28%) at 400 °C and 120 min. The biogas mixtures were rich in CO_2 and light hydrocarbons. The chemical composition of the bio-oil phases showed a dominance of nitrogen-containing compounds, while these compounds disappeared from the FTIR spectra in the solid phase after degradation with increasing temperature and reaction time. Similarly, the concentration of furfurals in the aqueous phase decreased with more severe conditions. The bio-oil produced by hydrothermal conversion had a relatively high HHV between 23 and 29 MJ/kg, which was higher than the HHV of the crude pumpkin cake material (19 MJ/kg) and strongly depended on the reaction conditions. The results show that the hydrothermal conversion of pumpkin cake is an effective and enwironmentally friendly method for the production of energy-rich oil and platform chemicals.

Keywords: pumpkin cake, sub- and supercritical water, biowaste, conversion, bio-oil

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Mineral CO_2 Sequestration in Industrial Waste Materials: A Comparative Study Using FTIR, TGA and Calcimetry

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The increasing concentration of CO_2 in the atmosphere has intensified global efforts to develop effective carbon capture and storage (CCS) strategies. Among them, mineral CO_2 sequestration in industrial waste is a promising, sustainable approach that not only reduces emissions but also adds value to the waste products (Li and Wu, 2022). Waste ashes and slags, by-products of industrial processes such as incineration and steel production, are of particular interest due to their high alkalinity and reactive mineral phases that increase their ability to chemically bind CO_2. In this study, the CO_2 sequestration potential of selected industrial residues from Austria

and Slovenia is investigated by a comparative analysis using Fourier transform infrared spectroscopy (FTIR), thermogravimetric analysis (TGA) and calcimetry.

Two different raw materials were selected: two different types of waste ash (biomass ash-A1 and co-combustion ash-A2) and two different types of slag (EAF slag-S1 and mixture of EAF-S slag and ladle slag-S2). The CO_2 storage capacity of each sample was tested using a modified method (Tominc and Ducman, 2023) at a controlled relative humidity of 80%, a temperature of 40±0.1 °C and a CO_2 concentration of 20±0.1 vol% for 72 hours. Prior to exposure in the carbonation chamber, the samples were mixed with 10 m% water. The fully carbonated samples were then dried at 105 °C for 24 hours for further analysis. FTIR was performed in attenuated total reflectance (ATR) mode. For calcimetry, which measures carbonate content based on its reaction with acid, CO_2 release was measured using a pressure calcimeter and TGA was performed in the temperature range of 25 to 1000 °C.

A comparative study of the $CaCO_3$ content before and after accelerated carbonation was performed using TGA, calcimetry and quantitative FTIR. Of the samples tested, biomass ash A1 showed the most significant increase in $CaCO_3$ content after CO_2 exposure with a CO_2 uptake of 9.1%. In contrast, ash A2 was found to be almost completely carbonated during sample storage, indicating a high reactivity even under ambient conditions. Sample S2 with a CO_2 uptake of 6.3% also showed a potential for CO_2 sequestration, while sample S1 with the CO_2 uptake of 4.2% showed a comparatively lower carbonation potential, which can be attributed to differences in the chemical and mineralogical composition. The CO_2 uptake was determined after complete carbonation using a pressure calcimeter by comparing the CO_2 content in the original and carbonated ash.

The potential for CO_2 storage in the analyzed samples was assessed to support ongoing research efforts aimed at reducing the carbon footprint of industrial processes. The selected waste materials have the potential for permanent binding of CO_2 and can be further used as feedstock for the development of alkali-activated materials (AAMs), which have significant potential for applications in construction, infrastructure and environmental technology.

Keywords: CO_2 sequestration capacity, accelerated carbonation, thermogravimetric analysis, calcimetry, fourier transform infrared spectroscopy

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Impact of Microwave Irradiation on Alkali-Activated Fly Ash With Removed Radionuclides and Incorporated Keratin-Based Fibres

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The building industry is a major contributor to global carbon emissions and is responsible for over 40% of human-made emissions. This is due to the energy-intensive production of materials (e.g. the synthesis of cement requires over 1000 °C), the enormous consumption of raw materials (almost two-thirds of the mass of Mount Everest annually), and the high demand for new infrastructure. In response to growing environmental concerns, research is increasingly focusing on reducing the sector's carbon footprint through the use of secondary raw materials such as industrial by-products and construction and demolition waste, which reduce embodied carbon.

If the secondary raw materials contain sufficient amounts of amorphous Si and Al, they can serve as a precursor for green cements (alkali-activated material, AAM), which are produced at temperatures below 100 °C, further reducing emissions. One of the potential sources is fly ash (FA), a by-product of coal combustion in thermal power plants. It consists mainly of fine spherical particles that rise with the flue gases and are captured by electrostatic precipitators or filters. However, FA often contains cellulose residues from incomplete combustion, which can reduce the performance of AAM. FA can also contain naturally occurring radioactive material (NORM) that is present in the coal and is concentrated during combustion. However, not enough attention is paid to the research and development of AAMs from radioactive sources.

Therefore, cellulose and NORM were removed from the used radioactive FA by sieving. The removal of cellulose was confirmed by Thermogravimetric analysis (TGA/DTG) and the removal of NORM by X-ray fluorescence (XRF). The remaining FA, labelled as FA_x, was milled and sieved below 125 μm before mixing with an alkali silicate solution in an optimal ratio that results in the highest strength (the molar ratio of Si to Al should be 1.9 to 1) while avoiding the efflorescence (Al to the sum of the chemical elements from the 1st group of the periodic table should be 1 to <1).

Because FA consists mostly of spherical particles, AAM made from FA lacks internal fibrous reinforcement, resulting in weaker bending strength. However, to keep the carbon footprint as low as possible, keratin-based organic waste fibres (cut below 1 cm) were homogenised with FA_x instead of commercially available fibres commonly used in the building industry. The fibres were sampled during shedding of winter coat from mature genetically tested intact Chesapeake Bay Retrievers (CBR), Curly Coated Retrievers (CCR), and Nova Scotia Duck Tolling Retrievers (NSDTR), which were selected due to their coats' water-work functional properties, and due to the winter dog-hair being hollow to provide additional thermal insulation to the AAM.

To maximise the mechanical strength of AAM, the freshly mixed and moulded samples were exposed to low-power microwave irradiation and compared to a non-irradiated reference and AAM without fibre addition.

The incorporation of 1 mass% fibres improved the mechanical performance for all fibre types. Among them, the CBR-reinforced samples reached the highest compressive strength, exceeding 65 MPa. However, microwave irradiation particularly benefited the CCR and NSDTR reinforced samples, with the CCR fibres almost reaching the compressive strength of the non-irradiated CBR fibres.

Keywords: alkali-activated material, radioactive fly ash, naturally occurring radioactive material, radionuclide separation, organic fibre, keratin-based fibre, microwave irradiation, circular economy

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Economic, Environmental-Climatic, and Social Consequences of Setting Minimum Food Self-Sufficiency Levels in Slovenia

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In the context of growing global instability driven by the Covid-19 pandemic and geopolitical conflicts, food security and sovereignty have gained increasing importance at the national level. The longer the supply chains, the greater the risk of disruption, prompting many countries to recognize the strategic value of domestic food production (Amare et al., 2021). Domestic food production must align with the goals of sustainable development and the Farm to Fork strategy. The aim of this contribution is to assess the economic, environmental-climatic, and social implications of setting minimum self-sufficiency levels for specific food categories in Slovenia. As a first step, Slovenia's food supply chain was optimized using a multi-criteria objective function, the Agriculture Circularity and Sustainability (ACS) index (Drofenik et al., 2024), which indicated a shift in agricultural focus from livestock production toward plant-based food. Such a transition would require profound structural changes that, based on assessments by experts in agricultural systems, are considered unlikely to be achievable within the next 25 years.

Subsequently, we systematically increased the self-sufficiency levels for four key food categories – wheat, potatoes, vegetables, and pork – whose current levels are considerably below full self-sufficiency. The increases were applied in 10-percentage-point increments to assess the associated economic, environmental, and social impacts.

As a first step, multi-objective optimization of the food supply chain based on a 10-percentage-point increase in self-sufficiency for selected food categories leads to lower greenhouse gas emissions, a higher share of land under organic farming, and an improved economic balance compared to the current situation. However, this scenario also results in an overall decrease of four percentage points in the total self-sufficiency rate relative to the baseline. When self-sufficiency levels for key food categories are increased by 20 percentage points, the overall self-sufficiency rate slightly surpasses the current level and continues to rise with each additional 10-percentage-point increase, reaching a maximum improvement at a 60-percentage-point increase, as this corresponds to achieving 100% self-sufficiency levels. The economic balance indicator also improves with multi-objective optimization, but it reaches the maximum value at 50-percentage-point increase. In contrast, environmental indicators – such as agricultural greenhouse gas emissions and the share of organic farmland – gradually deteriorate with each stepwise increase in self-sufficiency. This is primarily due to the rise in domestic pork production and the associated feed requirements, which place a higher burden on the environment. The ACS index value improves substantially when self-sufficiency is raised by 10 percentage points, mainly due to a reduction in both food imports and exports. However, subsequent increases in self-sufficiency yield only marginal gains in the ACS index, which reaches its maximum at the 50-percentage-point scenario.

The results show that moderately increasing minimum self-sufficiency levels can improve economic performance and overall system circularity and sustainability while reducing reliance on food imports and exports. However, higher targets -

especially for resource-intensive products like pork – can negatively affect environmental outcomes, such as GHG emissions and organic farmland share. These trade-offs highlight the need for carefully planned structural changes in the agricultural sector to enhance food security, while ensuring alignment with sustainable objectives.

Keywords: minimum self-sufficiency levels; food security; sustainable agriculture; multi-criteria optimization; economic, environmental and social impacts

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Optimization of Multi-Scale Reactor Networks for Power-To-X

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In the development of Power-to-X (P-t-X) technologies that uses renewable energy with chemical production, the ability to accurately model and optimize different reactor types - especially microreactors — is essential to enable process intensification, modularity and flexibility. This work presents a mathematical and optimization framework that supports the design of reactor networks for different types (batch, continuous) and scales (micro, meso, macro) by combining dynamic modelling with orthogonal collocation and mixed-integer nonlinear programming (MINLP).

The dynamic behaviour of chemical reactors is described by systems of nonlinear ordinary differential equations (ODEs) that include reaction kinetics, thermal effects and the transient evolution of the species. These ODEs are discretized using orthogonal collocation at Legendre–Gauss–Radau points, both globally (a single polynomial of high degree over the entire time domain) and locally by finite elements (piecewise polynomials of low degree). The transformation leads to a sparse system of algebraic equations that can be directly embedded in optimization frameworks. Compared to standard integration techniques, orthogonal collocation provides a structured, scalable and differentiable formulation that is suitable for embedding dynamic models in large-scale optimization problems.

This study investigates the advantages of local over global collocation strategies in capturing systems with sharp gradients or non-uniform dynamics, as is common in microreactors and fast-responding P-t-X processes. The approach is applied to a representative reaction from the P-t-X domain (e.g. dimethyl ether synthesis), allowing model validation against experimental or literature data and performance comparison of collocation methods.

The resulting framework enables a systematic evaluation of reactor type, size and configuration within a MINLP-based optimization environment implemented in GAMS. This supports the rational design of scalable and decentralized chemical production systems tailored to renewable energy integration and helps to identify optimal reactor network structures for different P-t-X scenarios.

Keywords: orthogonal collocation, reactor modeling, power-to-X (P-t-X), MINLP, microreactors

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Formation of Microplastics From Fibre-Reinforced Cement and Their Post-Released Behaviour

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The construction and building sector is one of the largest consumers of plastics, integrating them into a wide range of applications. With an increasing number of components being manufactured from plastic, these materials are often chosen as replacements for traditional ones due to their low weight, cost-effectiveness, and in some cases, improved mechanical properties. This was the key motivation for our investigation into the formation of microplastics from plastic fibre-reinforced cementitious composites, which are widely used due to their effectiveness in controlling shrinkage-induced microcracks and improving post-cracking ductility. The goal was to explore how these reinforcing fibres contribute to microplastics generation and release throughout their service life, driven by mechanical stress and

other degradation processes, since microplastics pose an increasingly pressing environmental threat.

As part of the experimental work, we prepared fibre-reinforced cement-based prisms, given that cement forms the basis of concrete, the most widely used material in construction and building. Polypropylene (PP) fibres were used as a benchmark material commonly found in commercial concrete reinforcement, while recycled polyethylene terephthalate (rPET) fibres were selected as a circular economy alternative. To simulate microplastic formation throughout the material's life cycle, we applied laboratory methods representing two scenarios: surface abrasion with a Taber Abraser to mimic use-phase wear and crushing and milling with a horizontal vibration ball mill to simulate demolition and subsequent processing of construction waste. Microplastics released in both scenarios were detected, and changes in their surface morphology and physical properties were monitored.

To further explore the environmental implications, we examined the differences in behaviour between pristine microplastics and those aged within the cement matrix. Cement residues adhered to the microplastic surfaces, leading to increased particle density. In the case of PP, this caused a shift from buoyancy to sinking in water, potentially influencing microplastic transport and bioavailability in aquatic environments. In contrast, no such change was observed for rPET, which already exhibited sinking behaviour prior to exposure. We also investigated the electrostatic behaviour of the microplastics, their tendency to agglomerate, and the pH of their leachates.

Although fibres embedded in construction materials are typically considered immobilized and environmentally harmless, our findings show that microplastic generation can occur throughout their life cycle. This is particularly concerning given the large volume of plastic-containing materials used in construction. The results underscore the need for strategies that promote the safe use of secondary materials, minimize microplastic pollution, and enable a responsible transition to a circular economy with minimal environmental impact.

Keywords: microplastics, fibre-reinforced cement, mechanical wear, demolition, construction materials

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A Review of Carbon Footprint and Decarbonization Efforts in Healthcare

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Introduction

The healthcare sector is responsible for 4.4% to 5.2% of global greenhouse gas (GHG) emissions, a share comparable to that of the aviation industry (Dutchen, 2023). Its environmental impact results from multiple sources, including energy-intensive machinery and hospital operations, pharmaceutical production, medical equipment manufacturing, and extensive supply chains (WHO, 2020).

The carbon footprint of the healthcare sector varies across countries, along with differing efforts and initiatives to reduce it. This overview examines these variations within the global context, with a specific focus on the European Union (EU).

Overview

In the EU, the carbon footprint of the healthcare sector varies significantly between countries. Italy´s share is estimated at 2.3% of national emissions, while Hungary and Croatia are at 3-4%, Austria at 4-5% and Germany at 5.2%. For comparison, the healthcare sector accounts for 5.4% of national emissions in the United Kingdom, 8.5% in the United States, and 10.7% in Russia (Dutchen, 2023).

According to the report by HCWH (2019), the United States and China are the largest distributors to global GHG emissions from the healthcare sector, accounting for 27% and 17%. They are followed by the EU with 12%. Japan with 5%, and Russia with 4%.

The primary sources of carbon emissions in the healthcare sector tend to be consistent across countries, with only slight variations in their relative contributions. On average, pharmaceuticals and medical devices (including their production, packaging, and distribution) account for approximately 30% of emissions. Hospital energy use contributes around 25%, single-use medical supplies about 20%, transportation and logistics 15%, and other sources the remaining 10% (HCWH, 2019).

According to the GHG Protocol (2024), Scope 3 emissions – those arising from supply chains – accounts for the largest share of the healthcare sector's carbon footprint, often exceeding 70% of total emissions.

Decarbonisation efforts within the healthcare sector are gaining momentum. For example, the Irish Health Service Executive has launched a national climate change strategy targeting a 51% reduction in energy-related emissions by 2030, with a goal to reaching net-zero emissions by 2050. Similarly, Belgium's Operation Zero initiative, part of its National Environmental Health Action Plan, aims to establish a carbon-neutral healthcare system by 2050 (CleanMed Europe, 2025).

There is in increasing interest in incorporating environmental sustainability into Health Technology Assessments. During the conference for health economics and outcomes research (ISPOR Europe, 2023), discussions highlighted the importance of incentives, including regulations, tax benefits, and public pressure, to promote greener pharmaceutical practices (WHO, 2020).

Summary

While the carbon footprint of the healthcare sector is significant, countries are implementing targeted strategies such as sustainable procurement and infrastructure, along with policy reforms, to reduce their footprint and pave the way for a more climate-resilient and environmentally responsible global healthcare system.

Keywords: healthcare sector, carbon footprint, decarbonization strategies, environmentally sustainable healthcare, review

Acknowledgement

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Virtual Technologie for Teaching About Drinking Water Preparation and Wastewater Treatment

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Introduction

Wastewater management and drinking water preparation are two of the priority areas of the Slovenian sustainable smart specialization strategy (Ministrstvo za kohezijo in regionalni razvoj, 2025). However, the connection between wastewater treatment and adequate drinking water supply is often overlooked. Due to the impact of increasing climate change, there is an urgent need to educate students, employees and the wider population, which can be successfully achieved through the use of new technologies (e.g. virtual reality) (Fauville et al., 2020; Thoma et al. 2023; Said et al., 2023).

Methods

Using a 360-degree camera (Insta 360), we filmed the premises and facilities for the preparation and distribution of drinking water at the Maribor Waterworks. At the Maribor Central Wastewater Treatment Plant, we filmed the wastewater treatment process, including the laboratory. The footage was processed using the H5P software tool.

Results

Digital interactive learning materials have been prepared for use in the Moodle online classroom, with the help of which we will raise awareness among users about the environmental determinants of health, more specifically about the importance and procedures for wastewater management and appropriate preparation and control of drinking water.

Conclusions

Innovative learning materials enable the acquisition of new skills, the upgrading of existing knowledge, as well as the verification and consolidation that is essential for maintaining a healthy environment and effectively combating climate change.

Keywords: drinking water, waste water, digital learning materials, 360 degree camera, virtual reality

Acknowledgement

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GreenChemForCE – Circularity in Central European Chemical Sector

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Circularity in chemical production is essential for reducing waste, conserving finite resources, and minimizing environmental pollution. By reusing materials and closing resource loops, it decreases reliance on fossil-based inputs and enhances the sustainability of industrial processes (Keijer et al., 2019). Within this contribution, the project GreenChemForCE will be introduced. GreenChemForCE is a collaborative project that promotes sustainable chemical practices across Central Europe by uniting academic, industrial, and professional partners. It focuses on three key areas: circular management of plastics, CO_2 emission reduction and utilization, and greener fine chemical production. Through a combination of strategic planning and innovative technologies, the project aims to drive a systemic shift toward a more sustainable and circular chemical industry. Structure, and the main goals of the project will be introduced, alongside the key points of our analyses, relevant to the plastic management and CO_2 circularity. This will serve as a background for the discussion of the results obtained within the practical part of the project, which includes nylon depolymerization, progress in development of carbon capture technologies (Roth et al., 2025), and others.

Keywords: circularity, nylone, carbon capture, pharmaceuticals, cyrene

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A Business Model Framework for Up-Scaling Bioleaching Technology: From Laboratory to Semi-Industrial Applications

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Innovative technological solutions for waste electrical and electronic equipment (WEEE or e-waste) are crucial for the transition to a circular and sustainable economy and a key priority for the European Union (EU) to secure sustainable sources of raw materials. According to the European Commission (EC), the circular economy rate in the EU was 11.8% in 2023, a slight increase compared to 2022 (EC, 2023).

Technological developments and social trends are leading to an ever-increasing demand for electrical and electronic devices with a relatively short life cycle.

However, these devices contain valuable and critical metals, which are limited natural resources (Pérez-Martínez et al., 2021). The increasing consumption of such devices by consumers is increasing the amount of e-waste in the EU and worldwide (EU Parliament, 2020; Baldé et al., 2024). For this reason, the EU adopted Directive 2012/19/EU on waste electrical and electronic equipment to promote the reuse and recycling of e-waste, reduce the number of landfills and protect human health and the environment (EC, 2018).

Despite the EU's efforts to reduce e-waste generation and increase recycling, data shows that currently less than 40% of e-waste in the EU is recycled and the rest is unsorted (Euric, 2021).

In 2021, the amount of e-waste was 57.4 million tonnes, of which 6 million tonnes were PCBs (Chakraborty et al., 2022). E-waste, especially printed circuit boards (PCBs), contains many valuable raw materials, including copper, cobalt, zinc and nickel, which can be recovered efficiently with the right technology (Wang et al., 2017; Kumar et al., 2015). These metals are ideal for recycling as they retain their properties and can be reused multiple times without any loss of quality, which brings economic and environmental benefits (Euric, 2025).

Bioleaching, which uses microorganisms such as *Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans* to extract critical raw materials (CRMs) with minimal environmental impact and relatively low cost, is one of the most important areas of laboratory research in the field of innovative technological processes for e-waste recycling (Manikandan et al., 2021; Ji et al., 2024; Marinič et al., 2025). However, most research of this kind ends in the laboratory testing phase (Technology Readiness Levels (TRL) 4–5), as the transition to a pilot or semi-industrial scale (TRL 7) requires greater financial investment and a longer testing period (Ellwood et al., 2020; EC, 2022). This has led to the emergence of the so-called 'funding gap' or 'valley of death', which can be overcome through public–private partnerships, among other things (Probst et al., 2013).

The WEEE-NET9.SPEED project is a good practical example where this phenomenon has been eliminated with the financial support of EIT RawMaterials. It is an upgrade of the WEEE-NET9 project, which was finalised in 2024 and enabled the transfer of knowledge and implementation of bioleaching technology

from laboratory scale to pilot and semi-industrial scale (TRL 7) in the company. PCB recycling using bioleaching technology and microorganisms will be carried out in reactors with different volumes (2 litres, 20 litres and 100 litres) and the monitoring parameters are important for the efficiency of bioleaching in a semi-industrial environment. A business model is also being developed for the RIS region to encourage further innovation and investment in industrial solutions for e-waste recycling.

Keywords: e-waste, recycling printed circuit borads, bioleaching, semi-industrial scale, business model

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Waste to Worth: Phosphorus Recovery from Sewage Sludge Pellets with Bioleaching

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Introduction

Phosphorus (P) is an essential element for all living organisms and plays a critical role in global food production through its use in fertilizers. Traditionally sourced from phosphate rock, phosphorus reserves are geographically concentrated, making supply chains vulnerable to political and economic instability (Alewell et al., 2020).

As demand for phosphorus increases, alternative recovery options are becoming increasingly important. Municipal sewage sludge, which is rich in phosphorus is a promising secondary resource. However, its use is limited by toxic metals, microplastics and pathogens, so that direct agricultural use is controversial and often restricted by EU regulations (Hušek et al., 2022).

Bioleaching is a microbiologically mediated process that uses acidophilic bacteria to solubilize metals and phosphorus under controlled acidic conditions. Species such as *Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans* oxidize elemental sulfur, producing sulfuric acid and lowering the pH, which in turn facilitates the release of phosphorus from inorganic complexes (Kasina et al., 2023). This study investigates the potential of bioleaching approach to recover phosphorus from pelletized municipal sewage sludge using a mixed bacterial culture under laboratory conditions.

Methods

Pelletised municipal sewage sludge was subjected to bioleaching with a mixed culture of *Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans*. The experiments were carried out at 30°C in a shaking incubator. The phosphorus concentrations in the solution were measured at seven time points - days 1, 3, 5, 7, 9, 13, 15 - using ICP-MS. Controls were carried out on days 5 and 13. pH was measured at the same time points.

Results

The phosphorus concentrations in the leachate increased steadily during the 15-day bioleaching period. Starting at 56.50 mg/L on day 1, the concentration increased to 895 mg/L by day 13 and peaked at 1350 mg/L on day 15.

Initial pH values were between 4.40 and 4.30 during the initial phase, but dropped to 2.70 by day 5 and 2.10 by day 13. This acidification is consistent with microbial sulphur oxidation promoting the solubilisation of phosphorus. In contrast, the control samples remained relatively acidic (pH 2.83 and 1.91) and showed minimal phosphorus release (13 mg/L and 6 mg/L), emphasising the essential role of active microbial metabolism in the bioleaching process.

Conclusions

Bioleaching with *A. ferrooxidans* and *A. thiooxidans* is effective in mobilising phosphorus from sewage sludge pellets. This method provides a viable pathway for phosphorus recovery, supports circular economy goals and reduces dependence on phosphate rock resources.

Keywords: sewage sludge pellets, phosphorous, bioleaching, *Acidithiobacillus ferrooxidans*, *Acidithiobacillus thiooxidans*

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Leveraging the FLUX Framework for Circular Business Models: Navigating Sustainable Transformation

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The urgent need to address global challenges such as resource depletion, waste proliferation, and climate change has driven the adoption of circular business models (CBMs). Unlike linear "take-make-dispose" systems, CBMs prioritize resource efficiency, waste minimization, and value retention through strategies like reuse, recycling, and product-life extension. However, implementing CBMs requires navigating complex market dynamics and stakeholder ecosystems. The FLUX Framework, defined by Fast, Liquid, Uncharted, and eXperimental principles, provides an agile and adaptive methodology to guide organizations through rapid transformation. This abstract, presented at the TBMCE2025 conference, explores how the FLUX Framework enables the design and scaling of CBMs to foster sustainable innovation in dynamic business environments.

The FLUX Framework was applied to CBMs through a systems-thinking approach, integrating its core principles: Fast decision-making to respond swiftly to market changes, Liquid adaptability to transcend industry boundaries, Uncharted exploration of innovative opportunities, and eXperimental prototyping to test and refine solutions. Case studies from the textile, manufacturing, and technology sectors were analyzed to assess the framework's effectiveness. These cases involved mapping resource flows, stakeholder collaboration, and iterative design processes. Digital technologies, including IoT, blockchain, and AI, were incorporated to enhance real-time data analysis and transparency. Feedback loops and cross-sector partnerships were established to address barriers such as fragmented supply chains and regulatory constraints.

The application of the FLUX Framework yielded significant outcomes in developing resilient CBMs. In the textile industry, FLUX principles enabled closed systems that integrated upcycling and material recovery, reducing waste by up to 30% in pilot programs. In the technology sector, modular product designs supported by the framework extended product lifecycles and reduced e-waste by facilitating repair and refurbishment. The framework's emphasis on fast decision-making and experimental prototyping allowed organizations to adapt quickly to consumer preferences and regulatory shifts. Digital tools enhanced supply chain transparency and resource tracking, though challenges like high implementation costs and data privacy concerns were noted. Stakeholder alignment through cross-sector collaboration further strengthened the scalability of these models.

The FLUX Framework offers a powerful approach to designing and scaling CBMs, enabling organizations to navigate the complexities of sustainable transformation. Its principles of agility, adaptability, and experimentation address key barriers to circularity, fostering innovation and resilience. While digital technologies amplify its impact, addressing challenges like cost and privacy is critical for broader adoption. This presentation highlights the framework's potential to drive systemic change, aligning with the conference's focus on sustainable innovation. Future research should explore integrating social equity into CBMs and scaling FLUX applications across diverse industries, paving the way for a regenerative economy that thrives in constant change.

Keywords: framework, system thinking, circular business models, sustainable innovation methods, prototyping to test

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The Evaluation of Processed Steel Slag for Its Use in the Production of Clay Bricks

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As clay deposits are scarce, the brick industry is constantly looking for possible additives and/or substitutes for clay. Some additives simply replace virgin clay and thus save resources; some other might have beneficial influence on process or product. In this sense, chemical and mineralogical compositions of steel slags as potential additives in clay brick sector are important as they can influence formation, drying and firing phases (Shih et. al., 2004). In particular, the quartz content is important as it affects both product properties and the drying process (reduces sensitivity), but also firing, where the phase transformation of the quartz at 573 °C during the cooling phase should be taken into account as it is associated with

volumetric changes and can lead to cracks in the products if the cooling process is not properly controlled (Ducman et al. 2022).

Ekominit S1 from SIJ Acroni is a mineral product obtained by processing a mixture of stainless slag (EAF S slag) and ladle slag and consists mainly of β-C2S/γ-C2S, merwinite, bredigite, mayenite and periclase. The chemical composition consists mainly of CaO (37 wt.%), SiO_2 (18 wt.%), MgO (14 wt.%), Al_2O_3 (10 wt.%) and Fe_2O_3 (7 wt.%).

10% by weight of the Ekominit was added to a clay sample and fired at two different temperatures (950 and 1050 °C). The brick samples were ground to a particle size of less than 63 μm and sintered in a HLF 100 laboratory furnace (Protherm) at 950 °C and 1050 °C for 2 hours at a heating and cooling rate of 150 °C/h. The pore distribution of the sintered samples was measured using mercury intrusion porosimetry (MIP). The compressive strength was measured using a ToniPRAX compressive strength testing machine (ToniTechnik, Berlin, Germany) at a force rate of 1.2 kN/s. The microstructure and elemental composition (complementary method to confirm XRD) of brick samples was observed by a JEOL IT500 HV Scanning Electron Microscope (SEM) equipped with an Energy Dispersieve X–ray spectrometer (EDS) with a W–filament.

The total porosity of clay samples fired at 950 °C was around 21% and with addition of Ekominit porosity increased to 26%. The lowest porosity was measured in the clay sample fired at 1050 °C (approx. 19%), which also had the highest mechanical strength and density. With the addition of Ekominit, porosity increased to 25%. The compressive strength of the clay also decreased with the addition of Ekominit, namely by 36% for the Ekominit clay fired at 950 °C and by 31% for Ekomint clay fired at 1100 °C The highest compresive strenght was measured for the clay sample fired at 1050 °C, 261 ±10 MPa. The clay with Ekominit fired at 1050 °C has even lower compresive strenght compare to clay samples fired at 950 °C. Despite the lower compressive strength of Ekominit fired at 1050 °C, the value of 162 ±4 MPa would still be above the limit of 10 MPa specified in the SIST EN 772–1 standard when used in bricks.

Partial replacement of clay with processed steel slag Ekominit (up to 10 by weight) resulted in a reduction in mechanical properties and an increase in porosity, and it could be used instead of quartz as opening agent. When processed steel slag can be incorporated into bricks, this would also reduce the environmental impact of this sector by using secondary products instead of virgin material.

Keywords: clay bricks, compressive strength, opening agent, porosity, steel slag

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Metal–Organic Framework-Based Platforms for Antibiotic Degradation via Immobilized β-Lactamase

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The uncontrolled use of antibiotics poses a serious threat to human health, as well as to the environment. Therefore, an increasing focus on biological methods for antibiotic degradation using enzymes is taking place, since they can degrade antibiotics due to their excellent catalytic properties, eco-friendly nature and high biocompatibility. Metal-organic frameworks (MOFs) are a versatile group of porous materials known for their extensive surface area, adjustable pore size, crystalline structure, and wide range of functionalities. Enzyme encapsulated MOFs present a versatile and effective tool for the elimination of hazardous pollutants from the environment and utilization for degradation of antibiotics in wastewater systems with high efficiency. ZIF-8 nanoparticles were synthesized. Briefly, zinc acetate (20 mmol/L) in water solution was quickly added to 2-methylimidazole (1.4 mmol/L) in water solution. The mixture was stirred for 12 hours at room temperature and 850 rpm. The synthesized ZIF-8 nanoparticles were collected by centrifugation at 11,000 rpm for 10 min and washed with deionized water three times. Enzyme encapsulated ZIF-8 (β-lact-ZIF8) were prepared by the same protocol, with 2-methylimidazole mixed with β-lactamase (2,5 mg/mL). The catalytic activity study was performed as follows; PEN solution (with varying concentrations of 0.1 mg/mL, 0.5 mg/mL and 1 mg/mL) was mixed with either 100 uL of free β-lactamase, 100 uL of β-lact-ZIF-8 or 20 mg or ZIF-8. Continual agitation was applied using orbital shaker at 200 rpm and room temperature. 1 mL of PEN solution was collected after 10, 20, 30, 60, 90, 120 min and monitored by the HPLC method. The catalytic study and performance of β-lactamase, β-lact-ZIF8 and ZIF-8 for the degradation of PEN was estimated in aqueous solution at room temperature. The results show excellent degradation properties of β-lact-ZIF8, compared to free β-lactamase. 90% of PEN degraded under the catalytic reaction with β-lact-ZIF8 after only 10 min and was fully degraded after 120 min, while free β-lactamase and ZIF-8 degraded only 5% and 66% of PEN after 120 min, respectively with equivalent concentration of the enzyme (2.5 mg/mL). The β-lactamase encapsulated MOFs show excellent properties for the degradation of PEN, which was significantly improved when compared to the use of free enzyme.

Keywords: metal-organic frameworks, ZIF-8, β-lactamase, immobilization, antibiotic degradation

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Sustainable Lignin Extraction: Transforming Agricultural Waste into Green Resources

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Slovenia's rich lignocellulosic biomass resources, particularly its extensive forest coverage exceeding 58% of the national territory, provide a strong foundation for advancing the country's bio-based economy (Preslica, 2019). However, beyond the well-recognized forestry sector, agricultural residues such as wheat straw, corn stover, and cereal husks remain an underexploited resource with significant potential for contributing to sustainable value chains. These materials offer an important alternative feedstock for biorefining, complementing the dominant cellulose pulp market shaped by the widespread Kraft process, which primarily targets cellulose

while largely overlooking the potential of lignin. Emerging biorefinery technologies, particularly organosolv treatment and ionic liquid fractionation, present significantly enhanced efficiency and environmental sustainability for non-woody biomass valorisation compared to conventional sulphate pulping processes. The comprehensive utilization of lignocellulosic biomass by extracting and isolating cellulose, hemicellulose and lignin into three distinct high-value product streams establishes a compelling framework for zero-waste bioprocessing paradigms (Rajan et al., 2024).

This study explores the application of distillable ionic liquids (DILs) for the selective fractionation of lignin from agricultural residues abundant in Slovenia, unlocking new avenues for high-value material utilisation. Compared to conventional organosolv biorefineries, which are operating across the EU already at pilot-scale and produce high-purity lignin (Tofani et al., 2024), the novel and underutilized DIL-based approach achieves comparable product quality (low molecular weights and excellent dispersity) under milder conditions – lower temperatures and operating pressure, and without requiring sulphur based acidic catalysts. The optimized DIL system yields a cellulose-rich pulp with >90% α-cellulose content while preserving the solvent's chemical stability for reuse. The extracted lignin serves as a versatile precursor for high-value applications, including the synthesis of phenolic monomers, biopolymers, and bioadhesives. Crucially, the DIL recovery via distillation maintains high efficiency over multiple cycles, enhancing process sustainability.

By shifting the focus from hardwood to regionally relevant agricultural waste, this work highlights the potential of DIL-based biorefineries for decentralized biomass valorisation in Slovenia and similar agro-forestry-rich regions.

Keywords: ionic liquids, lignin extraction, biomass valorisation, green solvents, circular process

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CarbonAction

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In 2020, Belinka initiated a strategic project aimed at decarbonizing its industrial production of hydrogen peroxide. The primary objective was to reduce carbon dioxide (CO_2) emissions generated by the steam-producing boiler, a critical component of the production process. Recognizing the environmental and economic importance of this goal, the team explored innovative approaches to capture and convert CO_2 emissions into less harmful compounds. The chosen method focused on the chemical carbonization of carbonates, where CO_2 reacts with a basic hydroxide solution, leading to the precipitation of carbonates from the main process stream.

The decarbonization process relies on a well-known chemical equilibrium reaction between carbon dioxide and hydroxide ions. However, the efficiency of this reaction is significantly influenced by the interfacial area between the gas and liquid phases. To address this, the team focused on enhancing gas-liquid contact by developing a microbubble system. In this system, gas is introduced through a specially designed sparger that produces extremely fine bubbles. These microbubbles increase the surface area available for the reaction, thereby accelerating the conversion of CO_2.

One of the major challenges encountered was the clogging of the sparger due to the precipitation of carbonates. To overcome this, an ultrasonic cleaning mechanism was integrated into the system. The ultrasonic waves prevent the accumulation of solid particles on the metal surface of the sparger, ensuring continuous operation. This innovation led to the development of a self-cleaning sparger, which was subsequently submitted for patent protection. The patented system combines a specific type of gas sparger with an ultrasonic device, enabling prolonged operation without mechanical blockages.

The implementation of the microbubble system and ultrasonic sparger yielded promising results. The intensified gas-liquid interaction allowed for a more efficient and continuous chemical reaction, minimizing the limitations typically imposed by interfacial surface area. The system demonstrated a significant reduction in clogging incidents, leading to longer operational periods and reduced maintenance requirements.

Furthermore, the ultrasonic sparger contributed to the disintegration of gas bubbles, preventing their agglomeration as they traveled through the reactor. This ensured that the CO_2 was rapidly consumed in the reaction, maintaining high conversion rates. The overall process achieved a lower mass transfer coefficient (kla), indicating improved efficiency in gas absorption.

The research and development efforts at Belinka have shown that the integration of microbubble technology with ultrasonic cleaning can significantly enhance the decarbonization process. By optimizing bubble size and applying ultrasonic waves at the correct frequency, the system achieves higher reaction yields, improved energy efficiency, and reduced operational costs.

The success of this project highlights the potential of combining mechanical and chemical engineering innovations to address environmental challenges in industrial settings. With continued refinement and scaling, this technology could serve as a model for sustainable practices in other chemical manufacturing processes.

Keywords: ultrasound microbubbles, aglomeration, clogging, process intensification, energy efficiency

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Bioactive Compounds in Avocado (*Persea Americana* L.) Seed With Enzymatic, Antioxidant, and Antimicrobial Activities

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Avocado (*Persea americana* L.) is a nutritious tropical fruit belonging to the Lauraceae family. Avocado seeds (AS) are underutilized as an inedible part and therefore discarded. AS account for up to 26% of the total weight of the fruit (Domínguez et al., 2016) and thus represent large amounts of waste biomass. On the other hand, they are an inexpensive alternative source containing potential bioactive compounds.

Food wastes present a renewable resource that can be converted into value-added products, while reducing the volume of waste gathered in landfills, and at the same time expanding the economic market share of new sustainable products.

Different methods can be used for the extraction of bioactive compounds from AS. Supercritical fluid extraction (SFE) with carbon dioxide (SC CO_2) as a solvent provides separation at near-ambient temperatures and therefore minimizing the degradation of thermo-labile compounds. Due to its green process (e.g., solvent-free products, short extraction time, low operating temperature, high extract quality etc.) and exceptional characteristics of SC CO_2 (e.g., environmental friendliness, non-toxicity, mild critical temperature, low critical pressure, non-flammability, prevents extract oxidation, etc.), it is one of the most promising techniques in the recovery of pure and clean extracts with bioactive compounds (Kupnik et al., 2022). 20 g of dried AS was placed into the extractor (60 mL), which was preheated to operating temperature (40 °C) using a water bath. SFE was performed at an operating pressure of 20 MPa. The flow rate of CO_2 was 2 mL/min while EtOH (as a co-solvent) was pumped continuously with a flow rate of 0.8 mL/min. The extraction took place for about 2 hours.

Content of total phenols (TPC), proanthocyanidins (TPAC) and total proteins (PC) in AS extracts obtained by SFE extract were 36 mg GAE/$g_{extract}$, 3 mg/$g_{extract}$ and 16 mg/$g_{extract}$, respectively. Among the phenolic compounds, the SFE extract contained many flavonoids such as (-)-epicatechin, hesperidin, quercetin. Plants are usually a valuable source of enzymes, which has also been demonstrated for the SFE extract of AS, where high activities of the cellulase, peroxidase, polyphenol oxidase, protease, transglutaminase, and superoxide dismutase were detected.

Using the DPPH method, the SFE extract showed 60% inhibition, which indicates its high antioxidant potential. Antimicrobial activity is attributed to many phytochemicals or biologically active compounds, which are present in high concentrations also in SFE extract; therefore, low MIC_{90} values for various tested microorganisms (e.g., *Escherichia coli*, *Pseudomonas aeruginosa*, *Pseudomonas fluorescens*, *Bacillus cereus*, *Staphylococcus aureus*) were detected. Due to its high TPC content and low MIC90 value for pathogenic *S. aureus*, the obtained AS extract may also have properties that positively affect the skin microbiome, which is beneficial for skin health. Hence, AS extract obtained with a sustainable, greener and modern SFE,

which contains value-added biologically active compounds with enzymatic, antioxidant, and antimicrobial activities, could be further utilized in biomedicine, pharmacy, cosmetics or other industries.

Keywords: avocado seed, extraction, supercritical, phenolic compounds, antimicrobial, antioxidant, enzymatic activity

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Multi-Criteria Optimization of Economic and Environmental Sustainability in Power-to-X Systems

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The European Green Deal Directive sets binding targets for a 55% reduction in greenhouse gas (GHG) emissions by 2030 compared to 1990 levels, aiming for climate neutrality by 2050 (European Commission, Secretariat-General, 2019). To achieve limits on GHG emission, industrial entities must either obtain free allowances under the EU Emission Trading Scheme (EU ETS) or trade allowances on the carbon market (European Commission, 2024). In addition, some Member States impose national carbon taxes. As free allocations of EU ETS are reduced annually, industrial entities are increasingly exploring carbon capture and utilization (CCU) technologies to reduce their GHG emissions and their requirements for EU ETS allowances.

This study presents a methodological framework for the integrated multi-objective optimization of techno-economic and environmental variables for systems that produce value-added compounds from renewable and recycled feedstocks. Such systems are not frequently addressed in this integrated manner, as most scientific studies typically present techno-economic analysis and life cycle assessment (LCA) separately.

A linear optimization model is developed for methanol synthesis (Hren et al., 2024), including upstream processes, i.e. CO_2 capture from a point source (Sollai et al., 2023) and hydrogen production via polymer electrolyte membrane (PEM) water electrolysis (Sollai et al., 2023). The model optimizes the balance between captured and emitted CO_2, considering investment and operating costs, environmental impacts, and enables selection between grid electricity and on-site produced renewable electricity for electrolysis. Environmental impacts of processes in the optimization model are considered simultaneously using LCA, applying IPCC 2021 GWP 100 and ReCiPe 2016 endpoint (H) life cycle impact assessment methods.

For the case study, a point source emitting 5,400 tons of CO_2 annually was selected. The results of the profit maximization indicate that, at the current carbon tax levels, the most favorable option is the direct release of CO_2 into the atmosphere. The methanol synthesis system becomes economically viable only when the carbon tax exceeds 214 EUR per ton of CO_2.

Minimization of CO_2 emissions leads to the implementation of methanol synthesis coupled with on-site generation of renewable electricity for electrolysis. However, minimization of overall environmental impact (e.g., global warming, terrestrial acidification, stratospheric ozone depletion, etc.) again favors direct CO_2 release.

When profit and CO_2 emissions are considered simultaneously within a multi-criteria objective function, methanol synthesis is preferred when a high weight is assigned to the environmental variable. However, it is not preferred when a comprehensive LCA is considered in the environmental part of the objective function.

Under current economic conditions, methanol synthesis from captured CO_2 and green hydrogen is less cost competitive than direct CO_2 release. While CCU systems can help reduce CO_2 emissions, LCA results indicate an overall increase in environmental impacts due to the construction and operational demands of methanol production and its upstream processes, primarily related to material and energy consumption.

The developed conceptual framework supports informed decision-making for the implementation of Power-to-X processes by integrating the optimization of both economic and environmental aspects of sustainability.

Keywords: circular economy, carbon capture and utilization, mathematical optimization model, techno-economic assessment, life cycle assessment, Power-to-X

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Optimizing Metal Recovery from EAF Dust: An Integrated Beneficiation and Extraction Strategy

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Electric Arc Furnace (EAF) dust, a byproduct of steel recycling (Guézennec et al., 2005), contains valuable metals alongside environmental hazards. Our research aims to offer a comprehensive alternative to the traditional Waelz kiln process, focusing on recovering iron, zinc, lead, manganese, nickel, and chromium (Regulation (EC) No 1907/2006).

The methodology involves initially separating EAF dust samples into magnetic and non-magnetic fractions using magnetic separation. These fractions are further refined into heavy and light fractions via gravity separation. This classification allows for tailored processing of each stream through specific pyrometallurgical and hydrometallurgical methods based on composition. EAF and cupola furnace dust samples from various sources underwent particle size-based separation, leading to diverse outcomes. Subsequent hydrometallurgical and pyrometallurgical treatments of these fractions achieved significant metal recoveries.

Two different EAF dusts were analyzed: Metal Ravne, SI, and Boleslaw, PL. In Metal Ravne, zinc forms, along with magnetite, constitute the majority of the sample. Additionally, Metal Ravne, Sl dust contains significant quantities of chromium, whereas the Boleslaw, PL, dust is notable for its chlorides and lead content. Magnetic separation proved more effective for Boleslaw, PL, whereas gravity separation achieved a significant enhancement for Metal Ravne, SI.

Optimization of the pyrometallurgical treatment of ferrous fractions revealed the necessity of reducing material at a specific temperature using cupola furnace dust as both a reductant and flux to ensure complete separation of slag and metal. The pyrometallurgical treatment successfully recovered three primary metals: Fe, Mn, and Cr, with recovery yields ranging from good to great for Fe, low to moderate for Mn, and moderate to good for Cr.

Hydrometallurgical extraction of Zn by the utilization of sulfuric acid showed optimal results. The application of beneficiation methods, followed by hydrometallurgical or pyrometallurgical processes, demonstrated significant improvements in the treatment of Electric Arc Furnace (EAF) dust. The process includes ideal conditions for leaching EAF dust at room temperature with a solid-to-liquid (s/l) ratio. These results underscore the feasibility and effectiveness of maximizing metal recovery from waste materials.

Keywords: EAF dust, Magnetic separation, Gravity separation, extraction, recycling

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Establishing the Critical Raw Materials Laboratory (CRM LAB) – A Strategic Pillar for Circular and Sovereign Rare Earth Value Chains in the EU

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Europe's increasing dependence on imported rare earth elements (REEs), especially for the production of permanent magnets used in e-mobility, renewable energy, robotics, and defense, poses a major threat to the EU's industrial sovereignty. Currently producing less than 1% of global rare earth output, the EU is vulnerable to supply chain disruptions, particularly due to its 98% reliance on imports from a single country. This paper presents the development of the Critical Raw Materials

Laboratory (CRM LAB) at the Jožef Stefan Institute in Slovenia, a strategic initiative that aims to build a complete, modular, and circular value chain for rare earth processing and permanent magnet manufacturing. The laboratory will bridge the gap between early-stage research and industrial implementation (TRL 1–6), providing pilot-scale infrastructure for extraction, separation, recycling, and magnet synthesis. Utilizing both primary sources (e.g., bastnäsite, monazite) and secondary waste streams (e.g., red mud, fly ash, electronic waste), the CRM LAB will apply advanced technologies such as electrochemical etching, hydrometallurgy, 3D printing, and rapid sintering. It will enable flexible and adaptive production lines, testing innovative processes in real industrial conditions. Key industrial partners include Magneti Ljubljana, Kolektor, Domel, and Zeos, while raw material supply links have been established with African and Balkan mining companies. Early pilot testing shows promising results in recycling Nd-Fe-B magnets and scaling magnet production with reduced critical material input. Supported by more than €1.5M of secured investment (out of €7M total), the CRM LAB is already aligned with the EU's Critical Raw Materials Act, including traceability, labelling, and recycled content obligations. Slovenia's existing know-how, production capacity, and central EU location uniquely position it as a future regional hub for sustainable magnet and rare earth material production. The initiative contributes directly to the European Green Deal, the Circular Economy Action Plan, and the Green Deal Industrial Plan for the Net-Zero Age. By strengthening the EU's resilience, enabling low-carbon technologies, and fostering strategic autonomy, the CRM LAB is not just a research facility but a blueprint for a circular, sovereign, and sustainable industrial future in Europe.

Keywords: rare earth elements, permanent magnets, circular economy, CRM LAB, strategic autonomy, recycling, pilot production, sustainable materials, TRL 3–6, European Green Deal

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Chlorine Hydrometallurgy for a Circular Economy: MONOLITHOS' Solution

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The accelerating demand for critical and strategic raw materials (C(S)RMs), driven by advanced technologies and the energy transition, underscores the need for sustainable secondary supply chains. Primary production of CRMs is constrained by limited geological availability, geopolitical risks, and environmentally intensive extraction methods. Consequently, the development of robust recycling processes capable of treating various end-of-life (EoL) materials is essential. MONOLITHOS has developed a patented chlorine hydrometallurgical process designed to achieve high-efficiency CRM recovery from multiple secondary sources.

The process is applicable to a broad spectrum of end-of-life (EoL) devices and industrial residues, including automotive catalytic converters, fuel cells, electrolyzers, lithium-ion batteries, permanent magnets from electric motors, waste electrical and electronic equipment (WEEE), as well as complex industrial and urban waste streams. Utilizing controlled chlorine-based hydrometallurgical leaching, the process achieves highly efficient dissolution and selective recovery of critical metals. Demonstrated recovery yields reach 99% for Pt, 92% for Pd, and 61% for Rh from automotive catalysts; approximately 99% for Pt and over 60% for Ir from membrane electrode assemblies (MEAs); and consistently exceed 95% for rare earth elements (REEs) and lithium. These recovery efficiencies surpass those typically achieved by conventional recycling methods, highlighting the process's superior performance across diverse CRM-containing waste streams.

From a process engineering perspective, chlorine hydrometallurgy offers several inherent advantages. Operating temperatures are significantly lower than those required by pyrometallurgical methods, resulting in reduced energy consumption and a smaller carbon footprint. Moreover, the high yield leaching and subsequent purification stages produce minimal secondary waste, while achieving product purities >99% suitable for direct reintegration into manufacturing value chains. These characteristics align with European and international objectives regarding resource efficiency, circular economy adoption, and the reduction of environmental externalities associated with CRM supply.

The circular economy concept is actively implemented through the recovery of metals in forms that are either directly reusable or possess high commercial value. In certain applications—such as automotive catalyst recycling—the leachate solution itself is used as a raw material in the production of new catalysts, without requiring further refinement. This closed-loop approach maximizes material efficiency and minimizes processing steps, further reducing environmental impact.

The patented MONOLITHOS process has been validated at pilot scale for multiple feedstocks, demonstrating scalability, technical robustness, and economic viability. Beyond CRM recovery, the process architecture is adaptable, enabling optimization for specific waste stream compositions and target elements. Collectively, these attributes establish the MONOLITHOS chlorine hydrometallurgical process as a technically mature and industrially scalable solution capable of mitigating raw material supply risks, reducing environmental impacts, and enabling a more resilient and sustainable circular economy for CRMs.

Keywords: chlorine hydrometallurgy, critical raw materials recovery, hydrometallurgical recycling, circular economy approach, clean technology materials

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Innovations in Additive Manufacturing for Recycled Permanent Magnets

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The recycling and sustainable manufacturing of permanent magnets (PMs) for electric motor applications represent critical areas for industrial innovation, driven by economic, environmental, and geopolitical factors. In this study, we present groundbreaking advancements in additive manufacturing tailored specifically for recycled permanent magnets. Our approach centers on two primary innovations: a novel inductance-based scanning method and an advanced Field- Assisted 3D-printing process.

We introduce a unique, inductance-based, non-destructive scanning method for the in-line assessment of magnetic fill factors within 3D printing filaments. This technique employs an inductance coil through which magnetic filament is continuously fed, detecting subtle variations in inductance. The data obtained allows precise determination of the magnetic material's spatial distribution along the filament, significantly enhancing quality control without interrupting the production process.

Complementing this, our project advances the state-of-the-art Field-Assisted 3D-printing technology previously developed and patented (P-202400038) by our research group. Originally, this patented method utilized fixed-field permanent magnets to achieve particle alignment within printed structures. Building upon this foundation, the current innovation incorporates electromagnets, enabling dynamic and precise adjustment of the magnetic field strength by controlling electric current. Furthermore, we integrate a custom-designed extruder directly into the 3D printer, bypassing separate filament production by directly utilizing magnetic particles mixed with an appropriate binder. This streamlined approach simplifies manufacturing, reduces complexity, and decreases labor intensity and overall production costs.

An additional novel feature is the integration of an innovative micro-Hall probe system into the printing setup. This pioneering addition allows real-time, high-resolution monitoring of the magnetic properties within the printed components, significantly improving quality assurance processes and ensuring optimized performance characteristics in final magnet products.

Critically, the our work leverages recycled, end-of-life PMs as feedstock, directly addressing Europe's dependency on conventional permanent magnet production centers, notably China. By transforming waste magnetic materials into high-performance PM components via additive manufacturing, the research aligns closely with the EU's circular economy objectives and contributes meaningfully to the region's resource autonomy.

In summary, our work demonstrates significant advancements in the additive manufacturing of recycled permanent magnets, combining innovative, non-destructive assessment techniques with cutting-edge, electromagnet-assisted 3D printing. By simultaneously addressing economic sustainability, technological performance, and geopolitical supply-chain dependencies, this research places itself firmly at the forefront of sustainable manufacturing innovation for electric motor applications.

Keywords: additive manufacturing, permanent magnets, anisotropic magnets, recycled permanent magnets, 3D printing

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Development of Sustainable Amidation Process using ATP-dependent Amide Bond Synthetase

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Amide bond formation is a key transformation in pharmaceutical synthesis, accounting for up to 16% of reactions in medicinal chemistry. Conventional methods rely on stoichiometric activation of carboxylic acids using coupling reagents, often resulting in poor atom economy and hazardous by-products (Tang et al., 2024). Enzymatic approaches, operating in aqueous media without toxic reagents, offer a more sustainable alternative (Lubberink et al., 2023). ATP-dependent amide bond synthetases (ABS) have emerged as promising biocatalysts, capable of catalyzing both acid adenylation and amidation within a single active site. (Tang et al., 2024; Winn et al., 2020).

We report initial process development for ATP-dependent amide bond formation between *trans*-cinnamic acid and 1,2- phenylenedimethanamine, catalyzed by ABS from *Streptomyces* TR1341 with inorganic pyrophosphatase (PPase). The reaction proceeds via an acyl–adenylate intermediate, followed by amide formation within the enzyme's single active site, enabling efficient coupling with low equivalents of the amine partner (Tang et al., 2024).

Temperature profiling indicated increased ABS activity at higher temperatures but also enhanced formation of a diamide side product; a working temperature of 30 °C was selected to balance activity and selectivity. The enzyme exhibited peak activity within a narrow pH range (7.50–7.82).

Stability studies in 30% (v/v) co-solvent revealed marked inhibition by DMSO (10.13% residual activity), whereas glycerol preserved 47.12 % activity. Gas sparging studies indicated that bubble exposure, rather than oxidation, primarily caused deactivation, with oxygen and nitrogen reducing activity to ~57% after 2 h and fully inactivating the enzyme after 3 h.

Kinetic studies using the isolated AMP intermediate demonstrated that the ratio of AMP to amine strongly controls selectivity. Excess free amine promotes amide formation but can also act as a competing nucleophile, favoring diamide formation. Adjusting substrate ratios showed that higher amine-to-acid ratios increased overall yield, whereas lower absolute concentrations (e.g., 10 mM amine with 5 mM acid) enhanced selectivity, consistent with substrate or product competition and solubility limitations at elevated concentrations.

These results provide essential insights for implementing ABS-catalyzed amidation in microflow systems. Microreactors allow precise control of residence time and reactant concentrations while minimizing bubble formation, thereby reducing interfacial deactivation and favoring selective product formation. This approach enables process intensification and offers a clear path toward scalable biocatalytic synthesis (Žnidaršič-Plazl, 2021).

Keywords: biocatalysis, amidation, amide bond synthetase, process development, process intensification

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Value Chain Creation in the Innovative E-waste Recycling Business Model

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Waste electrical and electronic equipment (WEEE) is the world's fastest-growing waste stream and an increasingly important secondary source of critical raw materials (CRM). According to Eurostat reports, the collection rate for WEEE in the EU was around 40% in 2022 (Eurostat, 2023), meaning that only a portion of the rapidly growing amount of discarded equipment is being captured for recycling or recovery — representing a significant untapped resource for CRM recovery and the development of the circular economy. While previous estimates suggested that around 12 million tonnes of WEEE is generated annually in the EU, official statistics report that 14.4 million tonnes of WEEE were placed on the market in 2022, with 5.0 million tonnes collected and 4.9 million tonnes treated (Eurostat, 2023).

In Eastern and South-Eastern Europe, there are structural barriers to effective WEEE recycling, including undeveloped infrastructure for collection and processing, fragmented value chains, and lower innovation capacity. In Greece, collection rates have consistently fallen below EU targets, with significant amounts of WEEE going through informal or unreported disposal channels, indicating that there is insufficient enforcement of extended producer responsibility (EPR), and limited consumer awareness (EERA, 2023). At the EU level, evaluation studies highlight the need for robust targets for the management of WEEE and improved value chain integration to promote the circular economy and maximise the recovery of recycled materials from WEEE (European Commission, 2025).

Despite these challenges, the ESEE Balkan region offers a significant opportunity — estimated at €2 billion — for the recovery of recycling facilities if supported by targeted investments and strengthened value chains (WEEE FORUM, 2025) Improving synergies between collectors, waste processing companies, recyclers, technology providers, and secondary raw material markets could increase efficiency, traceability, and profitability.

The WEEE-NET9.SPEED project addresses these gaps by establishing an innovative recycling ecosystem that integrates advanced pre-treatment with bioleaching, a sustainable biotechnology for CRM extraction from WEEE. A key objective is to scale up bioleaching from Technology Readiness Level (TRL) 4–5 to TRL 7, to enable near-industrial deployment. This includes optimising the process parameters and embedding bioleaching in the existing WEEE material flows. In parallel, WEEE-NET9.SPEED strengthens the regional innovation ecosystem by connecting recyclers, researchers, entrepreneurs, and local authorities, promoting technology transfer, market demonstrations, and providing customised support for start-ups and scale-ups (EERA, 2025; WEEE FORUM, 2025).

Expected impacts include improved e-waste value chain and recovery rates for recycling facilities, increased recycling performance for WEEE in line with the EU Critical Raw Materials Act (CRMA), and a strengthening of regional capacities in sustainable resource management that support Europe's transition to a circular, low-carbon economy.

Keywords: e-waste, recycling, bioleaching, technology transfer, value chain

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The Slovenian Centre for Circular Economy

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The prevailing linear economic model, based on the principle of "take, make, and dispose", has led to a pronounced imbalance between the finite availability of natural resources and the ever-growing demand for products (Geissdoerfer et al., 2020). This unsustainable paradigm has intensified pressure on the environment and contributed to climate change, biodiversity loss, and excessive waste generation. The concept of a circular economy (CE) has emerged as a systemic alternative. Unlike the linear model, the circular economy promotes reuse, repair, and recycling waste, creating closed material loops that minimise waste (Kirchherr et al., 2023). The CE is based on three basic principles: preventing waste and pollution, keeping materials and products in circulation for maximum benefit, and regenerating natural systems (EF, 2024; Velenturf et al., 2021). These CE principles support reducing environmental risks and open up opportunities for technological innovation, industrial competitiveness, and sustainable growth within the boundaries of our planet. Over the last decade, the European Commission has placed the circular economy at the strategic goals of its sustainable development strategy. These measures are gradually transforming business models, promoting new markets, and influencing labour market dynamics in the European Union. The significant challenges remain: Recycled materials currently account for less than 12% of total material demand in the EU (European Environment Agency, 2024), while the rate of circularity of material use in the EU was 11,8% (Eurostat, 2024). These figures emphasise the considerable gap between political ambition and practical implementation. Slovenia has formally adopted the European framework for a circular and sustainable economy. According to the Slovenian Development Report 2023 (IMAD, 2024), Slovenian companies show relatively modest ambitions in integrating circular economy practices into their business models. While awareness of sustainability as a strategic opportunity is growing, the country continues to perform relatively value of material productivity, emissions reduction, recycling rates, and clean technology adoption (European Environment Agency, 2024). Slovenian Development Report 2023 emphasises the need to create a supportive ecosystem that enables companies to accelerate their transition to a low-carbon, digital, and innovation-driven circular economy. This includes optimising production processes, promoting green technologies, and improving collaboration between businesses, research institutions, and local communities. These efforts are in focus with Slovenia's key strategic documents. These frameworks pursue common goals: reducing greenhouse gas emissions, improving resource efficiency, promoting the circular economy, innovation, and digitalisation. A key national support to transition into the circular economy was the establishment of the Slovenian Centre for Circular Economy (SCKG) in 2025, a national service platform to foster Slovenia's transition into a circular economy that consolidates initiatives, research, support with education and training, consulting through entry points, innovative practices and facilitates the exchange of expertise and best practices. Its establishment reflects Slovenia's acknowledgement that the transition to a circular economy constitutes not merely an environmental obligation, but at the same time a strategic imperative for safeguarding long-term competitiveness and systemic resilience (SCKG, 2025). Realising this transition requires integrated policymaking, strengthened institutional capacities and the active engagement of all stakeholders, including industry, government, academia, media, and civil society.

Keywords: circular economy, circular business models, integration, Slovenian Centre for circular economy, resource efficiency

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Yeast Biomass Production Using Spent Coffee Grounds in Cost-Efficient Growth Media

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Industrial applications of yeast cells — be it for bioprocessing, environmental bioremediation or the synthesis of bio-based products synthesis — usually require the production of large amounts of biomass. To obtain such biomass, cost-efficient and sustainable growth media are essential. Spent coffee grounds (SCG), a lignocellulosic waste rich in organic compounds (Ballesteros et al., 2014), represents a promising alternative carbon source for microbial cultivation and supports the principles of circular economy and waste valorization. We have investigated the potential of SCG for the biomass production of *Saccharomyces cerevisiae* (baker's yeast), one of the most commonly used yeasts in biotechnological processes, and of *Pichia kudriavzevii*, a potential new biotechnologically relevant yeast to produce bioethanol, organic acids, enzymes and other proteins (Chu et al., 2023). The cultivation parameters of natural isolates *P. kudriavzevii* ZMUM_K002 and *S. cerevisiae* ZMUM_K003, obtained from grape pomace compost and a discarded wine bottle, respectively (Vajdič & Starčič Erjavec, 2025), were compared with a commercially available industrial strain of *S. cerevisiae*.

The SCG was only minimally pretreated — by pre-grinding to determine and/or adjust the particle size and subsequent sterilization — before it was introduced into the classical cultivation media. The potential of SCG as an supplement to YP medium was compared to YP medium supplemented with glucose. The SCG content in the media was varied (4, 20 and 40 g/L) and the effects of adjusting the particle size by grinding on yeast growth and biomass yield, measured as wet cell weight (wcw), were evaluated. In YP medium with 20 g/L glucose, *P. kudriavzevii* ZMUM_K002 reached a wcw of 49.6 ± 4.2 g/L within 48 h, outperforming *S. cerevisiae* ZMUM_K003 by more than 30%. When glucose was replaced by 40 g/L SCG, *P. kudriavzevii* ZMUM_K002 and *S. cerevisiae* ZMUM_K003 reached wcw values of 41.1 ± 2.6 g/L and 34.3 ± 4.8 g/L, respectively. Both species tolerated SCG-derived inhibitory compounds and utilized the substrate effectively, confirming their robustness in complex waste-based media. The suitability of SCG-containing media was tested with an expanded set of *S. cerevisiae* strains. In addition, different harvesting methods were tested. Simple filtration proved to be effective, as more than 60 % of the yeast cells could be recovered while avoiding the co-collection of residual SCG particles.

These results position SCG as a viable and sustainable replacement for glucose in microbial cultivation media for industrial biotechnology applications. The demonstrated ability of the tested yeasts to grow efficiently on minimally processed lignocellulosic waste underlines the potential of SCG not only for cost-efficient biomass production, but also for integration into waste utilization strategies.

Keywords: yeast, spent coffee ground, secondary raw material, cultivation media, *Saccharomyces cerevisiae*, *Pichia kudriavzevii*

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The 8th international scientific, professional, and development conference on Technologies & Business Models for Circular Economy (TBMCE) was organized by the Faculty of Chemistry and Chemical Engineering, University of Maribor, in collaboration with SRIP – Circular Economy, managed by the Chamber of Commerce and Industry of Štajerska, and took place from 3 to 5 September 2025 at the Grand Hotel Bernardin in Portorož. TBMCE 2025 was dedicated to exploring circular economy concepts and showcasing advanced technologies, methodologies, and systemic approaches that foster the development of integrated solutions and support the transition of businesses and society as a whole towards sustainable resource management. The conference program included panel discussions, plenary and keynote lectures, oral presentations, and poster sessions covering the following fields: energy in the circular economy (energy efficiency and renewable and low-carbon energy sources), secondary raw materials and functional bio-composites (by-products and residues from biomass processing and non-biological sources), water in the circular economy and sustainable water management, green processes and technologies, and circular business models.

Keywords:
circular economy,
sustainable development,
processes and technologies,
circular business models,
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