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Book of Abstracts

Sanja POTRČ Miloš BOGATAJ Zdravko KRAVANJA Zorka NOVAK PINTARIČ
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9TH INTERNATIONAL CONFERENCE ON
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A Circular Monitor Tool for Cities: An Indicator Framework for Local Planning

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The transition to a circular economy (CE) is largely decided in the consumption phase, yet cities – major centres of resource use – often overlook household consumption in their planning. Municipalities lack a simple instrument to assess the status quo, challenges and potentials for circular lifestyles and to translate them into concrete measures and indicators. This paper presents a circular lifestyle monitor tool for cities, municipal planning departments and NGOs. Designed as an easy-to-use tool, it is the outcome of an iterative research and collaboration process: sustainable consumption patterns and supporting business models were assessed in nine Central European pilot cities (among them Graz, Brzeg Dolny, Košice and Ptuj), and seven established indicator frameworks were reviewed, including the OECD Inventory of Circular Economy Indicators (OECD, 2021), the WBCSD Circular Transition Indicators v4.0 (WBCSD, 2023) and ReSOLVE (Iyer-Raniga, 2019). The selected indicators follow the OECD interpretation across five categories and fifteen sectors and build on the Value Retention Options (9R) hierarchy (Reike et al., 2018), of which the first seven strategies relate directly to circular lifestyles. Organized into five types – circular lifestyle ecosystem, actions, performance indicators, policy interventions and result indicators – the indicators enable self-tailoring and support a six-step, community-based planning process from situational analysis to measuring short- and long-term effects. The circular tool offers a

transferable, indicator-based framework that links value-retention theory with practical local planning.

Keywords: circular economy, circular lifestyle, sustainable consumption, indicators, monitor tool, local planning

Acknowledgement

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Environmental Performance of Renewable and Waste Heat-Driven Rankine Cycle Systems

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The transition towards circular and low-carbon energy systems has increased interest in the utilization of renewable and waste heat sources for sustainable power generation. Rankine cycle technologies, including steam Rankine cycles (SRC) and organic Rankine cycles (ORC), enable the conversion of heat from a wide range of temperature levels into electricity, making them suitable for integrating diverse energy resources. This work presents a comparative environmental assessment of Rankine cycle systems utilizing biomass, industrial waste heat, solar energy, and geothermal resources.

Four standalone systems were modelled and optimized to maximize net electricity generation under representative operating conditions. Biomass was integrated with an SRC, whereas waste heat, solar, and geothermal energy were coupled with ORC systems. In addition to electricity generation, scenarios including heat recovery were evaluated to investigate the influence of combined heat and power utilization. The optimized systems were subsequently assessed using life cycle assessment (LCA) implemented in openLCA with the Ecoinvent database (version 3.12) and the

ReCiPe 2016 Midpoint (H) method. The assessment covered the complete life cycle of each system, including material production, construction, operation, and end-of-life management.

The results indicate noticeable differences in environmental performance among the systems investigated, reflecting the characteristics of the individual heat sources and system configurations. The comparison further highlights the importance of heat recovery and demonstrates the value of LCA as a decision-support tool for identifying environmentally preferable solutions for renewable and waste heat utilization within circular energy systems.

Keywords: life cycle assessment (LCA), organic Rankine cycle (ORC), steam Rankine cycle (SRC), renewable energy, waste heat recovery, circular economy

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Polycarbonate Recycling Using Supercritical Alcohols

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With the continuous growth of the global economy, plastic products have become an indispensable part of everyday life. The volume of plastic waste is growing exponentially due to excessive production and use, leading to serious environmental and economic consequences. Since the degradation of plastic waste in nature is a lengthy and complex process, the development of alternative recycling methods has become one of the most pressing research topics. Today, polycarbonate (PC) is among the fastest-growing plastics in terms of usage. It is an aromatic engineering plastic and, due to its high impact strength, transparency, and heat resistance, is widely used in various fields: in electronics for device housings, connectors, and insulating parts; in the automotive industry for lighting components and protective covers; in optics and lighting for lenses and protective glass; for protective equipment, primarily visors and safety goggles; and in medical and other products (Kim, 2020).

Supercritical fluids are substances above their critical temperature (T_C) and critical pressure (p_C), where the phase boundary between liquid and gas disappears, so their properties are a combination of those of both phases: like liquids, they have high solvent power, and like gases, they have high diffusivity and low viscosity. Polar protic solvents under supercritical conditions are an excellent potential medium for the degradation of polycarbonates: they penetrate the material more easily, reduce diffusion limitations, and enable faster polymer breakdown. Supercritical alcohols (methanol, ethanol) also serve as such a medium, as they are not only the medium

but also reactants: at high temperatures and pressures, they can effectively attack the carbonate bonds in PC and lead to alcoholysis products (e.g. dialkyl carbonate and bisphenol A, which is the basic monomeric unit of PC). The advantages of such reactions include high reaction rates and high yields; at the same time, the need for other reagents is reduced (Jie et al., 2006).

In this study, the decomposition of PC in supercritical methanol and ethanol was investigated to determine the optimal reaction conditions for recovering of valuable products. The experiments were carried out in a batch reactor at a temperature of 300 °C and reaction times ranging from 5 to 120 min. PC was effectively decomposed into valuable compounds, including bisphenol A (BPA), various alkylphenols, dialkyl carbonates, and phenol. Analysis of the influence of time and reaction medium showed that the highest yield of BPA (the main monomer unit of PC), 68.2 %, was achieved after a reaction time of 60 min using ethanol as the reaction medium. These results emphasise the crucial role of process parameters in determining the reaction pathway, product types, and their respective yields.

Keywords: polycarbonate, plastic recycling, supercritical alcohol, bisphenol A, methanol, ethanol

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Advancing Sustainable Shipping with Ammonia: An Integrated Techno-Economic and Environmental Assessment

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Decarbonization is imperative across all sectors of society, including power generation, heating and cooling, industry, and transportation. Maritime transport alone accounts for approximately 3% of global greenhouse gas (GHG) emissions. To address this, the International Maritime Organization (IMO) has established ambitious decarbonization targets: a 40% reduction in carbon intensity by 2030 compared to 2008 levels, and the achievement of net-zero emissions by around 2050. A major challenge lies in the fact that more than 95% of the existing fleet relies on fossil fuels. Maritime transport is considered a hard-to-abate sector, and several alternative pathways are being explored (Zanobetti et al., 2023). While direct electrification is one option, it is constrained by the large battery capacity required for long-distance routes, making it more suitable for short-range operations. The most promising strategy involves the adoption of alternative fuels, particularly hydrogen, methanol, and ammonia (McKinlay et al., 2021). Hydrogen involves a transition from conventional combustion engines to fuel cell–based electric propulsion, but its storage and transport remain costly and technically challenging.

Methanol, in contrast, is a liquid at ambient conditions, offering simpler storage with lower costs (Korberg et al., 2021), though it requires effective CO_2 management through strategies such as direct air capture or onboard carbon capture (Charalambous et al., 2025). Ammonia represents another attractive option, as it is carbon-free and has relatively straightforward storage requirements, avoiding CO_2 management challenges altogether.

In this work, a holistic assessment of ammonia as a maritime fuel is conducted through a techno-economic-environmental evaluation covering the entire value chain, from fuel production to onboard utilization. Ten ammonia production pathways are analyzed. When natural gas is used as feedstock, two configurations are considered: steam methane reforming (SMR) and SMR with carbon capture and storage (CCS). Biomass-based pathways include biomass gasification and biomass gasification with CCS. Additionally, six Power-to-ammonia processes are evaluated using different electricity sources: solar PV, onshore wind, hydro, nuclear, bioelectricity, and bioelectricity with CCS. Following production, the fuel is transported and utilized in the proposed vessel under two engine configurations. In the first, a blend of ammonia and hydrogen is supplied to the engine to address ammonia's low reactivity (low flame speed, high autoignition temperature). In this configuration, ammonia is cracked onboard to generate the blend, which is then fed to an internal combustion engine (Sánchez et al., 2023). A selective catalytic reduction (SCR) unit is included downstream to mitigate nitrogen oxide (NO_x) emissions. The second configuration envisions a future scenario in which ammonia can be directly combusted in the engine, eliminating the need for the cracker. All production pathways and engine systems are modeled using Chemcad. Environmental impacts are assessed following ISO 14040 and 14044 standards. Life cycle inventory (LCI) data are primarily derived from process simulations, complemented by Ecoinvent and literature sources. Life cycle impact assessment (LCIA) is carried out with Brightway using Activity Browser as the interface. Finally, an economic assessment quantifies capital (CAPEX) and operating (OPEX) expenditures for each alternative.

From an environmental perspective, the full ammonia value chain, including production and transportation, shows clear advantages in terms of global warming potential (GWP). All assessed pathways yield lower impacts compared to the business-as-usual (BAU) scenario using heavy fuel oil (HFO), except for ammonia produced via SMR. The most favorable options are based on biomass coupled with

CCS. Biomass gasification with CCS achieves negative GWP values of approximately -12×10^{-3} kg CO_2 eq/tkm, while Power-to-ammonia using bioelectricity with CCS achieves around -50×10^{-3} kg CO_2 eq/tkm. Across the entire life cycle, fuel production dominates the impact profile, contributing more than 80–90% of total emissions, whereas port and ship infrastructure have minor contributions. Combustion-related impacts are also minimal due to the absence of CO_2 emissions during ammonia combustion and the implementation of NO_x control technologies. Economically, the capital cost of the two propulsion systems is estimated at approximately 1000 €/kW, with small differences between them. Ammonia production costs range between 2500 and 9000 USD per ton-year, largely driven by the capacity factor of renewable electricity in Power-to-X pathways. Consequently, OPEX for the full system, including production and onboard utilization, range from 0.4×10^{-2} to 1.6×10^{-2} USD/tkm, which is 1.5 to 4 times higher than BAU. However, expected future reductions in renewable electricity and electrolysis costs (the current economic bottlenecks) are likely to narrow this gap. Overall, ammonia shows strong potential as a maritime fuel, offering substantial GHG mitigation opportunities and the prospect of becoming economically competitive as technologies mature.

Keywords: ammonia, decarbonization, hydrogen, life cycle assessment, shipping

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Deep Eutectic Solvents as Reaction Media for the Solvothermal Synthesis of Copper-Based Metal–Organic Frameworks

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In recent years, metal–organic frameworks (MOFs) have emerged as one of the most promising classes of porous materials owing to their high specific surface area, tunable porosity, and versatile chemical composition. These unique characteristics have enabled their application in gas adsorption and separation, catalysis, sensing, and environmental remediation. Among them, copper-based MOFs (Cu-MOFs) synthesized using terephthalic acid (H_2BDC) as the organic linker have attracted considerable attention because of their tunable framework structures, accessible Cu active sites, and broad application potential (Sonwane and Ingle, 2026). Concurrently, increasing efforts have focused on developing more sustainable synthesis routes by replacing conventional organic solvents with deep eutectic solvents (DESs), particularly choline chloride-based systems, which have emerged as environmentally friendly alternatives for MOF synthesis (Patil and Shankarling, 2020).

In this study, Cu-MOFs were synthesized via a solvothermal method using $Cu(NO_3)_2$ as the metal precursor and terephthalic acid (H_2BDC) as the organic linker. The influence of the reaction medium was systematically investigated using a conventional water–ethanol mixture as the reference solvent and two choline chloride-based deep eutectic solvents (DESs) as alternative media. The effects of DES composition, DES content, reaction temperature, and synthesis time on Cu-MOF crystallization were evaluated. The results demonstrate that the composition of the DES, particularly the nature of the hydrogen bond donor, strongly influences the crystallization process, reaction pathway, crystal formation, and physicochemical properties of the obtained Cu-MOFs. Furthermore, DES-assisted synthesis enabled the successful preparation of Cu-MOFs under selected reaction conditions, while the resulting materials exhibited an improved specific surface area compared with those prepared using the conventional solvent system. These findings highlight the potential of choline chloride-based DESs as sustainable alternatives to conventional solvents for the solvothermal synthesis of Cu-MOF materials.

Keywords: metallic organic framework, terephthalic acid, deep eutectic solvents, solvothermal synthesis, product properties

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Image-Based Assessment of *Pleurotus ostreatus* Mycelial Colonization on Municipal Sewage Sludge-Supplemented Substrates

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Municipal sewage sludge (MSS) represents a challenging residual biomass stream that requires innovative valorization strategies. One potential approach is its use as a component of fungal growth substrates, particularly in combination with lignocellulosic materials. *Pleurotus ostreatus* is well known for its ability to colonize various waste-based substrates, including sawdust-based systems supplemented with nutrient-rich organic residues (Hultberg et al., 2023). MSS has also been investigated as a material in mushroom cultivation systems, although its use requires careful evaluation due to its complex composition and potential contaminants (Kumar et al., 2022). In this study, the main objective was to assess whether MSS-containing substrates can support mycelial colonization of *Pleurotus ostreatus*.

Substrates were prepared from oak sawdust supplemented with wheat bran and gypsum, while MSS was incorporated at different mass fractions ranging from 15 to 70 wt.%. A reference substrate without MSS was also prepared. After pasteurization and inoculation, samples were incubated under controlled conditions. Following colonization, dried substrate samples were placed on Petri dishes and photographed inside a black photobox chamber to provide a standardized dark background and

comparable imaging conditions. The photographs were processed using a custom Python workflow. Each image was converted into a 8-bit grayscale format, and the distribution of bright and dark pixels was analysed. Since *Pleurotus ostreatus* mycelium appears white on the darker substrate background, the ratio between white and black pixels was used as a qualitative indicator of mycelial colonization. This approach follows the broader principle that digital image intensity can be used as a practical tool for evaluating fungal mycelial growth (Lee et al., 2021).

The developed method enabled comparison of mycelial overgrowth between the reference substrate and MSS-containing substrates. Despite some sample-to-sample variation, the white/black pixel ratio generally remained within a narrow range of approximately 6–8%. This suggests that MSS supplementation, even at higher mass fractions, did not substantially inhibit the ability of *Pleurotus ostreatus* to colonize the tested substrates. The results indicate that MSS-containing lignocellulosic substrates can support fungal colonization and that simple Python-based image analysis can provide a useful screening method for evaluating waste-based fungal substrates.

Keywords: pleurotus ostreatus, municipal sewage sludge, mycelial colonization, biomass valorization, image analysis

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A Chemical Clock for Polyolefin Pyrolysis: Time-Temperature Superposition of Product Yield Distributions

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Introduction

The pyrolytic conversion of polyolefin waste into wax, oil and gas is a major thermochemical route for chemical recycling. However, the product distribution is strongly governed by the thermal history of the process, particularly the heating rate, final reaction temperature and residence time. Establishing these dependencies experimentally requires extensive parametric testing and is therefore costly in terms of feedstock consumption, energy demand and experimental time. This work adapts the principle of time-temperature superposition (TTS), originally developed in polymer rheology (Williams et al., 1955; Ferry, 1980), to the kinetic analysis of polyolefin pyrolysis. Although shift-factor formalisms are already well established, the new contribution of this work is to derive, directly from the underlying reaction network, the explicit conditions under which a multi-product pyrolysis system can be reduced to a single master curve. This differs from conventional empirical severity indices, which typically collapse the process description onto a single conversion variable and do not explicitly account for product-resolved reaction pathways. The approach is developed for linear low-density polyethylene (LLDPE), while the

formulation is intended to be extendable, after appropriate kinetic recalibration, to other polyethylene grades and to polypropylene (PP).

Methods

An Arrhenius weighted reaction severity coordinate, here referred to as a chemical clock, was defined as:

$$\Psi = \int_0^t \exp\left[-\frac{E_{\text{sev}}}{R}\left(\frac{1}{T(t')} - \frac{1}{T_{\text{ref}}}\right)\right] dt'$$

where T_{ref} is the reference temperature, set to 500 °C, E_{sev} is the apparent activation energy associated with volatile release, R is the universal gas constant, and $T(t')$ is the measured reactor temperature profile. Temperatures in the exponential term were expressed in kelvin. In this formulation, Ψ represents the equivalent reaction time at Tref and condenses the complete nonisothermal thermal history into a single kinetic severity coordinate. Transformation of the lumped rate equations from real time to Ψ makes each product yield a function of Ψ alone only when the competing reaction pathways exhibit the same apparent temperature dependence. Departures between individual pathways are retained exactly through analytic decoupling factors.

$$g_i(T) = \exp\left[-\frac{E_i - E_{\text{sev}}}{R}\left(\frac{1}{T} - \frac{1}{T_{\text{ref}}}\right)\right]$$

where E_i is the apparent activation energy of pathway i. A given pathway is expected to superimpose onto the common master curve when g_i remains close to unity over the investigated temperature range. Linear low density polyethylene (LLDPE) was pyrolysed in a fixed bed batch reactor at several heating rates and final temperatures between 450 and 600 °C. The condensable products were operationally separated according to condensation temperature using two sequential condensers, the first maintained at approximately 200 °C to recover the wax fraction and the second cooled to approximately 20 °C to collect the oil fraction. The yield of noncondensable gas was calculated by difference from the overall mass balance. Fourier transform infrared spectroscopy (FTIR) was used to assess the relative alkane and alkene functionalities in the recovered products. Esev was obtained by Kissinger analysis of the volatile release peaks derived from the Gram Schmidt signal in thermogravimetric analysis coupled with Fourier transform infrared spectroscopy

(TGA FTIR), following established principles of nonisothermal kinetic analysis (Vyazovkin et al., 2011).

Results

Volatile release was characterized by an apparent activation energy Esev of approximately 100 to 110 kJ mol^{-1}, which is substantially lower than the global mass loss activation energy of approximately 257 kJ mol^{-1}. This indicates that the release of volatile products represents a kinetically distinct process from the overall bulk degradation and chain scission of the polymer matrix. When the wax and oil yields were plotted as functions of Ψ, both fractions merge onto common master curves. The system evolved from a wax dominated product distribution, with approximately 79 wt% wax at 450 °C, to an oil enriched product distribution, with approximately 32 wt% wax and 38 wt% oil at 500 °C. Yields obtained from an experiment performed at a different heating rate also followed the same master curves and agreed with the values predicted from Ψ alone, which represents the defining criterion for time temperature superposition in this kinetic framework (Chae and Choi, 2025). The analytical decoupling factors provided a quantitative basis for this behaviour. Wax and oil formation satisfied gi close to 1 over the investigated temperature range, indicating similar apparent temperature dependence relative to the selected chemical clock. In contrast, the primary gas pathway reached gi values of approximately 19 across 450 to 600 °C. Therefore, gas formation could not be collapsed using the same reaction coordinate and required a separate kinetic description with higher apparent activation energies. This is consistent with the requirement for greater thermal severity to crack long chain hydrocarbons into light C1 to C5 gaseous products.

Conclusions

Recast through Ψ, TTS reduces the wax and oil behaviour to one master curve and a single shift energy, while the decoupling factors give a derived, testable criterion for when collapse holds. This enables product prediction for any temperature programme and inverse design for a target slate, giving fewer experiments, lower energy and feedstock use, and a transferable basis for reactor design and scale-up of green processes.

Keywords: chemical recycling, polyolefin pyrolysis, time-temperature superposition, reaction severity, master curve, product distribution

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Comparative Life Cycle Assessment of Fossil-based Methanol and E-methanol Produced using CO_2 from Different Point Sources

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Due to the high CO_2 concentrations in flue gases, thermal power plants face substantial costs associated with emission allowances, making reductions in both emissions and associated expenditures increasingly important (Bui et al., 2018). Advances in carbon capture technologies have enabled the recovery of CO_2 from flue gases and its subsequent conversion into value-added products and energy carriers, including methanol (Pérez-Fortes et al., 2016). These technologies may reduce emissions while creating additional value from captured carbon.

However, focusing solely on carbon capture at point sources may overlook impacts elsewhere in the life cycle. Reducing greenhouse gas (GHG) emissions does not necessarily ensure that technology is more environmentally sustainable than conventional practices. A comparative Life Cycle Assessment (LCA) (ISO, 2006a; ISO, 2006b) is therefore required to identify potential burden shifting and determine whether alternative production pathways are environmentally preferable.

This study compares conventional fossil-based methanol production with e-methanol produced from captured CO_2 and electrolytic hydrogen. Different industrial point sources of CO_2 are considered, including coal- and natural-gas-fired power plants, aluminium smelting, and cement production. The energy requirements of e-methanol production are simulated on an hourly basis, considering renewable energy from solar power and biomass, together with surplus electricity from the grid. For the energy supply assessment, Slovenia was considered as a case study, with Maribor selected as the reference location. The analysis examines how the CO_2 source and hourly energy supply profile influence the life-cycle environmental performance of e-methanol.

The results quantify the environmental impacts of the evaluated e-methanol production pathways, using conventional methanol production as a reference. The findings support strategic decision-making for industries transitioning towards lower-carbon production systems.

Keywords: carbon capture, point sources, renewable energy, environmental impact, life cycle assessment, e methanol

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Bio-Based Methacrylate Miniemulsions for High-Performance Sustainable Coating Applications

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While extensive research on the production and radical copolymerization kinetics of bio-based monomers, particularly itaconates, has previously been conducted by our group (Pirman et al., 2024), this work explores a distinct direction focused on the development of sustainable coating systems from renewable biomass sources, particularly secondary (waste-derived) feedstocks. The study presents the incorporation of cardanol methacrylate into waterborne (meth)acrylic polymers using miniemulsion polymerization as an alternative route for preparing high-performance bio-based latexes.

Cardanol methacrylate, derived from cashew nut shell liquid, is an unsaturated, hydrophobic methacrylate monomer with high bio-based content. Its long aliphatic side chain provides strong hydrophobic character, while the pendant unsaturation in the side chain offers additional opportunities for post-polymerization functionalization or UV-induced crosslinking (Choi et al., 2014). However, due to its hydrophobicity and structural complexity, efficient incorporation of cardanol methacrylate into conventional emulsion polymerization systems can be challenging. Therefore, miniemulsion polymerization was employed to improve monomer

droplet stabilization, enhance monomer incorporation, and obtain stable bio-based latex dispersions suitable for coating applications (Schork et al., 2005).

The resulting cardanol methacrylate-containing miniemulsions were formulated into waterborne wood coatings and evaluated with respect to key application properties. The coatings exhibited excellent chemical resistance and anti-blocking performance, demonstrating the potential of cardanol-based acrylic latexes as sustainable alternatives for high-performance wood coating systems.

A further advantage of cardanol methacrylate lies in the double bonds present in its side chain. These structural features enable the investigation of the same miniemulsion systems not only as conventional waterborne wood coatings, but also as candidates for UV-curable coating technologies. This dual functionality provides an opportunity to combine waterborne formulation principles with additional curing mechanisms, potentially improving coating performance while maintaining a high renewable carbon contribution.

In addition to cardanol methacrylate, the versatility of the miniemulsion approach was further explored through the incorporation of a cellobiose-derived saccharide monomer, representing a complementary strategy for introducing hydrophillic, carbohydrate-based renewable structures into acrylic polymer dispersions (BIONEER, 2024).

Overall, this work demonstrates that miniemulsion polymerization is a promising platform for the design of advanced bio-based (meth)acrylic coating binders. By combining hydrophobic biomass-derived monomers, carbohydrate-based building blocks, and UV-reactive functionalities, the presented approach contributes to the development of more sustainable coating technologies with improved performance and reduced dependence on fossil-derived raw materials.

Keywords: bio-based monomers, miniemulsion, cardanol methacrylate, cellobiose, sustainable coatings, UV coatings

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Multi-Objective Techno-Economic Assessment of Onshore Wind Turbine Configurations Under Uncertainty

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Renewable energy technologies are playing an increasingly important role in modern power systems, with wind energy being one of the most mature and economically competitive options. However, wind turbines performance depends strongly on wind conditions, turbine geometry, and economic assumptions. Wind turbine design therefore requires balancing energy production, turbine size, investment cost, and long-term economic performance. Because these factors are uncertain during early project assessment, turbine configuration should be evaluated not only for nominal performance but also for its robustness under varying technical and economic conditions.

This work developed a techno-economic optimization framework for assessing onshore wind turbine configurations. The turbine was defined by hub height, rotor diameter, and rated power, which determined the wind speed available at the rotor, power curve behavior, annual energy production, and investment cost. Wind conditions were represented using statistical wind-resource model adjusted to the hub height, while the resulting energy production was linked to an economic model that evaluated investment costs, operating costs, electricity revenue, net cash flows, levelized cost of energy (LCOE), and net present value (NPV) over the project

lifetime. The optimization considered annual energy production, LCOE, and NPV as objective functions, together with a combined multi-objective function representing a compromise between technical performance and economic viability. This enabled comparison of energy-oriented, cost-oriented, profit-oriented, and balanced design strategies within a unified framework. To account for uncertainty, Monte Carlo simulation was applied after deterministic optimization by evaluating the selected turbine configurations under varying wind-resource, technical, and economic conditions.

The results showed that the selected optimization objective had a major influence on turbine sizing and project performance. Maximizing annual energy production generally led to larger and more expensive turbine designs, while minimizing LCOE and maximizing NPV favored configurations that better balanced additional energy output against investment cost. The combined objective provided an intermediate design strategy that avoided purely energy-driven oversizing while maintaining favorable economic performance. Monte Carlo analysis further demonstrated how frequently each turbine configuration remains financially viable and quantified the uncertainty in energy production, generation cost, and profitability indicators. Overall, the proposed framework provided a practical basis for wind turbine sizing, financial assessment, and early-stage investment decision-making under uncertainty.

Keywords: renewable energy, wind power, optimization, techno-economic assessment, uncertainty analysis

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Cascade Valorisation of Shredded Waste Electrical Cable Insulation Following Initial Incorporation into Geopolymer Composites: A Life Cycle Assessment with Longevity and Loop Factors

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Electrical cables at the end of their primary service life are mainly recycled for their metallic components, while the polymeric insulation fraction remains a challenging waste stream due to its complex composition, potentially hazardous substances, and limited recycling options. This study therefore investigates the valorisation of shredded waste electrical cable insulation through incorporation into geopolymer composites and evaluates their potential multi-loop utilisation pathways.

The first step of cascade valorisation was based on our previous experimental study on rubber-like waste from end-of-life electrical cables, where shredded cable insulation was incorporated into the exposed surface layer of geopolymer slabs during geopolymer slurry preparation and cured under room conditions (Horvat & Mušič, 2023). In the composite, the shredded cable insulation provided a functional role, i.e., geopolymer slabs without cable insulation exhibited excessive slipperiness, limiting their practical application (Horvat & Mušič, 2023). However, even if the

first-step reuse of the electric cable insulation waste in geopolymers was experimentally demonstrated as useful (Horvat & Mušič, 2023), the research on geopolymers still remains largely confined to laboratory-scale studies. Consequently, the subsequent reuse loops and end-of-life pathways of such composites remain largely unexplored.

To bridge the gap, several end-of-life scenarios were proposed in this study: reuse of crushed slabs as construction elements, utilisation of intermediate fractions as aggregates in concrete, and further processing of milled composite fractions as secondary raw materials for geopolymer or cement production.

To evaluate the multi-loop reuse pathways proposed in this study and identify environmentally preferable options, the life cycle environmental performance and future reuse potential of the geopolymer composite were assessed using Life Cycle Assessment (LCA).

The LCA was performed using ReCiPe Midpoint (H) in OpenLCA 2.6.2, based on primary data, literature sources, and Ecoinvent v3.12 datasets. To quantify the benefits and limitations of prolonged material retention within the technosphere and delayed transition to the end-of-life stage, longevity and loop factors were introduced.

The results demonstrate the potential of waste cable insulation as a functional secondary raw material in geopolymer composites and highlight the importance of evaluating multi-loop material pathways as interconnected systems rather than as isolated end-of-life scenarios. Such a holistic approach requires reliable tracking of material flows and quality evolution across multiple life cycles, as material degradation may limit future applications and ultimately determine whether the material can re-enter another productive cycle or must be directed to final disposal. Digital material traceability can therefore play an important role in enabling informed circular construction strategies.

Keywords: waste electrical cables, electrical insulation, geopolymers, circular economy, reuse, end-of-life, longevity factor, loop factor

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Composition-Controlled Formation and Swelling Stability of Crosslinker-Free Polyelectrolyte Hydrogels from Quaternized Chitosan and Hyaluronic Acid

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Hydrogels are among the most intensively studied biomaterials for biomedical use, yet their development increasingly demands biodegradable, biocompatible and environmentally friendly building blocks produced without toxic crosslinking agents (Rumon et al., 2024). In this work, hydrogels were prepared from two natural, renewable polysaccharides – quaternized chitosan (QCS) and hyaluronic acid (HA) – by polyelectrolyte complexation (PEC) between the quaternary ammonium groups ($–N^+(CH_3)_3$) of QCS and the carboxylate groups ($–COO^-$) of HA, entirely avoiding chemical crosslinkers. Four formulations were produced by systematically varying the HA/QCS molar ratio (r) and the NaCl molarity used to screen the electrostatic interactions: two QCS-excess systems (r = 0.56; 0.5 and 1 M NaCl) and two HA-rich systems (r = 1.008 and 1.24; 0.5 and 1 M NaCl).

The complexes were stabilized by controlled, stepwise dialysis to gradually lower the ionic strength, then lyophilized, and characterized by FT-IR and a swelling test in phosphate-buffered saline (PBS). The hydrogel formation yield differed markedly with composition: the QCS-excess systems reached about 50 %, whereas the HA-rich systems yielded only about 8 %. FT-IR confirmed that the network is held together by electrostatic interactions rather than covalent bonds, as no new absorption bands appeared; the higher NaCl content (1 M) produced less pronounced ionic bands, consistent with stronger ionic screening and a more homogeneous network organization, while for the HA-rich pair the near-stoichiometric ratio – not screening – governed the band intensities.

The swelling test revealed the decisive role of composition for aqueous stability: the QCS-excess hydrogels disintegrated within one minute in PBS, attributable to the excess cationic ammonium groups and the resulting electrostatic repulsion upon hydration, whereas the HA-rich hydrogels maintained a stable network over 48 h with rapid initial hydration and maximum swelling of approximately 573 % (near-stoichiometric) and 631 % (HA excess). Ionic screening by NaCl was therefore not the primary determinant of network stability; rather, the HA/QCS molar ratio dictated whether a robust hydrogel network formed.

These results show that a simple, crosslinker-free PEC route based on renewable polysaccharides can yield structurally stable hydrogels when the polymer stoichiometry favours HA, providing a sustainable basis for further biomedical material development.

Keywords: quaternized chitosan, hyaluronic acid, polyelectrolyte complexation, crosslinker-free hydrogels, swelling stability, sustainable biomaterials

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Valorisation of Flaxseed Cake Through Randall Extraction of Bioactive Compounds

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Flaxseed cake, a by-product of flaxseed oil processing, contains various groups of bioactive compounds, including phenolic compounds and flavonoids, and therefore represents an interesting secondary material for further valorisation (Kaur et al., 2024). Despite its potential, this material remains underutilised.

Various extraction methods are used to isolate valuable components from this type of biomass, including maceration, Soxhlet extraction, and the Randall method. Among them, Soxhlet extraction is a classical continuous extraction method using a heated solvent, but it requires long extraction times and high solvent and energy consumption. To overcome these limitations, the Randall method was developed, offering shorter extraction times, lower solvent use, and improved efficiency (Quispe-Fuentes et al., 2025). Automated Randall-based extraction systems further improve reproducibility, process control, and solvent reuse, which is advantageous from both environmental and economic perspectives.

Based on these considerations, the aim of this study was to investigate the influence of operating conditions and extraction solvent composition on the extraction of bioactive compounds from flaxseed cake using the automated Randall extraction method. Extractions were performed using ethanol–water mixtures with an

automated VELP extractor. The obtained extracts were evaluated in terms of extract mass yield, total phenolic content, determined spectrophotometrically using gallic acid as a standard, and antioxidant activity, determined using the DPPH method.

Under the selected conditions, the EtOH/H_2O ratio of 70:30 (v/v) provided the most favourable combination of extraction yield, total phenolic content, and antioxidant activity, whereas higher water content favoured the extraction of other soluble compounds. Changes in operating conditions significantly influenced the composition and properties of the obtained extracts. Moreover, a higher extraction yield did not necessarily correspond to higher total phenolic content or stronger antioxidant activity, indicating the co-extraction of non-phenolic compounds, such as residual lipids, soluble sugars, and proteins. The results confirm that the Randall method is an effective approach for obtaining extracts from flaxseed cake. For the targeted extraction of bioactive compounds, appropriate selection of operating conditions, such as extraction time and temperature, is essential.

Keywords: flaxseed cake, Randall extraction method, phenolic compounds, antioxidant activity, solvent extraction

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Adsorbent Design for Process Intensification in CO_2 Valorisation to Methanol

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The increasing concentration of atmospheric CO_2 and its impact on climate change have intensified the search for sustainable carbon utilization technologies. Among the available carbon capture and utilization routes, the catalytic hydrogenation of CO_2 to methanol has emerged as a particularly attractive pathway, enabling the production of a versatile chemical feedstock, energy carrier, and platform molecule for a future circular carbon economy (Bukhtiyarova et al., 2017). However, despite significant advances in catalyst development, the direct hydrogenation of CO_2 remains thermodynamically limited, typically achieving only 10–25% methanol conversion per pass under industrially relevant conditions (Reichert et al. 2019). One promising strategy to overcome these limitations is process intensification through in situ product removal. By selectively removing methanol and water from the reaction medium, the reaction equilibrium can be shifted towards higher conversions, reducing recycle requirements and improving overall process efficiency. Within the framework of the Horizon Europe ILIMITED project, ionic liquids (ILs) are being explored as selective absorbents capable of operating directly under methanol synthesis conditions. The design of suitable ILs presents a complex multi-objective challenge. Candidate solvents must exhibit high affinity for methanol and water, low CO_2 absorption to preserve selectivity, low viscosity to ensure efficient mass transfer, and, critically, high thermal and chemical stability at

temperatures around 513 K. To address this challenge, a computational workflow combining COSMO-RS molecular thermodynamics, large-scale virtual screening, and machine-learning tools was developed to evaluate millions of ionic liquid structures and identify promising candidates. Approximately 19 million ILs were screened, enabling the identification of a small set of promising candidates exhibiting high methanol/water affinity, low CO_2 uptake, and suitable thermal stability for operation under methanol synthesis conditions. These candidates have been selected for experimental validation, including thermal and chemical stability assessments under relevant reaction conditions, to verify their applicability in equilibrium-shifting methanol synthesis processes.

Keywords: CO_2 utilization, methanol, production, ionic liquids, COSMO-RS, circular economy,

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Expired Pumpkin Seed Oil as a Green Co-Additive for Copper Corrosion Protection

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Within the framework of circular economy principles, waste-derived and expired natural products represent a promising source of functional additives for sustainable corrosion protection systems (Verma et al., 2021). Copper samples were exposed to a model acidic rain solution (pH 5) to simulate mildly acidic corrosion conditions. SAHLs were prepared by immersion in an ethanolic solution of 0.05 M stearic acid containing varying concentrations of pumpkin seed oil (0.5, 1.0, 2.0, 3.0, and 4.0 wt%). Corrosion protection performance was evaluated using electrochemical techniques and SEM. The results show that the addition of pumpkin seed oil significantly enhances the corrosion resistance of the stearic acid-based SAHL. At lower concentrations (0.5–1%), the inhibition efficiency remained around 80%, while higher additive contents (≥2%) yielded efficiencies exceeding 90% after 5 days of exposure. SEM analysis revealed a hierarchical, flower-like surface morphology in the presence of pumpkin seed oil, indicating modified self-assembly behaviour and enhanced surface coverage. This structured morphology is associated with improved barrier properties, reducing the access of corrosive species to the copper surface. The existing study should be expanded to cover a wider range of corrosion systems involving various materials and corrosive media.

Keywords: corrosion, pumpkin seed oil, self-assembled hydrophobic layer, flower-like structure, copper, SEM, EIS

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VIRIDI Academy: Cross-Border E-Learning for Circular Business Models in SMEs

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SMEs are decisive for the shift from a linear to a circular economy, yet many lack the knowledge, financing literacy and digital skills to redesign their business models (Van Opstal and Borms, 2023).

The VIRIDI Academy, developed within the project VIRIDI under the Interreg Slovenia–Austria programme, gives SMEs a free, openly accessible, bilingual (Slovenian/German) self-learning programme on a Moodle platform (https://viridi-academy.eu/) that they can complete at their own pace. Following a quadruple-helix logic, the six project partners each contributed one module, so that users gain practical, ready-to-use knowledge on the SI–AT regulatory framework, financing the

transition (ESG, EU taxonomy), digitalisation (digital product passports, BIM, AI), waste and recycling, and circular business models and value chains. Each module combines bilingual materials, recommended reading and self-assessment, complemented by good-practice cases.

To keep the content directly applicable, the Academy focuses its value-chain and business-model guidance on three priority sectors selected for the region – construction, wood processing and plastics – so that SMEs gain targeted know-how to redesign products and business models, navigate regulation and financing, and adopt digital tools for circularity. The principal output (deliverable D.1.5.1) is a functioning bilingual Moodle classroom with six modules, freely available to SMEs across the programme area, piloted in Austria (online sessions and a Makerspace event, Oct 2025–Mar 2026) and Slovenia (online workshops, early 2026). Module 5 targets circular business models and value chains; the financing and digitalisation modules support sustainable decision-making.

The Academy shows how a coordinated, cross-border, quadruple-helix instrument can lower SMEs' knowledge barriers to circular business models, providing a free, durable and transferable capacity-building resource for the Slovenia–Austria region.

Keywords: circular economy, circular business models, cross-border cooperation, SME capacity building, e-learning (MOOC), Interreg Slovenia–Austria

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Wastewater Treatment Plants as Circular and Flexible Energy Hubs through Sludge Management, Biogas Utilization and Renewable Energy Integration

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Wastewater treatment plants are increasingly relevant beyond pollution control, as modern wastewater infrastructure is expected to contribute to environmental protection, energy performance and renewable energy use in addition to conventional treatment functions (European Parliament and Council, 2024a). This broader role is important in the circular economy transition, particularly because Europe's circular material use rate remained limited at 11.8% in 2023 (European Environment Agency, 2024). The growing importance of renewable energy also creates opportunities for wastewater treatment plants to integrate local renewable generation and reduce dependence on external energy supply (European Parliament and Council, 2023a). Energy efficiency is another important driver, as European policy reinforces the "energy efficiency first" principle and the need to reduce final energy consumption (European Parliament and Council, 2023b). Energy security further strengthens the motivation for local energy recovery and clean energy integration, especially in the context of REPowerEU and its focus on energy savings,

supply diversification and faster deployment of clean energy technologies (European Commission, 2022). As electricity systems include higher shares of variable renewable generation, flexible operation, demand response and storage become increasingly important for balancing supply and demand (European Parliament and Council, 2024b).

This work focuses on evaluating the role of wastewater treatment plants flexible energy hubs in active participation in flexibility markets on wide range of timescales. The evaluation is made with modular wastewater treatment plant models which describes time-dependent mass and energy flows. It is implemented using a MATLAB Live Editor structure, where interactive elements such as sliders and panels support parameter variation, scenario definition and visualization. The framework enables the assessment of dynamics of biogas production based on sludge input, different biogas utilization pathways, including combined heat and power units, boilers, upgrading and synthesis.

Photovoltaic generation and battery storage are integrated into the model to evaluate their contribution to energy self-sufficiency, peak-load reduction, and demand-side flexibility. The model supports different temporal resolutions, including daily, hourly, and minute-based time steps. This allows for both long-term energy-balance assessment and short-term operational analysis.

Preliminary simulations indicate that fluctuations of approximately 20% in sludge input can significantly affect the profile of available energy. The sludge type considered in the model also significantly influences the resulting energy balance, particularly in the case of plants which treat industrial and municipal wastewater simultaneously. These results suggest that both sludge quantity and sludge characteristics are important parameters when assessing the flexibility potential of wastewater treatment plants and that they can be exploited to maximize flexibility upfront, in a predictive manner. Special attention is therefore given to the impact of strategic dosing on plant performance, energy demand, biogas availability, and operational flexibility.

By linking sludge management, biogas utilization, renewable energy integration, battery storage, component sizing and multi-time-step simulation, the developed framework supports scenario-based evaluation of wastewater treatment plants as flexible circular energy hubs. The work contributes to the technological and

business-oriented transition toward more sustainable, flexible, and energy-resilient utility infrastructure.

Keywords: wastewater treatment, circular economy, sludge treatment, biogas utilization, CHP, photovoltaic integration, battery storage, energy flexibility, MATLAB modelling

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Application of LCA and S-LCA to Low-TRL Technologies: A Case Study of a Novel Current-Limiting Solution for the Energy Transition

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Low-voltage Direct Current (LVDC) power systems are increasingly recognised as a key enabler of a clean and efficient energy transition, particularly for decentralized generation and storage applications. Despite their technical and operational advantages, safety concerns–especially related to fault current management–continue to limit their widespread adoption. The NOVETROL project (NOVEL CURRENT CONTROL FOR CLIMATE NEUTRAL ENERGY INFRASTRUCTURE, Grant Agreement No. 101192615) addresses this critical barrier by developing innovative current-limiting (CL) technologies based on high-mobility materials exploiting the extraordinary magnetoresistance (EMR) effect. The project further aims to integrate these solutions into both Direct Current (DC) and hybrid AC/DC energy systems.

To ensure a comprehensive sustainability assessment, the project employs both Life Cycle Assessment (LCA) (ISO, 2006a; ISO, 2006b)and Social-Life Cycle Assessment (S-LCA) (UNEP, 2020), two internationally recognised methodologies for evaluating environmental impacts and socio-economic risks across the entire life

cycle of a technology. The LCA study focuses on quantifying environmental impacts associated with the production of current-limiting devices, identifying key hotspots and opportunities for impact reduction, including strategies related to material efficiency and the use of recycled content. In parallel, S-LCA is employed to assess social risks along the supply chain, with particular attention to affected stakeholders and issues related to labour conditions, occupational health and safety, and broader socio-economic implications. The combined application of LCA and S-LCA allows for a multidimensional understanding of the sustainability performance of the proposed CL technologies. Preliminary findings indicate the presence of key environmental hotspots linked to material extraction and manufacturing processes, highlighting areas where targeted improvements can significantly reduce the overall environmental footprint, also implementing circular economy principles. Similarly, the S-LCA analysis identifies critical supply chain stages where social risks are more pronounced, enabling the prioritisation of mitigation strategies and stakeholder engagement.

The integration of LCA and S-LCA within the NOVETROL project provides a robust framework for the systematic evaluation of both environmental and social dimensions of emerging LVDC technologies. By addressing both technical and sustainability challenges, NOVETROL contributes to enhancing the feasibility and acceptability of LVDC systems, facilitating their transition toward large-scale deployment.

Keywords: current limiter, LCA, S-LCA, direct current, sustainability

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The Future of the Circular Aluminum Economy: From Material Circularity to Performance-Based Circularity

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In policy discourse, the circular economy is often presented as a unified and largely self-sustaining model. In industrial reality, however, it comprises materially and economically distinct process routes. In the aluminum sector, circularity includes both the remelting of new and industrial scrap and the recycling and upcycling of post-consumer scrap (PCS). While all these flows contribute to circularity, they differ fundamentally in technological complexity, environmental impact, and economic performance. Recognizing these differences is essential for realistic circular economy strategies. In this context, performance-based circularity refers to circular material systems in which recycled content is deliberately engineered and controlled to meet the performance requirements of demanding applications.

Aluminum is widely regarded as a benchmark material for circularity. In Europe, more than 75% of aluminum products at end of life are collected, and secondary aluminum production typically requires around 90–95% less energy than primary production. These characteristics underpin aluminum's strong environmental performance. However, experience with high-performance wrought aluminum alloys shows that high circularity does not equate to material self-sufficiency, particularly when circularity relies on increasing shares of PCS.

In demanding application areas such as automotive safety components, aerospace structures, defense systems, and dual-use technologies, strict requirements apply regarding chemical composition, mechanical properties, fatigue resistance, and long-term reliability. Industrial practice indicates that PCS shares of approximately 20–40% can generally be integrated into wrought aluminum alloys without compromising performance, provided that rigorous process control is applied. In selected alloy systems, PCS shares approaching 50–60% are technically feasible, but only with increased process constraints and reduced alloy design flexibility. Beyond these levels, the accumulation of trace and tramp elements–most notably iron, copper, and zinc–progressively limits formability and fracture toughness.

From an environmental perspective, the benefits of PCS-based recycling and upcycling are clear and quantifiable. Increasing the PCS content of wrought aluminum alloys by 10 percentage points typically reduces specific greenhouse gas emissions by approximately 0.6–0.8 t CO_2 per ton of product and lowers primary energy demand by around 8–12 MWh per ton, depending on process efficiency and electricity sourcing. These figures confirm that PCS utilization is a powerful lever for industrial decarbonization.

Industrial experience from Impol Aluminum Industry illustrates both the potential and the recognized limits of this approach. Through long-term process development, Impol has enabled significantly increased PCS utilization by implementing rigorous, precise, and consistent quality control of incoming scrap at the foundry level, combined with enhanced melt treatment, tight control of trace elements, and extensive quality assurance. These measures enable the production of high-quality wrought products with a reduced carbon footprint, even for demanding markets.

At the same time, industrial practice clearly shows that ecological and economic optima diverge. PCS-based recycling and upcycling typically incur production cost premiums in the range of 10–25% compared with primary-based routes, reflecting higher process complexity, reduced flexibility, and increased quality assurance requirements. In contrast, the remelting of new and industrial scrap–also an integral part of the circular economy–tends to deliver predominantly economic benefits due to its compositional stability, high process yields, and lower processing risk.

Still, the broader system perspective remains decisive. Growing aluminum demand in mobility, energy infrastructure, and defense applications exceeds the availability of PCS suitable for high-performance alloys, while unavoidable material losses prevent full loop closure. Primary aluminum production therefore remains a structural component of a functioning circular aluminum economy.

From a policy perspective, aluminum demonstrates that leading metallurgical practice can deliver high circularity and substantial environmental benefits, but only within recognized limits. Effective circular economy frameworks must therefore clearly distinguish between different circular material flows and align environmental ambitions with economic and industrial realities.

Keywords: circular aluminum economy, performance-based circularity, post-consumer scrap (PCS), trace elements in aluminum alloys, industrial decarbonization

Metrology as the Foundation of Trust in Circular Aluminum: From Impol's Industrial Practice to Advanced Tools for European Circular Industry

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The transition toward a circular economy in aluminum is often framed in terms of recycling rates and carbon reduction. However, the industrial feasibility of high-recycled-content aluminum depends on a more fundamental condition: the ability to maintain material reliability and certification credibility under increasing compositional variability. In such conditions, metrology becomes a critical infrastructure of trust within circular production systems.

This paper presents an operational industrial model implemented within Impol Group, one of the leading European producers of wrought aluminum products, with annual output of approximately 230,000–240,000 ton and recycled input approaching 78%. A substantial share of production is delivered to technically demanding sectors such as automotive, transport systems, construction, and energy applications, where compliance, traceability, and long-term reliability are essential.

The model is based on an integrated system of independent quality control covering virtually all material flows. Its core components include institutional independence of quality assurance from production hierarchies, comprehensive laboratory testing of mechanical properties, metallographic characteristics, and chemical composition,

as well as a centralized Catalogue of Measurement Systems defining measurement methods, standards, and uncertainties.

Within this framework, metrology functions as an independent arbiter of measurement validity and conformity decisions. Measurement uncertainty is systematically integrated into the evaluation of test results, enabling transparent and reliable assessment of product compliance. The metrological infrastructure is further connected with digital data processing and automated certificate generation, ensuring full traceability and consistency of quality documentation.

Between 2015 and 2025 the implementation of this system has been associated with measurable industrial outcomes, including reduced complaint rates, improved melt efficiency, and increased process stability despite the growing share of recycled material. At the same time, the number of laboratory analyses exceeded 400,000 annually, reflecting a significant expansion of measurement-based process control.

The Impol case demonstrates that circular aluminum production at industrial scale requires not only metallurgical expertise and recycling technologies, but also robust metrological governance embedded within the organizational structure of quality control. In this perspective, metrology becomes a structural enabler of safe circular production: it transforms heterogeneous secondary resources into certifiable industrial materials.

The presented model illustrates how industrial practice can contribute to broader European efforts toward sustainable metallurgy. By combining independent quality governance, systematic measurement uncertainty management, and digital validation of test results, the system provides transferable tools for strengthening trust and reliability in circular aluminum supply chains.

Keywords: circular aluminum production, industrial metrology, measurement uncertainty, independent quality control, circular economy and metallurgy

Assessing Natural Yeasts as Immobilizable Biocatalysts for Bioremediation of Metal-Contaminated Soil and Valorization of Waste Cooking Oil

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Bioremediation and waste valorization are key components of green biotechnology and circular economy strategies. Yeasts are metabolically diverse microorganisms with potential for pollutant removal, metal binding, and waste-stream bioconversion (Mohiuddin et al., 2024). Different organic polymers, such as chitosan and dextran, have been extensively employed in the synthesis of magnetic nanoparticles (MNPs)

as coating materials for constructing adsorptive and highly functional materials, mainly due to their high adsorptive ability and low cost. They are also environmentally friendly, renewable, biodegradable, biocompatible, and easily modified. We assessed the potential of natural yeast isolates for bioremediation of metal-contaminated soil and valorization of waste cooking oil. Moreover, several different polymer-modified MNPs were tested for their potential for immobilization of biocatalysts.

Publicly available Slovenian soil-quality data of several industrial and mining areas contaminated with inorganic pollutants, including the Meža Valley and Celje Basin, were screened for the most important metal pollutants. The identified metal pollutants (Cu, Fe, Zn, Pb, and Cd) were subsequently used in a colorimetric assay for siderophore-mediated metal interactions (Alexander and Zuberer, 1991) to assess the bioremediation potential of natural yeast isolates from the ZMUM collection, which comprises 30 yeast isolates from anthropogenic and natural environments, including *Candida*, *Metschnikowia*, *Meyerozyma*, *Lodderomyces*, *Hanseniaspora*, *Pichia* and *Saccharomyces* isolates. Moreover, the lipolytic activity of the used yeast isolates was determined to assess the yeasts' potential for valorization of waste cooking oil and different polymer-modified MNPs were prepared by the co-precipitation method using ferric and ferrous ions in the presence of ammonia solution and later modified with a specific polymer.

Yeast isolates were inoculated on Chrome Azurol S solid media, supplemented with $CuCl_2$, $FeCl_3$, $ZnCl_2$, $Pb(NO_3)_2$ or $CdCl_2 \cdot xH_2O$, and on control YEM medium (Silva-Bailao et al., 2014). After seven days at 30 °C, colony growth and halo formation, color and size were recorded. In parallel, lipolytic activity was determined employing the solid modified Czapex-Dox media (Hussein and Joo, 2019) with phenol red pH indicator and glucose, 1% household waste cooking oil, or 1% waste cooking oil with 0.5% Tween 80 (Kumari et al., 2023).

Most isolates tolerated metals, with colony size reaching at least 30% of the metal-free control. Growth was observed for 29 isolates with Cu (0.05 mM), Fe (0.05 mM), and Pb (0.01 mM), 27 with Zn (1 mM), and 21 with Cd (0.05 mM)-containing media. Halo formation was observed in 15 strains on copper-containing medium, 14 on iron, 10 on lead, 7 on zinc, and 5 on cadmium. The most promising isolates were *Metschnikowia pulcherrima* K010 and *Candida palmioleophila* K019, both from the Meža River.

The lipolytic activity assay revealed *Pichia* isolates, particularly all *P. kudriavzevii* strains, as promising potential isolates for lipase-mediated waste cooking oil bioconversion without Tween 80.

The synthesized polymer-modified MNPs were revealed to possess a high potential to be used as functional materials for immobilization of different biologically active molecules for environmental remediation, such as removal of metals or waste cooking oil bioconversion.

Overall, the project underpins the possible integration of yeast-based metal bioremediation, waste cooking oil valorization with immobilization by polymer-modified MNPs into a circular biotechnological platform.

Keywords: metal-contaminated soils, bioremediation, Metschnikowia pulcherrima, Candida palmioleophila, Pichia kudriavzevii, CAS metal-interaction screening, polymer-modified magnetic nanoparticles, lipase-mediated oil valorization

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Formalin Production from Waste

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The usage of fossil fuels and accumulation of waste into landfills have a negative effect on the environment and generates climate changes. Waste, such as municipal solid waste (MSW), contains hydrocarbons. Flue gas (FG) is a resource of steam and carbon dioxide, which can both reduce the dependence on natural gas. Waste and flue gas conversions into formalin production and energy have the potential for CO_2 emission reduction by using the complete circular economy, which is supported by the mathematical model and the Aspen Plus® simulator for syngas converted into formalin. The mathematical model includes real-simulated results. Gassed MSW 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 formalin product. The molar flow rate of hydrogen is generated in surplus, therefore hydrogen can be cleaned and produced as co-product. Formaldehyde is produced industrially by the catalytic oxidation of methanol using a mixture of iron oxide with molybdenum and vanadium catalysts.

Although formaldehyde is a gas at room temperature, it is readily soluble in water, and is most commonly sold as a 37% solution in water known by trade names, such as formalin or formol.

Keywords: waste, flue gas, formalin, syngas, Aspen Plus, methanol

Experimental Evaluation of Dry Sludge Combustion from Sewage Treatment Plants

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Municipal sewage treatment plants generate substantial volumes of sewage sludge as a by-product of biological wastewater treatment. As global wastewater infrastructure continues to expand, sustainable management of this waste stream has become increasingly critical (Ferrentino et al., 2023; Kacprzak et al., 2017). Thermal treatment through combustion offers key advantages: significant volume and mass reduction, destruction of hazardous organic compounds, and potential energy recovery to support the drying process (Gao et al., 2020). For reliable combustion, sludge must be dewatered and dried to approximately 90% dry matter (DM) content. This study presents the experimental evaluation of dry sewage sludge combustion conducted in a fixed-grate, batch combustion configuration.

The laboratory device was designed to replicate conditions relevant to full-scale moving-grate combustion plants. Experiments were conducted across a range of dry matter contents (65–95%) and primary air preheating temperatures (200 °C, 230 °C and 260 °C), with systematic variation of preheating duration. Thermodynamic parameters, including maximum combustion temperature (T_{max}), time to peak temperature, and the intensive heat release interval (IHRI), were recorded alongside flue gas composition (CO_2, CO, O_2) in the primary combustion chamber (Cui et al., 2006; Magdziarz and Werle, 2014). A structured experimental dataset was constructed for calibration and validation of numerical combustion models.

Key findings indicate that a preheating temperature of 230 °C is insufficient for reliable ignition of sludge with DM content below 85%, while 260 °C ensures stable combustion across all tested conditions. At higher preheating temperatures, lower peak combustion temperatures were achieved, while the IHRI was longer, reflecting a more gradual and distributed energy release. Extended preheating duration correlated with greater mass reduction, particularly pronounced at 260 °C and 230 °C. With regards to potential phosphorous recovery, the lowest contamination of the ash samples with semi volatile metals was obtained at lower preheating air temperatures. The results confirm that dry sewage sludge can serve as a standalone fuel without supplementary measures to enhance its heating value.

Keywords: sewage sludge combustion, fixed-grate furnace, moisture content, primary air preheating, flue gas composition

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Effect of Storage Conditions on the Extractives Content in Silver Fir (*Abies alba* Mill.) Bark

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Silver fir (*Abies alba* Mill.) bark is a forest by-product and a promising source of bioactive polyphenols with potential applications in nutraceutical, pharmaceutical, and biobased products (Vek et al., 2023, Domazet et al., 2023, Oven et al., 2023, Benković et al., 2014, Vek et al., 2021). To ensure efficient use of this low-value biomass, losses of valuable extractives during storage and handling must be minimized. However, the chemical composition of bark can be significantly altered by environmental exposure and biomass processing prior to extraction. This study examined how storage conditions, bark particle size, and timing of bark removal affect the preservation of extractives and polyphenols in silver fir bark during one year of storage.

Bark samples were obtained from mature silver fir trees felled in the forests of Kočevska Reka, Slovenia. Bark samples were analyzed in three forms: crude bark, ground bark, and industrial bark collected from a sawmill debarker. Samples were stored either indoors under dry, dark conditions or outdoors under direct weather exposure. In addition, bark removal timing was assessed using samples that were left attached to the stem during storage and removed immediately before extraction and analysis. Changes in chemical composition were monitored monthly over a 12-month period. Total extractives content (TEC), total phenolic content (TPC), and

total catechins content (TCC) were determined after water extraction, while fresh bark extracts were additionally characterized by GC-MSD.

GC-MSD analysis identified 24 compounds in silver fir bark extracts, including sugars, sugar alcohols, organic acids, flavonoids, and lignans (Vek et al., 2023). Long-term storage experiments revealed that both storage conditions and biomass processing strongly influenced the retention of extractives and polyphenols. The greatest losses were observed in samples stored outdoors, where precipitation promoted the leaching of water-soluble compounds. This effect was particularly pronounced in ground bark, which exhibited the largest reductions in TEC, TPC, and TCC due to its increased surface area and greater exposure to environmental factors (Hrovatič et al., 2025; Humar et al., 2019; Keržič et al., 2024).

Analysis of TPC showed a greater decrease in content related to storage than gravimetrically analyzed TEC. Catechins were most susceptible to weather exposure, and their concentrations in bark stored outdoors dropped below the detection limit during the final months of storage. In contrast, bark stored indoors exhibited substantially lower losses, especially in crude and industrial bark fractions. The timing of bark removal also played an important role. Bark that remained attached to stem throughout storage retained nearly unchanged extractives and polyphenol contents over the 12-month period, whereas mechanically disintegrated bark stored outdoors experienced significant leaching of extractives (Hrovatič et al., 2026).

The results demonstrate that preserving the chemical quality of silver fir bark for extraction depends not only on storage conditions but also on the degree of biomass processing and the timing of bark removal. To maximize the recovery of valuable bioactive compounds, bark should be stored under sheltered conditions, unnecessary mechanical disintegration prior to storage should be avoided, and bark removal should be postponed until shortly before extraction. These findings provide practical recommendations for improving the valorisation of silver fir bark within circular bioeconomy systems (Hrovatič et al., 2025, 2026; Routa et al., 2020, 2021).

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

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Surrogate Neural Network Modeling of Biomass Indirect Gasification: Predicting Syngas Composition and Optimizing Process Conditions for Renewable Hexamine Synthesis

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The transition towards energetic materials with reduced environmental impact requires the development of alternative production routes for industrially relevant compounds, such as hexamine [$(CH_2)_6N_4$], a common raw material in hydrogel-type formulations. This work presents the conceptual design of a renewable hexamine production route from regionally available residual lignocellulosic biomass, developed in collaboration with the industrial partner MAXAMCORP INTERNATIONAL, S.L. with pilot and industrial-scale experimental capabilities. The selected biomass, sourced from the cereal and winemaking sectors, is converted into syngas through indirect gasification, which is subsequently upgraded to methanol, formaldehyde and, finally, hexamine via reaction with ammonia (Alamdari and Tabkhi, 2004; Hernández and Martín, 2016).

Building on the conceptual design developed in a first phase of the study, the novel contribution of this work lies in modeling the indirect gasification stage by means of an artificial neural network, replacing the kinetic or thermodynamic equilibrium approaches traditionally used for this type of multi-reactor system (Sanz et al., 2026). The strongly nonlinear and coupled nature of the variables governing gasification such as feedstock composition, operating temperature, and the ratio between the gasifying agent and biomass makes it difficult to formulate mechanistic models that are both accurate and computationally light enough to be embedded within a full process optimization framework. The proposed neural network is trained to simultaneously predict syngas composition (CO, H_2, CO_2, CH_4) as well as char and ash yields from the operating conditions and feedstock characteristics, thereby acting as a differentiable, low-computational-cost surrogate model replacing the gasification block.

Integrating this surrogate model within the overall process flowsheet allows the simultaneous optimization of operating temperature and gasifying agent-to-biomass ratio to be formulated as a Nonlinear Programming (NLP) problem, in which the neural network acts as a constraint within the equation system describing the complete process, implemented in algebraic modeling environments oriented towards optimization (GAMSpy). This approach overcomes the typical limitations of detailed kinetic models, whose direct integration into process optimization problems is often computationally expensive or numerically unstable, while preserving the predictive capability needed to capture the nonlinear dependence of syngas yield and quality on operating conditions.

The expected results of this methodology will make it possible to identify the optimal operating conditions of the gasification stage that maximize syngas quality while minimizing the generation of carbonaceous by-products, thus laying the groundwork for the subsequent techno-economic analysis of the renewable hexamine production route at different operating scales. This work also constitutes an example of the application of machine learning techniques as a supporting tool for the design and optimization of biomass residual valorization processes.

Keywords: biomass indirect gasification, neural networks, renewable hexamine, nonlinear programming, surrogate modeling

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Towards Sustainable Packaging Materials: Poly(vinyl alcohol) Biocomposite Films Reinforced with Green Fillers

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Introduction

Petroleum-based polymers are widely used in packaging due to their favorable mechanical, barrier, and processing properties; however, their environmental impact has accelerated the search for sustainable alternatives (Espinosa et al., 2019, Bascón-Villegas et al., 2021). Poly(vinyl alcohol) (PVA) is a biodegradable and biocompatible polymer with excellent film-forming ability, low gas permeability, and good thermal stability (Tretinnikov and Zagorskaya, 2012, Kassab et al., 2019). Nevertheless, its application is limited by its hydrophilic nature and poor moisture resistance (Lee et al., 2009, Chou et al., 2021, Liu et al., 2022). The incorporation of cellulose nanofibrils (CNFs) into PVA matrices has been shown to improve mechanical, thermal, and barrier properties (Osolnik et al., 2023, Osolnik et al., 2025, Kalia et al., 2011, Wu et al., 2019). More recently, lignocellulose nanofibrils (LCNFs), which retain lignin within their structure, have attracted increasing attention due to additional functionalities such as antioxidant, antimicrobial, and UV-protective properties (Bian et al., 2018, Yang et al., 2020, Fu et al., 2021). Furthermore, biologically active compounds such as tannic acid (TA) can provide antioxidant

activity and contribute to the development of active packaging materials (Osolnik et al., 2023, Pinto et al., 2021). This study investigates the combined effects of CNFs, LCNFs, and TA on the properties of multifunctional PVA-based biocomposite films.

Methods

CNFs were supplied by the Centre for Biocomposite and Biomaterial Processing (University of Toronto, Canada), while LCNFs were produced by esterification of spruce wood with maleic anhydride followed by high-pressure homogenization at University of Ljubljana, Biotechnical faculty. PVA/CNF/TA and PVA/LCNF/TA biocomposite films with varying nanofibril and TA contents were prepared by solvent casting. Their chemical structure and morphology were characterized by FTIR spectroscopy and SEM, respectively. Mechanical properties were determined according to ASTM D882-02, thermal stability by thermogravimetric analysis (TGA), surface hydrophilicity by water contact angle measurements, and antioxidant activity using the DPPH radical scavenging assay.

Results

To evaluate the contribution of individual components, two-component PVA systems containing CNFs, LCNFs, or TA were first prepared. Both nanofibrils improved tensile strength at all investigated concentrations, although elongation at break generally decreased. The strongest reinforcing effect was achieved with 10% CNFs, increasing tensile strength by 40% compared with neat PVA. TA also improved mechanical performance despite being primarily incorporated as a bioactive additive.

Based on these results, three-component PVA/CNF/TA and PVA/LCNF/TA films were developed. The formulation containing 2% CNFs and 10% TA showed a 30% increase in tensile strength and a water contact angle about 20° higher than neat PVA, indicating reduced hydrophilicity. Films containing 4 or 6% CNFs with TA exhibited enhanced thermal stability, with the onset degradation temperature increasing by approximately 30 °C. Replacing CNFs with LCNFs improved flexibility; 2% LCNFs increased elongation at break by more than 100% relative to neat PVA. Films containing 2 or 6% LCNFs and 10% TA also showed water contact angles over 20° higher than neat PVA. Antioxidant activity, determined by the

DPPH assay, was observed exclusively in TA-containing films, with only negligible activity detected in PVA/LCNF films containing the highest concentration of LCNFs.

Conclusions

The results demonstrate a pronounced synergistic effect between tannic acid and nanofibrils, leading to improved mechanical, thermal, surface, and antioxidant properties. These multifunctional PVA-based biocomposites show considerable potential for sustainable and active packaging applications.

Keywords: bionanocomposite films, (ligno)cellulose nanofibrils, poly(vinyl alcohol), tannic acid, active packaging

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Controlling Calcium Carbonate Polymorphism in CO_2-Based Precipitation: Vaterite, Aragonite and Scalenohedral Calcite Towards Microreactor Synthesis

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Introduction

Calcium carbonate ($CaCO_3$) is one of the most widely used industrial mineral fillers, and the performance of precipitated calcium carbonate (PCC) is governed by its polymorph (calcite, aragonite or vaterite) and crystal habit, which together set particle morphology, specific surface area and surface charge. Producing PCC by carbonation simultaneously consumes CO_2, linking a functional mineral product to circular CO_2 valorisation. The central challenge is selectivity: because the metastable phases follow Ostwald's step rule, the same $CaCO_3$ system can yield any of the three polymorphs depending on supersaturation, temperature, additives and mixing (Gakis et al., 2025).

Method

We established dedicated precipitation routes targeting each phase. Vaterite is obtained at room temperature under high supersaturation by rapidly combining concentrated $CaCl_2$ and Na_2CO_3 solutions in an ethanol cosolvent (~40 vol %), which lowers water activity and kinetically traps the metastable phase. Aragonite is precipitated by slow carbonate addition into hot $CaCl_2$ (85–90 °C) followed by ageing at temperature, with a comparative Mg^{2+}-assisted route (Mg/Ca = 5, 60 °C). Scalenohedral ("dogtooth") calcite is grown by carbonating $Ca(OH)_2$ milk with a moderate, diluted CO_2 stream under sustained Ca^{2+} excess (García-Carmona et al., 2003; Jung et al., 2000). These batch routes are being translated towards microreactor/flow operation, where intensified mixing and controlled CO_2 mass transfer aim to deliver reproducible supersaturation for polymorph and habit control at scale. Products are characterised by SEM, powder XRD and FTIR, complemented by particle-size distribution, BET specific surface area and porosity, and zeta-potential measurements of suspension stability.

Results

Each route targets a phase with diagnostic signatures: vaterite (XRD ~24.9° 2θ; FTIR $\nu_4 \approx 745$ cm^{-1}; spherical/cauliflower aggregates), aragonite (XRD doublet at ~26.2/27.2° 2θ; FTIR doublet ~700/713 cm^{-1}; needle-like to columnar habit) and calcite (XRD (104) at 29.4° 2θ; FTIR $\nu_4 \approx 712$ cm^{-1}; elongated scalenohedra). Preliminary syntheses confirm phase-selective formation and the expected morphologies; standardisation of each route for reproducible high-purity fractions and for the larger quantities needed to measure physical properties is ongoing (Konopacka-Łyskawa et al., 2019).

Conclusions

A CO_2-based, polymorph-selective precipitation platform that progresses from batch to microreactor operation can deliver tailored vaterite, aragonite and scalenohedral calcite with controlled morphology and surface characteristics. This couples circular CO_2 utilisation with the application-driven development of functional PCC materials.

Keywords: calcium carbonate, CO_2 utilisation, polymorph control, precipitated calcium carbonate, vaterite, aragonite, scalenohedral calcite, microreactor synthesis

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Continuous-Flow Synthesis of Carboxymethyl Dextran-Coated Magnetic Iron Oxide Nanoparticles in a Modular Microreactor

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Magnetic iron oxide nanoparticles (SPIONs) have attracted considerable attention owing to their unique magnetic properties and their wide range of environmental and biomedical applications. Carboxymethyl dextran (CMD) is widely employed as a stabilizing coating because it enhances colloidal stability and provides reactive surface functional groups for further functionalization (Makovec et al., 2015). However, despite extensive research on CMD-coated SPIONs, their production still relies predominantly on batch synthesis. Continuous-flow microreactor technology offers a promising route for the transition from conventional batch synthesis to continuous-flow production of functional magnetic nanoparticles, supporting future process intensification and industrial implementation.

In this work, a modular continuous-flow microreactor platform for the one-step synthesis of CMD-coated SPIONs was successfully developed. The synthesized nanoparticles were characterized using Fourier-transform infrared spectroscopy (FTIR), thermogravimetric analysis (TGA), dynamic light scattering (DLS), zeta potential measurements, transmission electron microscopy (TEM), scanning

electron microscopy (SEM), and vibrating sample magnetometry (VSM). FTIR confirmed the characteristic iron oxide and CMD functional groups, while complementary TGA, DLS, zeta potential, TEM, SEM, and VSM analyses verified successful surface coating, appropriate physicochemical properties, particle morphology, and magnetic properties of the synthesized nanoparticles. Furthermore, the applied redispersion purification procedure effectively removed residual synthesis by-products and improved nanoparticle dispersion.

The developed modular microreactor platform demonstrates the potential of continuous-flow technology for producing functionalized magnetic nanoparticles. Future work will focus on improving microreactor geometry to reduce particle fouling and channel clogging, improve long-term operational stability, and integrate downstream processing, thereby facilitating the transition toward semi-continuous and fully continuous manufacturing of these nanomaterials.

Keywords: continuous-flow microreactor, magnetic iron oxide nanoparticles (SPIONs), carboxymethyl dextran (CMD), process intensification, nanoparticle characterization

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Pretreatment-Enabled Enzymatic Depolymerization of PET Polymer for High-Purity Terephthalic Acid Recovery

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Poly(ethylene terephthalate) (PET) remains a challenging polymer for enzymatic recycling because its semi-crystalline structure, hydrophobic surface, and limited accessible surface area restrict effective enzyme–polymer interactions. In this study, an integrated pretreatment-assisted enzymatic recycling workflow was developed to enhance the depolymerization of solid PET films and enable the recovery of high-purity terephthalic acid (TPA).

Methods

Cleaned and size-reduced PET polymer were subjected to a controlled alkaline surface pretreatment, followed by enzymatic hydrolysis using a commercial PET hydrolase formulation under aqueous conditions. Polymer conversion yield was determined gravimetrically, while changes in chemical structure, surface morphology, and thermal behaviour were evaluated using attenuated total

reflectance Fourier-transform infrared spectroscopy (ATR-FTIR), scanning electron microscopy (SEM), differential scanning calorimetry (DSC), and thermogravimetric analysis (TGA).

Results

Pretreatment-assisted enzymatic hydrolysis achieved approximately 98% gravimetric degradation of the PET films. Microscopic analysis revealed extensive surface erosion, cracking, and cavity formation, while spectroscopic and thermal characterization confirmed substantial modification of the PET matrix. The resulting hydrolysate produced a TPA-rich precipitate, which was subsequently validated using ultraviolet-visible spectroscopy (UV-Vis), high-performance liquid chromatography with ultraviolet detection (HPLC-UV), and proton nuclear magnetic resonance (^{1}H NMR) spectroscopy. HPLC analysis indicated a TPA purity of approximately 97.3%, while UV-Vis and ^{1}H NMR analyses confirmed TPA as the dominant recovered product.

Conclusions

Overall, this study demonstrates that controlled alkaline surface pretreatment can overcome the accessibility limitations of PET, significantly improve enzymatic depolymerization, and facilitate the recovery of high-purity TPA. The main contribution is an integrated recycling strategy combining substrate preparation, enzymatic degradation, monomer isolation, and multi-technique product validation, supporting the development of closed-loop and application-oriented recycling approaches for PET waste.

Keywords: PET recycling, enzymatic hydrolysis, PET, alkaline pretreatment, terephthalic acid, monomer recovery

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Towards Decarbonizing Agri-food Industrial Heat: A Case Study Applied to a Jam Waste Valorization Process

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Emissions mainly derived from fuel combustion constitute a dominant factor driving climate change and global warming (United Nations, 2022). The continuous increase in these gas emissions, in particular carbon dioxide (CO_2), has become one of the most critical challenges of the 21st century, with a direct impact on human health, biodiversity, and global security. In this context, decarbonizing sectors with the highest emission levels is crucial. Among them, the chemical industry is the largest energy consumer and the third subsector with the highest direct emissions (Glavič et al., 2023; IEA, 2023). Most of these emissions stem from utility generation services, such as steam, high-quality heat, or refrigeration, which supply the different processes. Focusing on thermal energy, most heat is currently obtained by direct fuel combustion, specifically natural gas, due to its low cost and availability. Nevertheless, its non-renewable origin and increasing environmental concerns have increased interest in reducing the carbon footprint of industrial heat (Martín, 2025).

This work aims to economically and environmentally compare three heat supply alternatives: i) steam generated by natural gas combustion (Base Case); ii) renewable steam generated by concentrated solar power (CSP) or biomass combustion; and iii) direct electric heat generated using photovoltaic panels, wind turbines, CSP, or

biomass combustion. In the renewable steam and electrified scenarios the same types of biomass are considered: corn stover, wood pellets, olive stones, wood chips and switchgrass. The analysis is applied to a jam waste valorization process, involving phenolic compounds recovery using ethanol, pectin extraction using citric acid and ethanol as a precipitating agent, and on-site ethanol production. Additionally, two final solid treatments are considered: anaerobic digestion (AD) and gasification (GA). The process analysis is based on mass and energy balances, which determine the plant's energy demand and allow for an assessment of how to meet this demand with either renewable steam or electricity. Instead of redesigning the process or incorporating heat integration, the study focuses on substituting conventional heating equipment with electric heating systems or replacing conventional steam with renewable steam while maintaining the original configuration. For each alternative, costs are estimated over 15 years and environmental impacts are evaluated with a life cycle assessment (LCA), considering Global Warming Potential (GWP-100) as the primary indicator.

The results show that CSP-based steam has the highest capital costs, 30-40 times higher than the AD base case and 10-12 times higher than the GA. In contrast, biomass-based steam is economically feasible when low-cost feedstocks like corn stover, wood chips, or switchgrass are used, being the corn stover the most competitive. All electrified scenarios present investment costs substantially higher than natural gas option. From an environmental perspective, nearly all renewable configurations achieved significant emission reductions: 57%-74% for AD and 54-68% for GA when using renewable steam and 20-70% for both under electrified scenarios depending on the electricity source. Across all scenarios, AD consistently outperformed GA.

Overall, renewable steam heating technologies, specifically biomass-based steam, not only provide significant environmental benefits, but are also economically viable, supporting industry progressive decarbonization.

Keywords: renewable steam, electrification process, industrial decarbonization, heat supply, jam waste

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Optimization of Clay-Based Plasters Reinforced with Hemp Shives: Effect of Sand-Clay-Shives Ratio on Mechanical Properties (CHOICE)

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The transition toward sustainable and circular construction materials has become increasingly important in response to growing environmental concerns associated with conventional cement-based building products (Geissdoerfer et al., 2017). Clay-based plasters are recognized as environmentally friendly alternatives due to their low embodied energy, recyclability, vapor permeability, and compatibility with natural reinforcement materials (Melià et al., 2014). Among bio-based aggregates, hemp shives have gained significant attention because of their lightweight structure, thermal insulation capacity, carbon sequestration potential, and contribution to indoor hygrothermal regulation (Walker et al., 2014). However, the incorporation of hemp shives can considerably influence the mechanical and physical behaviour of clay plasters depending on the proportion of clay, sand, and bio-aggregate within the mixture (Busbridge et al., 2019). Therefore, this study investigates the optimization of clay-based plasters reinforced with hemp shives by evaluating the influence of sand–clay–shives ratios on the mechanical properties and water absorption

behaviour of the developed composites within the framework of the CHOICE project.

The industrial MKG clay from Termit Moravče, Slovenia, and locally sourced hemp shives were used in this research. The experimental program focuses on optimizing the sand–clay–shives (S–C–Sh) ratio to improve the balance between mechanical strength, dimensional stability, and performance of wall plasters. Hemp shives were incorporated as natural reinforcement and lightweight bio-aggregate to reduce density and minimize shrinkage cracking, like approaches reported in previous bio-based material studies (Laborel-Préneron et al., 2018).

Various substrates, like Oriented Stand Board (OSB), Gypsum board, Clay-board and ceiling bricks like were tested for their compatibility with clay layer, for what 10mm of clay-based plaster was applied onto them and cured under controlled laboratory conditions of 20°C and 55% RH prior to further testing. Mechanical characterization included compressive strength, flexural strength, density measurements, and visual crack assessment. In addition, surface water absorption behaviour was evaluated using Karsten tube measurements on different substrates. The influence of hemp shive incorporation on capillary water uptake and surface durability is also analysed. The experimental results demonstrated the flexural strength of conventional plaster 1 MPa, while plaster with shives of 1.5% reached 1.75-1.86 MPa. Water absorption ranged from 0.5 kg/m² for brick, indicating the lowest absorption, to 7.2 kg/m² for plastered clay board, showing the highest absorption; plastered OSB exhibited moderate absorption of 3–5 kg/m², while plastered gypsum board absorbed 6.14 kg/m².

The addition of hemp shives enhanced ductility and contributed to better shrinkage control due to the porous and fibrous nature of the material (Arizzi and Cultrone, 2012). However, excessive hemp shives incorporation resulted in reduced compressive strength because of increased porosity and weaker interfacial bonding between the clay matrix and the bio aggregate. The inclusion of sand improved particle packing density, dimensional stability, and overall mechanical resistance. Karsten tube measurements indicated that optimized plaster compositions maintained low water absorption rates while preserving vapor permeability characteristics desirable for sustainable building envelopes. Among the tested formulations MKG Clay of 55%, Sand 42% along with shives of 2-3% reported the better mix and mechanical outcomes. The findings confirm that hemp shive-

reinforced clay plasters can serve as sustainable and low-carbon alternatives to conventional interior plaster systems.

Keywords: MKG clay, hemp shives, plasters, substrate mechanical properties

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Environmental Assessment of Biobased Products Exposed to Different pH Conditions

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The AshCycle project (2022–2026), funded by the Horizon Europe initiative, focuses on developing innovative solutions for the valorisation of ash residues generated from municipal solid waste, biomass, and sewage sludge incineration. Rather than treating these ash streams as waste, the project aims to recover valuable resources and transform them into sustainable products for applications in sectors such as construction and water treatment.

A key objective of AshCycle is to demonstrate the technical performance and environmental sustainability of products manufactured from recovered ash-derived materials. To support their safe implementation, several pilot products have been developed and tested under different environmental conditions. As these materials may be exposed to a wide range of pH environments during their service life, it is important to evaluate their stability, durability, and potential environmental impacts.

As part of the environmental assessment, selected pilot products were subjected to leaching tests under various pH conditions to investigate the potential release of contaminants. Samples from Croatia, the Netherlands, Finland, Denmark and Slovenia, were included in the study. The leachates were analysed for toxic trace elements to assess the environmental behaviour of the materials and their suitability for long-term use. The results show that for most investigated elements, significantly higher concentrations are released at lower pH values than at higher pH conditions. This finding is particularly relevant in real environmental exposure scenarios, as materials may be subjected to acidic deposition, including acid rain, which can increase the mobility and leaching of potentially toxic elements.

These results provide valuable information on the performance of ash-derived products under adverse conditions and contribute to the development of safe and sustainable circular economy solutions.

Keywords: bio-based ashes, pilot products, leaching, envirnmental assesment, recycling

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Consumer Decision-Making in the Circular Bioeconomy: Evidence from a Multi-Country Discrete Choice Experiment

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At the heart of sustainable development lies a fundamental paradox: improving access to essential goods such as food, energy, and water while simultaneously reducing environmental pressures. Addressing this requires both a reduction in the disproportionately high footprint (issue pertinent in particular in high-income countries) and a decrease in the resource intensity of consumption overall. This dual objective can only be achieved through a combination of technological innovation, behavioural change, and greater consideration of long-term impacts in decision-making (Meadows et al., 2004).

The circular economy and the bioeconomy offer a complementary pathway to address this challenge. The bioeconomy focuses on replacing fossil resources with renewable biological inputs and valorising biomass and waste streams (Gaffey et al., 2021), while the circular economy promotes the prolonged use of materials through reuse, recycling, and closed-loop systems. Together, as the circular bioeconomy, they

contribute to lowering the environmental footprint of consumption while maintaining or enhancing value creation (Fasolino et al., 2025).

These approaches are embedded in global and European policy frameworks. The United Nations' 2030 Agenda highlights responsible consumption and production (SDG 12) as a key priority (United Nations, 2015), while the European Green Deal operationalises this ambition through initiatives such as the Circular Economy Action Plan and the EU Bioeconomy Strategy (European Commission, 2019).

However, policy and technology alone are insufficient. Effective implementation depends on consumers–their values, habits, and willingness to adopt circular bio-based products, prefer them over conventional alternatives, pay a "green premium," and engage in behaviours that help close material loops (Russo et al., 2019; Gaffey et al., 2021; Wensing et al., 2021; Wensing et al., 2025). Ultimately, the uptake of these products hinges on whether consumers understand, trust, and select them in practice. Identifying the factors that shape such decisions is therefore essential for advancing more sustainable consumption and production patterns and provides the core motivation for this study.

The study follows a mixed-methods research design comprising six stages: a literature review and secondary research; interviews with experts, stakeholders, and consumers; focus groups to validate product attributes, informational nudges, terminology, and pilot cases; selection of attributes and interventions; design, pilot testing, and online implementation of the survey questionnaire; and statistical analysis of willingness to pay (WTP), attribute importance, and consumer preferences. To approximate real-world decision-making, the empirical analysis focuses on business-to-consumer (B2C) products that reflect everyday purchasing contexts. Consumer preferences are examined across three product categories: a fashion accessory made from a biopolymer (representing bio-based materials), a biostimulant for hobby gardening (representing plant nutrients), and dietary fibre (representing upcycled food products). This selection captures diverse application domains of the circular bioeconomy while maintaining a consistent focus on final consumer choice. The core research instrument is a two-layer discrete choice experiment (DCE), which assesses consumer preferences, attribute trade-offs, and WTP (Layer 1), while measuring the effects of informational nudges and Digital Product Passport information on product choices and consumer engagement (Layer 2). The research is conducted in Slovenia, Greece, Italy, and Lithuania.

The study aims to improve understanding of how consumers evaluate circular bio-based products and how different forms of information influence their choices. By identifying key product attributes, preference structures, and the effects of informational interventions, the findings provide an empirical basis for the design of more effective consumer-facing tools. In particular, the results will directly inform the development of the ARGONAUT AI- and blockchain-based digital solution (JASON), supporting the creation of Digital Product Passports that enhance transparency, build trust, and guide consumer decision-making. In this way, the study contributes to the development of data-driven strategies for increasing consumer engagement and enabling more informed, responsible, and sustainable consumption.

Keywords: circular bioeconomy, bio-based products, consumer preferences, discrete choice experiment, informational nudges, digital product passport

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Unlocking Underutilized Woody Biomass: Extractives of Damaged and Bark Beetle-Attacked Norway Spruce Trees

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In recent years, natural disturbances alongside windstorms and bark beetle outbreaks have severely degraded forest ecosystems, reducing both the quality and commercial utilization of wood. Consequently, bark beetle-attacked trees and dead woody biomass represent an important yet underutilized raw material of extractives. The aim of this study was to determinate the content of extractives within the specific tissues of Norway spruce (*Picea abies* (L.) Karst.) trees following bark beetle (*Ips spp.*) attacks and in trees damaged in a major windstorm in 2017, in comparison to healthy trees. The sampling was done in the Plešivška kopa and Plešivec regions in 2021 and 2022. After harvesting, 3-5 discs were dissected along each stem at different heights in order to obtain samples of sapwood, heartwood, knotwood, and bark. The samples were extracted via Accelerated Solvent Extraction (ASE), using cyclohexane and acetone/water mixture (95/5, v/v). The content of lipophilic and hydrophilic extractives was determined gravimetrically, while the UV-Vis spectrophotometry was used for determination of total phenols and proanthocyanidins. Results showed that the contents of hydrophilic extractives were the highest in knots across all investigated groups of trees, followed by bark, sapwood, and heartwood. The highest contents of lipophilic extractives were in the bark, followed by knots and sapwood,

and the lowest in the heartwood. Total phenolic content was the highest in the knotwood (87.53 mg/g, 71.67 mg/g, and 71.43 mg/g), whereas the bark was highly enriched with proanthocyanidins.

The study confirms that this underutilized and underappreciated woody biomass represents a valuable raw material of extractives recovery. The possibility of integrating such feedstock into biorefining pathways can increase the optimization for sustainable forest utilization and recover value of low-quality wood.

Keywords: *Picea abies* (L.) Karst., Norway spruce, natural disturbances, bark beetle, dead woody biomass, extractives, wood, bark, biorefinery, circular bioeconomy

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Polysaccharide-Functionalized Magnetic Nanoparticles for the Removal of Strategic Metals from Printed Circuit Boards

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Strategic metals, including copper, are essential raw materials for modern industry, particularly for producing electronic and electrical devices. Because primary resources are limited and demand for these metals is increasing, recovering them from secondary sources, such as electronic and electrical waste, has become an important research priority. In this context, magnetic nanohydrometallurgy represents a promising approach, combining hydrometallurgical principles with nanotechnology through the use of functionalized magnetic nanoparticles for selective metal ion adsorption.

In this work, magnetic iron oxide nanoparticles were functionalized with λ-carrageenan, a natural polysaccharide containing sulfonic groups, and evaluated as nanoadsorbents for the removal of the strategic metal Cu^{2+} from aqueous media. The sulfonic groups of λ-carrageenan served as active adsorption sites for metal-ion binding. The morphology and particle size were determined by transmission electron microscopy, while surface chemistry and colloidal properties were investigated using

attenuated total reflectance Fourier-transform infrared spectroscopy, electrokinetic measurements, and dynamic light scattering. The fraction of organic coating was determined by thermogravimetric analysis. Magnetic properties were evaluated using vibrating sample magnetometry.

The developed λ-carrageenan-coated magnetic nanoparticles showed strong potential for Cu^{2+} removal. The effects of adsorbent dosage, solution pH, initial Cu^{2+} concentration, and contact time on adsorption efficiency were systematically investigated. Copper concentrations were determined using a colorimetric photometric method. Under optimal conditions, $\gamma(Cu^{2+}) = 1.3$ mg L^{-1}, $V = 20$ mL, pH = 6, $T = 298$ K, 20 mg of nanoadsorbent, and a contact time of 2 h, a Cu^{2+} removal efficiency of 84.6% was achieved. The designed nanoadsorbent was also applied for metal removal from printed circuit boards from waste mobile phones.

These results demonstrate that λ-carrageenan-functionalized magnetic nanoparticles are promising, sustainable nanoadsorbents for strategic metal recovery from secondary sources, including printed circuit boards from discarded mobile phones.

Keywords: nanoadsorbent, λ-carrageenan, strategic metals, magnetic nanohydrometallury, e-waste recycling.

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CarbNETs: CO_2 Capture, Thermal Energy Management, and Electrification Using Net-Zero Industrial Technologies for Decarbonisation

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Decarbonising hard-to-abate industrial sectors requires integrated technological solutions that reach beyond single-process emission reduction and address entire carbon, heat, water and material flows. CarbNETs is a Slovenian flagship research and development programme that deals with CO_2 capture, thermal energy management and electrification using net-zero industrial technologies for decarbonisation. It was designed to accelerate transition from fossil-based industrial systems toward circular, electrified and climate-neutral value chains. The programme connects leading research organisations and industrial partners from emission-intensive sectors, including cement, glass, metals, papermaking, chemicals, advanced materials, mobility, biotechnology and waste management.

CarbNETs is structured around five interconnected pillars: (i) advanced CO_2 capture, (ii) CO_2 conversion to green platform chemicals, (iii) carbon-smart materials from secondary streams, (iv) circular management of waste heat and water, (v) and techno-economic and life-cycle-based process development. The programme will develop technologies from TRL 3 to TRL 6, including upgraded hot potassium carbonate absorption, electroswing adsorption, membrane-based CO_2 separation, magnetically heated catalytic reactors, direct electrochemical and photocatalytic CO_2 capture, bio-based sorbents, mineral carbonation, waste heat recovery systems and circular water reuse modules.

The programme targets to improve the performance of industrially relevant processes, including high-efficiency CO_2 capture, rapid sorbent regeneration, production of high added value mineral/organic products from CO_2, dynamic CO_2 conversion compatible with renewable electricity, and recovery of low-grade industrial waste heat. CarbNETs aims to achieve at least 30% waste heat recovery, reduce energy demand for sorbent regeneration by at least 25%, improve process efficiency by at least 15%, and demonstrate measurable CO_2 emission reductions and utilisation through integrated heat utilisation. In parallel, captured CO_2 and secondary raw materials will be converted into value-added products such as green chemicals, biochar, graphene, mineral carbonates and bio-based thermoplastic composites, as well as assessing the potential of obtaining advanced materials from industrial wastewaters.

By combining CO_2 capture, utilisation, electrification, thermal energy management and circular material flows, CarbNETs provides a unique cross-sectoral platform for industrial decarbonisation. Its integrated approach supports the European Green Deal, Fit for 55, the circular economy transition and the development of scalable net-zero industrial technologies. The expected outcomes will include new pilot-scale technologies, circular business models, strengthened science-industry collaboration and practical pathways for reducing emissions in sectors where decarbonisation remains technically and economically challenging.

Keywords: CO_2 capture, industrial decarbonisation, thermal energy management, electrification, carbon utilisation, circular economy, net-zero technologies

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PeCATHS: A Sustainable Way to Store Hydrogen

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Present technology to obtain green hydrogen is based on water splitting through electrolysis using green energy sources or photo-electrocatalysis. However, the cost of producing green H_2 from water electrolysis is high compared to traditional methods, mainly due to the cost of electricity and catalysts. This is why, over 90% of Europe's H_2 production is derived from natural gas, with a cost of 1-2 €/kg compared to 2.7-8.8 €/kg for green H_2 (World Energy Council, 2021).

When using catalysts based on earth-abundant materials, the oxygen evolution reaction (OER) poses significant challenges, with high overpotentials and sluggish kinetics and currently constitutes the bottleneck limiting global H_2 production from water splitting (Suen et al., 2016). Furthermore, OER generates low-price oxygen (O_2) as a by-product, which hinders competitiveness. This makes the forecast for the price of green H_2 very slow in reaching similar prices to present conventional technologies, which is estimated to occur by 2050 according to PWC (PWC, 2022).

That is too late for the urgent need of transforming the energy system to stop climate change.

To ease the transition to a CO_2-free society through green H_2, it is crucial to create cost-effective and highly efficient catalytic (photo)electrodes, to explore alternatives to OER and develop efficient ways for H_2 storage. Our approach in PeCATHS aims to develop an integrated long-term energy storage system utilizing hydrogen in the form of liquid organic hydrogen carriers (LOHCs), coupled with innovative biomass conversion.

This approach enables the direct transfer of hydrogen from biomass to LOHCs in the cathode without the need of hydrogen gas production, while simultaneously generating high-value chemicals at the anode. By integrating chemical and energy sectors, the project aims to synthesize platform chemicals and achieve long-term energy storage in liquid form, enhancing both the sustainability and efficiency of energy systems (Solera-Rojas et al., 2025).

The direct storage into a stable liquid energy carrier significantly facilitates the storage, transport and distribution, while the combined use of renewable power and biomass as simultaneous source of hydrogen and platform chemicals provides the opportunity to successfully solve the economic and sustainability challenges associated with green H_2 production and storage and eases the transition to CO_2-free chemical industry.

In this work we will present some of the latest results of PeCATHS consortium in the implementation of this cost-effective strategy.

Keywords: green H_2, H_2 storage, LOCHs, electrocatalysis, photoelectrocatalysis, green platform chemicals

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Assessment of the Economic Feasibility and Environmental Sustainability of Acid Whey Valorization With Ultrafiltration

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This study presents results obtained within the Interreg Italy–Slovenia project Dairy+, which focuses on the development of shared circular bioeconomy approaches for the valorisation of dairy by-products in transboundary regions. The project addresses both the territorial dimension–covering border areas between Slovenia (Upper Soča Valley) and Italy (regions Friuli Venezia Giulia and Veneto)– and the thematic challenge of improving sustainability and resource efficiency in the dairy sector through circular use of by-products.

The study areas differ significantly in scale and production structure. On the Italian side, the project covers 52 municipalities with an estimated annual production of approximately 240 million kg of milk, while the Slovenian area includes four municipalities characterised by smaller-scale, dispersed production systems with an estimated output of about 9 million kg of milk (Posoški razvojni center et al., 2024). Cheese production is strongly represented in both regions, making acid whey the

most promising by-product for valorisation. Among various valorisation pathways, the project focused on ultrafiltration and the integration of whey protein concentrate (WPC35) into fresh dairy products such as yoghurt and cheese spreads. While the larger quantities on the Italian side enable the development of scalable solutions, the dispersed production and smaller volumes on the Slovenian side require alternative, small-scale approaches. Accordingly, this contribution presents a prototype of a small-scale ultrafiltration unit designed for operation at the single-farm level.

Five whey samples, originated from cheese production in the project regions were analysed in order to assess dry matter and protein content. Tests were performed on the pilot ultrafiltration unit (Osmosys Lab), showed stable processing across a wide pH range, with a volume yield calculated from the measured initial volumes of whey and the volumes of whey concentrate obtained between 11.6% and 24.8% (Università degli Studi di Udine et al., 2025). The protein fraction in dry matter ranges from 30.9% to 41.5% with respective average of 36.8%, supporting the working assumption of 35% WPC (Whey Protein Concentrate) in the techno-economic model.

The techno-economic analysis was developed for a model Slovenian farm with 1.000 litres of milk production daily, processed in yogurt, cream, cheese spreads, semi-hard cheese, quark, ricotta and pasteurized milk. All of the whey produced as a by-product from cheese, was valorized via ultrafiltration into WPC and incorporated into yogurts and cheese spreads with the aim to increase its protein content and market value. The main focus for decision-making is on own-cost calculation, where it determines whether ultrafiltration can be economically viable for a small on-farm processing system. Table 1 presents the own-price calculations for on-farm dairy products, while own price for 35% WPC obtained from farm-based cheese production are estimated at 0.74 €/kg. Taking into account that fresh dairy products, such as yoghurt and cheese spread can be augmented by up to 20% of WPC 35, whey ultrafiltration can be a profitable alternative, especially when combined with premium product positioning related to high-protein content.

Table 1: Own-price calculation for milk-processing on a farm level.

Processing program	yoghurt	cheese spread	semi-hard cheese	cottage cheese	ricotta	milk
Own price (€/kg)	2,02	3,36	8,06	2,62	2,02	0,67

At the same time, this approach eliminates whey waste and transforms it into a functional, high-quality ingredient rich in proteins. In conclusion, whey ultrafiltration is technically robust and economically feasible for small-farm processing. It enables the conversion of low-value by-products into a functional protein ingredient for premium dairy products. Model calculations show that cost performance is most favourable when WPC is integrated into yoghurts and cheese spreads, thereby improving product macronutrients and added value, while reducing whey disposal and supporting circular resource use.

The presented results represent an intermediate stage of ongoing research within the Dairy+ project. Further work will extend the current analysis by incorporating a detailed assessment of the economic feasibility of investing in a whey ultrafiltration processing unit, including capital and operational cost considerations at farm level. In addition, the study will be complemented by an evaluation of the environmental performance of the proposed solution, focusing on avoided impacts associated with improved acid whey management. This assessment will be conducted in accordance with life cycle assessment (LCA) methodology. The extended results will be presented at the conference and detailed in the forthcoming full paper.

Keywords: acid whey, ultrafiltration, techno-economic analysis, life cycle assessment, circular bioeconomy, resource efficiency

Acknowledgement

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Maize Cobs as Circular Bio-Resources: Quality and End-of-Waste Perspectives

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The transition to a circular economy requires coordinated approaches for the sustainable valorisation of agricultural biomass, ensuring environmental safety, product quality and regulatory compliance. One of the main challenges in utilisation is its legal classification as a by-product or as a material that has achieved End-of-Waste status, depending on specific requirements (Delgado Sancho L. et al., 2009). "By-products" can enter further utilisation without becoming waste when the relevant regulatory conditions are met, while "End-of-Waste" applies when materials have undergone recovery operations and satisfy defined criteria for losing their waste status. According to the EU Waste Framework Directive, End-of-Waste criteria are supported by technical requirements related to the quality of input materials, treatment processes, product specifications, quality management systems and information provided to producers and end users (Delgado Sancho L. et al., 2009; Directive 2008/98/EC).

Maize cobs represent an abundant lignocellulosic residue with significant potential for valorisation and application for different purposes (Fu et al., 2022). In addition to conventional energy applications, maize cobs can be used for the production of animal bedding, insulation materials, bio-based composites and other bio-based products (Jansen et al., 2012; Fu et al., 2022). However, the successful integration of such biomass streams from agriculture into circular value chains requires a clear

understanding of their regulatory status and quality requirements (Delgado Sancho L. et al., 2009).

This contribution explores the relationship between the concepts of "by-product" and "End-of-Waste", using maize cobs as a case study. A quality assurance framework is proposed, integrating five key elements: (i) quality of the recovered product and/or extracted molecular components, (ii) environmental and health safety of the input material, (iii) technological processes and treatments, (iv) process quality management and (v) traceability and information transfer throughout the value chain. These elements provide the technical foundation for demonstrating compliance with End-of-Waste requirements and for increasing confidence in secondary raw materials. The aim of the proposed approach is to show how common quality principles and requirements within the framework of "by-product" and "End-of-Waste" pathways can enable the transformation of agricultural residues into safe, valuable and market accepted secondary raw materials.

Keywords: circular economy, End-of-Waste, by-product, agricultural biomass, maize cobs, biomass valorisation, quality assurance, secondary raw materials

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Optimization of Red Gypsum Granulation and Stabilization for Sustainable Construction

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Red gypsum (RG), generated as a by-product during TiO_2 production, represents a significant industrial waste stream with considerable potential for valorization in sustainable construction materials. This study investigates the minimal and most suitable pre-treatment procedures for successful granulation of red gypsum and evaluates the influence of key process parameters on granule morphology, stability and potential industrial applicability. Three different input forms of RG were considered: filter cake, suspension and dry powder. Particular attention was given to the influence of moisture content, particle preparation, granulation conditions and stabilization approaches.

Granulation experiments were performed using an Eirich EL1 laboratory granulator by systematically varying rotational speed (1000–7000 rpm) and granulation time (30–180 s).

Besides direct granulation, the study also investigated stabilization and crosslinking approaches intended to reduce sulfate leaching and improve the environmental suitability of the material. Red gypsum contains significant amounts of sulfates, which may dissolve and leach when exposed to water, representing one of the major limitations for its wider use in construction applications. For this reason, different stabilization strategies were evaluated in order to chemically and physically immobilize the material within more stable granular structures. Different forms of RG (filter cake, powder and suspension) were combined with various binders, primarily lime and cement, while the influence of water addition and mixing conditions on granule formation was systematically investigated.

Results showed that both rotational speed and granulation time strongly affect granule formation. Lower speeds and longer mixing times resulted in formation of large plastic agglomerates, while shorter processing times enabled formation of individual granules. The most suitable conditions were identified at 7000 rpm and 30 s, where stable granules with sizes around 2 mm were obtained. Additional fluid-bed drying improved granule sphericity and reduced particle size.

Granules were further analyzed using ImageJ image analysis software to quantitatively determine morphological parameters including particle area, circularity, aspect ratio, roundness and solidity. The obtained results confirmed the trends observed during visual evaluation. Higher rotational speeds enabled formation of more compact and spherical granules, while excessive mixing times negatively affected granule morphology.

A preliminary analysis of potential applications indicated possible use of RG granules in concrete plants, asphalt production facilities, earthworks and aggregate manufacturing. Assuming approximately 5% replacement of conventional aggregate or filling material, larger concrete or asphalt plants could potentially consume between 10 and 50 tons of granules per day, with even higher demand possible in major infrastructure projects. However, further optimization and validation are still required to ensure compliance with mechanical, physical, chemical and environmental requirements, particularly regarding sulfate leaching and long-term material stability.

Keywords: red gypsum, granulation, waste product, sustainable material, construction industry

Geotechnical Characterization of Red Gypsum

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Red gypsum is a fine-grained calcium sulfate-rich by-product generated during the sulfate process of TiO_2 production. With hundreds of thousands of tonnes per year produced annually across Europe, its responsible management represents both an environmental challenge and an opportunity for circular economy-oriented material valorisation. Redirecting such industrial by-products toward construction applications can significantly reduce landfill dependency and lower the environmental footprint of earthworks and infrastructure projects. Despite its production in large quantities at Cinkarna Celje d.d., the geotechnical potential of red gypsum remains largely unexplored. This study presents a comprehensive geotechnical characterization of red gypsum produced at Cinkarna Celje d.d. and evaluates its suitability as a secondary construction material for earthworks and embankment applications.

A full geomechanical laboratory testing program was carried out on samples in their natural state, covering consistency limits, compaction characteristics, shear strength, compressibility, and hydraulic conductivity. The material was classified as a medium to highly plastic silt to clay (MH-CH) with a natural moisture content of 40.78% and a dry density of only 1.11 Mg/m³, reflecting a loose, porous structure. Notably, the

optimum moisture content determined by the Standard Proctor test was 33.52%, with a maximum dry density of 1.212 Mg/m³, indicating that significant improvement in density and mechanical performance is achievable through controlled compaction at reduced moisture levels.

Shear strength parameters were favorable for a fine-grained material, with a friction angle of $\varphi = 35.2°$ and cohesion of $c = 14.4$ kPa, suggesting adequate resistance to shear deformation and acceptable slope stability at moderate inclinations. Compressibility moduli ranged from 2,100 kPa at low stress levels to 9,300 kPa at intermediate stresses, indicating stress-dependent stiffening behavior typical of structured fine-grained materials. The measured hydraulic conductivity of $k = 1.17 \times 10^{-6}$ m/s places the material in the medium to low permeability range, warranting careful consideration of drainage conditions in any proposed application.

Overall, the findings suggest that red gypsum holds genuine potential as a secondary construction material, particularly in earthworks, provided that moisture content is managed prior to placement. Further testing under optimum compaction conditions, including CBR and unconfined compressive strength, is recommended to support practical application guidelines.

Keywords: red gypsum, geotechnical characterization, waste valorization, earthworks, circular economy

Hydrothermal Conversion of Waste Cigarette Filters

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The use of tobacco and tobacco products is continually increasing worldwide, resulting in cigarette filters becoming an ever-growing problem for municipal waste. Each year, between 4.5 and 5 trillion cigarette filters end up in the environment (Novotny and Slaughter, 2014). Despite their small size, they are extremely complex and problematic for the environment, as they consist of filters made of cellulose acetate (a polymer material that is difficult to biodegrade) and numerous other hazardous chemical compounds. The most dangerous of these compounds are nicotine, heavy metals, and polycyclic aromatic hydrocarbons. These chemicals are released during smoking and, when improperly discarded, leach into soil and water, posing risks to both aquatic and terrestrial life (De Fenzo et al., 2020). Current waste management methods, such as landfilling and incineration, contribute to environmental pollution through groundwater contamination and emissions from incomplete combustion. However, this waste also contains numerous compounds with significant potential for conversion into value-added products through advanced chemical recycling.

This study investigated the sustainable recycling of cigarette filters using hydrothermal processes, which offer a green alternative to conventional incineration. Experiments were conducted in a high-pressure, high-temperature batch reactor at reaction temperatures of 350, 400, and 450 °C, and reaction times of 15, 30, and 60 min. The resulting gas and oil products were analysed by gas

chromatography-mass spectrometry. The higher heating value (HHV) of the oil was determined using a bomb calorimeter.

The results show that temperature and reaction time significantly influenced hydrothermal decomposition and product distribution, with the oil phase predominating under all conditions. The highest yield of oil phase (67.8%) was obtained at 350 °C and 60 min, attributed to more efficient decomposition of cigarette filter components into smaller organic compounds that contribute to oil formation. The results indicate that increasingly severe reaction conditions reduce the yield of the oil phase to 38.4% at 450 °C and 60 min. In contrast, the yield of the gas phase gradually increases, with the lowest value obtained under the mildest conditions (3.4% at 350 °C, 15 min) and the highest (39.3% at 450 °C, 60 min) under the most severe conditions, where the gas phase was rich in light hydrocarbons. The resulting oil contained a high concentration of organic compounds (ketones, aromatics, hydrocarbons). The highest HHV was observed at 400 °C and 30 min (24.73 MJ/kg), exceeding the heating value of the raw material (17.12 MJ/kg). The study demonstrates the potential of hydrothermal processing of cigarette filters to produce secondary raw materials and energy-rich fuels.

Keywords: cigarette filters, tobacco waste, sub- and supercritical water, recycling, hidrothermal conversion

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Integrating High-Fidelity Process Models into Circular Supply Chain Superstructures via Neural Networks

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The transition to a low-carbon and circular economy requires the development of sustainable supply chains that enable the efficient use of renewable resources and their conversion into high-value chemicals. Due to the large number of available technologies and their interconnections, planning such supply chains is a complex optimization problem.

A superstructure approach is commonly employed, in which all feasible process technologies and their material and energy interconnections are incorporated into a single mathematical model. The optimization simultaneously determines the selection of process technologies, material and energy flows, and their interconnections, giving rise to large-scale mixed-integer nonlinear programming (MINLP) problems (Ryu et al., 2019; Mencarelli et al., 2020). Although individual processes can be accurately described using rigorous simulation models (e.g., Aspen Plus), their direct incorporation into the superstructure optimization framework is impractical due to increased computational demand and numerical instabilities caused by the need for repeated exogenous model evaluations during optimization (Caballero et al., 2007). Consequently, in existing supply chain optimization approaches (Potrč et al., 2022; Dautel et al., 2024), individual process technologies are typically described using simplified linear input-output models. Although such approximations reduce the computational complexity, they may fail to capture the

complex behavior of processes, which often limits the accuracy and reliability of optimization results.

To overcome these problems, we propose a methodology in which individual process systems are represented by physically consistent surrogate models embedded directly in the mathematical superstructure optimization model. Physics-informed KKT-hPINN neural networks (Chen et al., 2024), trained on datasets obtained from rigorous Aspen Plus simulations, were chosen as surrogate models. The proposed methodology offers a promising, flexible framework for incorporating high-fidelity process models into the mathematical programming framework.

Keywords: supply chains, mathematical programming, process simulation, neural networks, circular economy

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Developing a Surrogate Reactor Network Model for Sewage Sludge Gasification and a Reduced Kinetic Mechanism for CFD Use

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Accurate simulation of sewage sludge gasification in rotary kilns requires a model that can represent both the heterogeneous biochemical structure of the feedstock and the coupled gas-phase, tar and char conversion chemistry. This work presents a surrogate reactor network model and a reduced kinetic mechanism implemented in Aspen Plus V15.0 for this purpose. The sludge is represented by biochemical macromolecule pseudo-components, including proteins, cellulose, hemicellulose, lignin and lipids. Their devolatilization is described through four cascaded RStoic reactors following the surrogate strategy of Netzer et al. (2023), allowing tar precursors, nitrogen-containing species and char-forming fractions to be retained explicitly. Downstream gasification is represented by two isothermal RPlug reactors: a short oxidation zone and a longer reduction zone. For these zones, the detailed Ranzi-type thermochemical network containing more than 3,200 reactions is reduced to 104 power-law Arrhenius reactions covering heterogeneous char combustion, gas-phase oxidation, water-gas shift, tar and methane reforming, methanation and char gasification. The model is validated against four bench-scale rotary kiln experiments from Freda et al. (2018), covering equivalence ratios of 0.05-0.24 and temperatures of 750-850 °C. Predicted dry N_2 free syngas compositions reproduce the main H_2, CO, CO_2 and CH_4 trends, with mean absolute errors of 1.9-5.2 percentage points.

The model also captures key performance trends: tar yield decreases by approximately 65% as equivalence ratio increases, carbon and nitrogen balances close within about +/-0.1% and <1%, respectively, and cold gas efficiency peaks at 65% at ER = 0.16, increasing to 83% when tar and residual char energy are included. The resulting framework provides a physically interpretable, computationally tractable Aspen Plus model and a CFD-ready reduced kinetic basis for future rotary kiln gasification simulations.

Keywords: gasification, surrogate modeling, chemistry reduction, waste valorization, sewage sludge

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Sustainable and Intelligent: Shaping the Future of the Global Packaging Market

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The global packaging industry is undergoing a profound transformation driven by the twin imperatives of ecological sustainability and digital integration. Once regarded purely as passive containment systems, modern packaging solutions are evolving into highly functional, interactive and environmentally responsible formats. This paper provides a comprehensive analysis of the current state and future trajectories of the global smart packaging market, examining the convergence of active, intelligent and sustainable technologies over the next decade.

Through a systematic evaluation of market data, technological developments, and regulatory frameworks, we chart the growth of key segments, including indicators, sensors, and interactive carriers (e.g. RFID and NFC), alongside active functional agents. We pay particular attention to how the incorporation of advanced bio-based materials, nanotechnologies, and eco-friendly coatings is resolving the historic tension between high-tech electronic functionality and circular economy requirements. We highlight emerging innovations, such as biodegradable sensors, bio-sourced barrier coatings, and intelligent functionalisation, that enable real-time freshness monitoring, active preservation, and brand protection without compromising recyclability or adding toxic waste to the environment.

Furthermore, we present updated market forecasts that identify key regional growth drivers, emerging sector opportunities in pharmaceuticals and food logistics, and critical barriers to widespread commercial adoption. Our analysis demonstrates that the future of the packaging sector lies in integrated solutions where "green" and "smart" are not competing paradigms but mutually reinforcing design criteria. By bridging the gap between advanced materials science and global market dynamics, this study offers a strategic roadmap for researchers, manufacturers and policymakers navigating the next era of intelligent circular packaging.

Keywords: smart packaging, intelligent packaging, sustainable materials, market forecast, circular economy

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Assessment of Thermal Degradation Effects on Dielectric Performance of Electrical Insulation Materials

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Electrical cables are indispensable components of modern infrastructure and are widely used in buildings, industrial facilities, transportation systems, and electrical equipment. Their reliable operation is essential not only for ensuring the safe and continuous supply of electrical energy but also for extending service life and supporting sustainable use of electrical infrastructure. However, electrical cables are also recognised as one of the potential sources of electrical fires, particularly when insulation degradation leads to overheating, electrical faults, or short circuits (Anghelescu et al., 2025; Shea, 2011).

During service, cable insulation is continuously exposed to thermal stresses arising from electrical loading, environmental conditions, and localised overheating. Although appropriate cable design and installation facilitate heat dissipation, thermal exposure cannot be avoided. Over time, elevated temperatures accelerate the degradation of insulation materials, i.e., cause faster ageing of the insulation, resulting in gradual deterioration of their dielectric properties and overall performance.

Understanding the effects of thermal exposure is therefore essential for assessing the current condition of electrical insulation, predicting its long-term behaviour, and estimating the remaining service life of cables. Namely, reliable ageing assessment

supports preventive maintenance strategies and enables timely replacement before the risk of insulation failure increases significantly, while also contributing to more sustainable asset management by avoiding unnecessary replacement of serviceable cables.

Therefore, in this study, several conventional electrical insulation materials were assessed: (i) transparent colourless polyvinyl chloride (PVC), (ii) non-transparent red PVC, and (iii) transparent colourless silicone. The materials had different initial dielectric properties, all lower than desired for practical electrical insulation applications. Electrical insulation-weaker materials were deliberately selected to enhance the detectability of ageing-induced changes during thermal exposure.

Samples, prepared as 3-mm-thick slabs measuring 10×10 cm^2, were kept under room conditions and used as reference. When exposed to elevated temperatures, slabs were placed into a preheated drying chamber for 20 minutes, after which they were cooled under room conditions. The first elevated temperature was 50 °C, which was increased in steps of 50 °C or smaller up to 350 °C.

Insulation performance of samples was evaluated by measuring: (i) dielectric frequency response (DFR; frequency domain spectroscopy, FDS; instrument Megger IDAX with booster VAX, at voltages of 500 and 1000 V RMS, in frequency range of 0.5 mHz to 1 kHz, under room conditions, using standard test cell for hard dielectric materials described in the standard IEC 60893-2) and (ii) partial discharge (PD; instrument Haefely DDX 9160 / DDX 9121b at voltage 1000 V RMS, frequency 50 Hz, under room conditions, in air and oil, using standard IEC 60270).

Based on FDS and PD measurements, the temperature at which a clear deterioration of electrical insulation performance (T_d) was determined for investigated materials. Samples of the respective materials were subsequently exposed to the corresponding T_d for different durations, using time intervals of 5 min or shorter, to determine the rate and mathematical model of ageing-induced degradation.

The results obtained for the selected materials demonstrate that increasing the exposure temperature above T_d and extending the exposure duration both accelerate the degradation of electrical insulation performance.

Keywords: electrical cables, electrical insulation, thermal degradation, dielectric properties, PVC, silicone, longevity

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Digital and Standardized Governance for Circular Business Models: Industrial Symbiosis in Slovenia

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The transition from linear production to circular business models requires decision-making frameworks that are environmentally ambitious, operationally clear, digitally supported, and safe and sustainable by design. Circular economy scholarship defines this transition as a systemic shift in production and consumption, while circular business model literature emphasises value creation, delivery, and capture through reduced resource input, extended material use, and closed loops (Bocken et al., 2016). The research examines industrial symbiosis as a policy-relevant circular business model in Slovenia, focusing on resource sharing, by-product exchange, waste valorization, and cross-sector collaboration.

It draws on 25 qualitative semi-structured interviews with representatives of small and medium-sized enterprises, research organizations, intermediary institutions, and local policymakers. The analysis focuses on actors' perceptions of regulatory frameworks, institutional incentives, coordination mechanisms, standardization needs, and digital infrastructures that shape collaboration between firms and public institutions.

The findings show that awareness of circular economy principles is widespread, but implementation remains fragmented. Respondents identify regulatory ambiguity, administrative complexity, limited cross-sectoral coordination, uncertainty regarding

responsibilities for secondary resource use, and short-term market pressures as key barriers to industrial symbiosis. Where formal institutional pathways are unclear, collaboration often depends on informal networks, interpersonal trust, and individual leadership. Such arrangements can initiate pilot projects, but they remain difficult to scale without stable standards, transparent procedures, and durable policy support. Three priority areas are identified. First, standardized definitions, responsibilities, and quality criteria are needed to reduce uncertainty in the use of secondary materials and by-products, thereby aligning with the circular business model and value-network orientation of ISO 59010 (ISO, 2024). Second, intermediary platforms should support trust-building, knowledge exchange, data-enabled matchmaking, and monitoring of environmental and economic benefits. Third, financial and regulatory incentives should be aligned with long-term sustainability outcomes rather than short-term cost minimization.

The research argues that industrial symbiosis should be treated not merely as a technical environmental measure, but as a governance innovation for circular business models. By integrating standardization, digital coordination tools, and safe-and-sustainable-by-design principles, as promoted in the European assessment framework for safe and sustainable chemicals and materials (European Commission, 2022), circular business models can become more transparent, socially robust, and environmentally responsible, while strengthening regional resilience and cooperation between business, research, and public authorities.

Keywords: circular business models, industrial symbiosis, sustainable decision-making, standardization, safe and sustainable by design, digitalization, Slovenia

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Circularity of Material Flows in Slovenia: How to Advance the Use of Secondary Resources

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Introduction

The circularity of country economies is monitored by Eurostat through a combined set of indexes, split into five thematic areas: production and consumption, waste management, secondary raw materials, competitiveness and innovation; global sustainability and resilience.

Methods

The Circularity of material flows, i.e. circularity rate is determined as the share of secondary, recycled materials are used in the economy compared to the total material needs of the economy obtained from primary national and imported (virgin) materials and secondary national (recycled) materials.

Results

In 2024, the circularity rate was highest in the Netherlands (32.7%), followed by Belgium (22.7%) and Italy (21.6%). Slovenia's score was 10,1% just below the EU average of 12,2%. EU's Clean Industrial Deal set a target to double EU's circular economy rate to 24% by 2030.

Conclusions

Our panel will shed light on and promote discussion of existing and possible additional domestic measures and actions to promote circularity, with emphasis on the role and tools available from the Slovenian Centre for Circular Economy. The discussion will provide insight into the main current domestic waste material flows and potential gaps that should and could be addressed to enhance circularity more systematically. Last, but not least, possible opportunities and advantages to be gained from the announced EU Circular Economy Act will be considered, as the Act aims to support an increase of circularity at EU level through the mechanisms of the single market.

Keywords: circularity ecomomy rate, material flows, waste, recycling, gaps, opportunities, tools

Multiscale Approaches to Develop a Biocircular Economy

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Biowaste is one of the major issues in our society. The volume, its distributed availability and composition presents important management challenges. However, biowaste valorization and exploitation are essential towards energy and food security as well as for social development of the rural areas. Only through a multiscale analysis, from the selection of the chemical/product to obtain to the strategic investment plan it is possible to come up with guidelines towards deploying a biocircular economy

The methodoly integrates a process and product design stage, where optimal process systhesis and experimental data are key to predict the performance of the transfomation stages, and a supply chain design (Martín et al., 2023) that requires proper process scale up/down (Sánchez and Martín, 2018) including the concept of economies of numbers, due to the special features of biowaste management, as well as the development of social metrics. We use this methodology to valorize typical biowaste in Spain in ana attemp to create a biuocircualr economy.

Process level is the basic layer of analysis. Food residues are a major challenge. We first focus on the fruit industry. While fruit is itself an added value product, juices and jams are also highly appreciated consumer products. Oranges, apples and grapes are good examples. For instance, an integrated facility for oranges allows producing

orange juice, added value food products, fertilizers and utilities. The process begins with juice production. From the peel limonene can be extracted using steam explosion or a solvent, hexane. Next, the waste is digested to produce utilities and fertilizers. The flue gas from the gas turbine can either be used to produce electricity in a regenerative Rankine cycle or as utility within the facility. While the use of steam explosion requires 50% lower production costs, it shows 30% higher investment. The use of hexane consumes 4 times more thermal energy but the processing of the waste requires less digesters. Combined cycles are less profitable. The lower production cost of the steam explosion allows for smaller facilities to become profitable at smaller scales than those using hexane limonene recovery. Grapes produce already a very high value-added product, wine, but the residues can be used to produce a wide range of products, from energy to dyes. The selection of the byproduct production depends on the production capacity that is linked to the wine production where multiproduct refineries are preferred. Apples can be used for juice production or jam and candies elaboration. Linked to the production of apple juice, apple pomace can yield phenolic compounds, pectin and ethanol, that can be used as extraction media for the first one and subcritical water for the second. The sugars released during pectin extraction are used to produce ethanol, although purchasing it is also evaluated. Results show that subcritical water allows easier integration since only energy is required. On-site ethanol production reduces external dependence, showing competitive costs and similar profitability to purchasing at large scales, despite higher electricity consumption. Jam waste is valorized to obtain the same products, but pectin is extracted via citric acid hydrolysis, and an additional stage generates energy via anaerobic digestion (AD) or gasification (GA). Results indicate this hydrolysis requires large amounts of citric acid, which demands substantial sugar inputs, preventing its on-site production. Economically, AD outperforms GA due to lower investment. Finally, renewable-based heating and electrification can reduce the CO_2 footprint across both systems but remain less competitive.

The use of lower value bioresidues, can also help reduce our dependence on fossil resources and foreign imports, by producing, pellets, power or synthetic natural has. The methodology is applied in its full extend by first synthesizing the process that valorises biowaste, scale it up/down and formulate a facility location problem for the optimal selection of product, technology and facilities location. The availability of agricultural biowaste make it possible to meet the thermal energy demand of a country like Spain. The problem involves analysing the performance of pellet factories from different residues as well as biomass-based power plants at the

process level. Complete demand for thermal energy can be met with an investment of 2175 M€, where up to 47.3% corresponds to palettization and the remaining 52.7% to electricity generation and generating 10 k jobs in rural areas. Going beyond thermal energy, synthetic methane can be produced from lignocellulosic dry residues via gasification and anaerobic digestion of wet waste. The current budget for energy transition would allow achieving a fraction of natural gas self-sufficiency.

Keywords: circular economy, fruits, juices, supply chain, social issues process design

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Opportunities and Challenges of AI Support in the Assessment of Environmental Impacts of Circular Bio-based Products

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The transition towards a circular bioeconomy requires robust and transparent environmental assessment methods that can address the complexity of circular biobased value chains. Compared to conventional product systems, circular biobased products involve variability in biomass feedstocks, multifunctional processing pathways, cascading resource use, and uncertainty related to circular end-of-life performance, creating significant methodological challenges for Environmental Impact Assessment (EIA) and Life Cycle Assessment (LCA) (Dahiya et al., 2020; Cascione et al., 2025). Additionally, issues such as data availability, biological variability, multifunctionality, system boundary definition, and comparability with fossil-based alternatives further complicate the assessment of their environmental performance (Schrijvers et al., 2021; Wang et al., 2025).

This paper examines the opportunities and challenges of applying Artificial Intelligence (AI) to the environmental assessment of circular biobased products. The analysis is based on a feasibility assessment conducted within the Horizon Europe ARGONAUT project and focuses on how AI can support environmental assessment processes.

The study reviews EIA and LCA methodologies relevant to circular biobased products and outlines the opportunities and challenges associated with the AI support along the methodological framework and phases of LCA, outlined in the relevant standards (ISO 14040/14044). The discussion focuses on the role of AI in different phases of the LCA process, examining its potential to support assessment activities and the limitations that may affect the reliability and transparency of the results.

The analysis indicates that AI has considerable potential to support the most data-intensive phases of environmental assessment. Specifically, AI can facilitate data collection and inventory development, support the estimation of missing information, assist in hotspot identification, and enable uncertainty and scenario analyses (Popowicz et al., 2025; Wang, 2025; Romeiko et al., 2024). However, important methodological and practical challenges remain. The reliability of AI-supported assessments depends on data quality, transparency, explainability, uncertainty management, and consistency with established environmental assessment methodologies. In addition, key methodological decisions regarding goal and scope definition, allocation procedures, interpretation of results, and policy-relevant recommendations still rely on expert judgment and cannot be fully automated.

The paper concludes that AI should be considered an enabling technology that complements, rather than replaces, conventional environmental assessment practices. When combined with standardized and internationally recognized environmental assessment methodologies, Digital Product Passports, and transparent data governance mechanisms, AI can contribute to more efficient, scalable, and transparent environmental assessment of circular biobased products. However, maintaining methodological rigor, explainability, and stakeholder trust remains essential for successful implementation.

Keywords: circular bioeconomy, environmental impact assessment, artificial intelligence, bio-based products, digital product passport

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Emission Factor Sensitivity in Spend-Based Scope 3 Carbon Footprint Assessment of Hospitals

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Background

Hospitals need practical methods to screen greenhouse gas emissions embedded in purchased goods, services, and capital goods before supplier-specific or product-level data become available (WBCSD, 2011; WBCSD, 2013; Doucet et al., 2025). Spend-based Scope 3 accounting is valuable under such data constraints, but results are sensitive to the source of emission factors, sector mapping, country context, the monetary year, and model uncertainty. Reporting a single unqualified footprint value can therefore overstate the accuracy of the estimate.

Objective

This study developed and applied a reproducibility-focused decision-support framework for spend-based screening of hospital Scope 3 Category 1 (purchased goods and services) and Category 2 (capital goods), integrating deterministic factor-set sensitivity, price-year harmonisation, and model-based uncertainty propagation.

Methods

A two-stage analytical design was applied. First, emission-factor sets were compared independently of expenditure to assess inter-database variability, mapping confidence, and sector comparability across hospital-relevant categories. Second, a Slovenian national aggregate hospital-sector expenditure profile for 2024, calibrated against publicly available Ministry of Health financial reporting (Ministry of Health of the Republic of Slovenia [MZ], 2025), was allocated to 11 analytical procurement and capital-goods categories. The profile comprised 985 MEUR of Category 1 expenditure and 144 MEUR of Category 2 investment expenditure. Expenditure was mapped to the Slovenian CEDA 2025 release (Watershed, 2025) and EXIOBASE 3.9.6 sectors for 2022 (EXIOBASE, 2025; Stadler et al., 2018). EXIOBASE factors were evaluated on their original 2022 monetary basis and after adjustment to 2025 monetary terms. UK CEDA and UK EXIOBASE were used only as external benchmark stress tests, not as Slovenian footprint estimates. Model uncertainty was propagated by Monte Carlo simulation (Groen et al., 2014).

Results

The Slovenian context deterministic totals were 213 kt CO_2e under SI CEDA 2025 and 199 kt CO_2e under SI EXIOBASE 2022, adjusted to 2025 monetary terms. Despite the difference in totals, medical devices and consumables, pharmaceuticals, and administrative, information technology, and professional services remained leading hotspots in both Slovenian-context scenarios. The external UK benchmarks produced a wider range of estimates, underscoring the need to distinguish between scenario role and country-specific inference.

Conclusions

Spend-based Scope 3 accounting can support hospital carbon-management decisions when presented as transparent screening and prioritisation evidence, not as a definitive measurement system. For hospitals, the most useful output is therefore not only a single emissions total, but a clear indication of major hotspots, method-sensitive categories, mapping limitations and the areas where improved procurement or supplier data should be collected next.

Keywords: healthcare carbon footprint, Scope 3, purchased goods and services, capital goods, spend-based accounting, emission-factor sensitivity, price-year adjustment, Monte Carlo analysis, data-quality priority

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Development and Evaluation of a Python-Based Fluid Simulation Framework Using the Lattice Boltzmann Method

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The recent shift towards circular and sustainable industrial systems has been increasingly reliant on digital tools that enable efficient process design, optimization and evaluation before implementation. Computational fluid dynamics (CFD) play an important role in this field, as they can provide an important insight into flow and transport phenomena that affect the efficiency of chemical and energy related processes. One approach to CFD are the lattice Boltzmann methods (LBM) that model fluid behavior as simplified discrete particle interactions. This allows for efficient simulation of complex flows and relatively simple incorporation of different chemical or physical phenomena (Kruger et. al, 2016).

Our work presents the development and evaluation of a LBM-based fluid flow simulation framework implemented in a Python programming environment. The framework incorporates both the standard lattice Bhatnagar-Gross-Krook (LBGK) model and its extension with the Shan-Chen (SC) model, which were implemented from first principles using a D2Q9 lattice formulation.

The developed models were evaluated with a series of benchmark simulations, including Poiseuille flow, Couette flow, flow past a cylinder and lid-driven cavity flow. Numerical results were compared with analytical solutions and established reference data to assess the models' accuracy, stability and treatment of boundary conditions. Both models successfully reproduced characteristic flow behavior and demonstrated good agreement with theoretical predictions for laminar flows. A grid resolution sensitivity analysis further confirmed the convergence of the numerical simulation and highlighted the influence of discretization on simulation accuracy. Compared with the standard LBGK approach, the SC model generally exhibited improved accuracy and stability, but also a greater sensitivity to model parameters.

The results demonstrate that Python provides a flexible and accessible platform for the development of numerical simulation tools, despite its lack of computational performance. As a digital modeling framework, the developed LBM implementation represents a useful foundation for future applications involving process modeling and optimization, multiphase systems, complex geometries and other physical and chemical phenomena. Such tools can contribute to the digitalization of engineering work by supporting the decision-making process and reducing the need for resource intensive experimental investigations.

Keywords: computational fluid dynamics (CFD), lattice Boltzmann method (LBM), Python, Shan-Chen model, fluid simulation, numerical modeling

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Conceptual Design and Agronomic Evaluation of a Bio-Based Soil Improver Derived From Food Production Residues in the Slovenia-Istria Living Lab

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This study presents the conceptual design of a circular solution and evaluation of a soil improver (SI) developed within the Slovenia-Istria Living Lab, aiming to valorise food production residues (FPR) within a circular bioeconomy framework. The Living Lab approach ensured integration of stakeholder knowledge and regional constraints, enhancing practical relevance and scalability. The SI DIGOL was formulated from the solid fraction of anaerobic digestate derived from FPR (80 %), olive mill waste (17 %), and biochar enriched with the liquid fraction of digestate (3 %). Agronomic performance was assessed through laboratory and pilot-scale experiments, including:

– fertilisation potential,

- suppressiveness against soil-borne pathogens, and
- effects on soil microbial activity.

Fertilizers based on food waste play a fundamental role in plant nutrition by providing essential macronutrients, particularly nitrogen (N), phosphorus (P), and potassium (K). Within the transition towards more sustainable nutrient management, biofertilizers have gained increasing relevance due to their capacity to support nutrient cycling and improve nutrient-use efficiency (Eronen & Tuomala, 2025; Senevirathne & Kaparaju, 2025; Zrnec Drobnjak et al., 2025).

In this study, we examined the effects of SI DIGOL on different crops. Field trials on lettuce, tomato, potato and cabbage were conducted in Slovenia between 2024 and 2026, comparing Waste4Soil SI with mineral NPK fertiliser, organic fertiliser and an untreated control.

Results indicate that the SI DIGOL combines short-term nutrient availability with enhanced carbon persistence and improved soil biological functioning. The developed SI DIGOL demonstrated fertilisation potential, the capacity to suppress soil-borne pathogens, and positive effects on soil microbial activity.

Overall, soil improver DIGOL shows potential to close nutrient loops, increase soil organic carbon, and support climate-resilient soil management in Mediterranean agroecosystems.

Keywords: food waste, anaerobic digestate, olive pomace, biochar, soil improver, circular bioeconomy, living lab

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Magnetic Nanocellulose-Based Functional Nanoadsorbents for Efficient Heavy Metal Removal

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Heavy metal contamination poses a significant threat to environmental and human health due to the persistence, toxicity, and bioaccumulation of metal ions in aquatic systems. Among these pollutants, hexavalent chromium (Cr(VI)) is considered one of the most hazardous because of its high mobility, strong oxidizing capacity, and well-established carcinogenicity. Herein, a novel magnetic nanocellulose (mNC) adsorbent was fabricated from *Polypodiophyta* biomass via in situ co-precipitation of Fe_3O_4 nanoparticles and systematically evaluated for the efficient removal of Cr(VI) from aqueous media.

Batch adsorption experiments were performed to investigate the effects of solution pH, contact time, and initial Cr(VI) concentration. The synthesized magnetic nanocellulose exhibited strong pH-dependent adsorption behavior, achieving complete Cr(VI) removal (100%) within 120 min at pH 5 and an initial concentration of 1 mg/L. At higher Cr(VI) concentrations, removal efficiencies of 98% and 44% were obtained for 5 and 10 mg/L solutions, respectively, demonstrating progressive saturation of available adsorption sites. The incorporation of Fe_3O_4 nanoparticles

enabled rapid magnetic separation of the adsorbent after treatment, eliminating the need for filtration or centrifugation.

Adsorption equilibrium was evaluated using Langmuir and Freundlich isotherm models. The Freundlich model provided a significantly better fit ($R^2 = 0.93$) than the Langmuir model ($R^2 = 0.71$), indicating heterogeneous multilayer adsorption on the nanocellulose surface. The results confirm that the combination of renewable nanocellulose with magnetic nanoparticles creates an environmentally friendly, reusable, and highly efficient adsorbent for Cr(VI) removal. This work highlights the potential of biomass-derived magnetic nanocellulose as a sustainable material for advanced wastewater treatment and provides a promising platform for the future removal of a broader range of heavy metal contaminants.

Keywords: magnetic nanocellulose, nanoadsorbent, heavy metals, chromium, environmental remediation

Acknowledgement

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Thermal Cascade Management for Quality-Resolved Heat Integration in Modular Microfluidic Systems

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Serial microfluidic modules often heat feeds electrically and subsequently reject reaction heat to chilled utilities, creating an energy-quality mismatch that conventional plant-scale heat-integration methods cannot resolve at module level. This study introduces thermal cascade management, which coordinates heat recovery across module position, Carnot-based quality, and time. The framework combines unit modeling, energy-quality mapping, network targeting, and digital orchestration while accounting for heat losses, numbered-up module banks, and safety-critical quench duties. Applied to continuous-flow toluene mononitration with twenty parallel modules and 5.7 kW of hot process streams, the method reduces hot utility by 88.9%, chilled duty by 68.3%, and annual utility cost by 76.6% at a 5 K minimum approach temperature, while increasing exergy efficiency from 5.7% to 36.1%. The framework is transferable to other modular flow-chemistry systems.

Keywords: thermal cascade management, microfluidic modules, heat integration, exergy efficiency, chemistry

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BioFarms Cluster: A Transnational Model for Circular Biorefinery Value Chains

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Introduction

Converting agri-food residues and underused medicinal and aromatic plants into standardised high-value ingredients requires scalable green technologies and business models linking biomass suppliers, research infrastructures and SMEs. The BioFarms Cluster (BFC – A project under Interreg VI-B IPA ADRION call) addresses this gap through a transnational innovation ecosystem for nutraceutical and biopharmaceutical value chains.

Methods

BFC brings together nine partners and twelve associated organisations within seven local innovation Nodes across seven Adriatic–Ionian countries. Its methodology combines territorial biomass mapping, matrix characterisation, harmonised pre-treatment, pilot-scale extraction, analytical standardisation, and SME-oriented technology transfer. Demonstration pilots include grape pomace and seeds, plum kernels, chamomile, and *Helichrysum italicum*, which represent valuable sources of functional and nutraceutical bioactive compounds (Elejalde et al., 2024; Ferrara et al., 2025; Bahadirli et al., 2026). Building on technical and scientific pilot activities,

BFC supports the development of sustainable business models by engaging Quadruple Helix actors (research organizations, businesses, public authorities, and civil society) to foster co-creation, knowledge transfer, and the market uptake of sustainable and bio-based solutions.

Results

The BFC project has established a shared framework linking biomass availability, technological feasibility, extract quality, scalability and market relevance. The cluster-and-Node model supports comparison of region-specific feedstocks and transfer of pilot protocols to SMEs, facilitating replicable and sustainable value chains. Its distinctive feature is the integration of modular biorefinery technologies with capacity building, standardisation and market-access services.

Conclusions

BFC offers a transferable model for converting secondary biomass into higher-value botanical ingredients. It addresses secondary raw materials valorization, green processes and biorefineries, and circular business models, while promoting cross-border industrial symbiosis and innovation capacity in the Adriatic-Ionian region.

Keywords: circular bioeconomy, biomass residues, green extraction, biorefineries, botanical extracts, nutraceuticals, circular business models

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Sustainable Treatment of Pharmaceutical Industry Wastewater Using Vacuum Evaporation

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The pharmaceutical industry generates large volumes of wastewater containing high concentrations of organic and inorganic contaminants, making treatment a significant technical, environmental, and economic challenge (Kotwani et al., 2021). Recovering and reusing these waste streams to produce value-added products is therefore highly desirable (Li et al., 2024). This study was conducted using representative wastewater samples from a pharmaceutical manufacturing process. The objective was to determine the optimal operating conditions for vacuum evaporation using low-temperature waste heat and to evaluate the quality of the resulting products.

Vacuum evaporation experiments were carried out at different operating pressures while continuously monitoring concentrate temperature and the physicochemical properties of the resulting distillates and concentrates. The results showed that an operating pressure of 50 mbar enabled evaporation at a concentrate temperature below 60 °C, allowing efficient utilization of low-temperature waste heat. Approximately 90% reduction in the initial wastewater volume was achieved. The resulting distillates exhibited low conductivity, pH, and viscosity, indicating a high degree of purity and confirming their potential for reuse in the production process (Cahyadi et al., 2018).

Results demonstrate that, under appropriate operating conditions, vacuum evaporation is a promising technology for the sustainable treatment of pharmaceutical wastewater. In addition to significantly reducing waste volume, it enables the reuse of treated water, the recovery of concentrates for energy utilization, and the effective use of low-temperature waste heat, thereby improving resource efficiency and supporting the principles of the circular economy.

Keywords: vacuum evaporation, pharmaceutical wastewater, low-temperature waste heat, water reuse, circular economy

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Trace Element Leaching, Phase Composition, and Mechanical Strengths of Conventionally and Paper Sludge Ash-Activated Slags

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The cement industry remains the world's largest source of CO_2, accounting for almost 7% of total annual emissions (Pan et al., 2020). As demand for cement continues to grow, greener alternatives are needed, and the construction sector is working towards net-zero emissions by reusing industrial by-products such as ashes and slags (Pan et al., 2020; Snellings et al., 2023). For most of those by-products to act as binders, they should be activated, through alkali activation, typically using NaOH, KOH, or sodium silicate (Na_2SiO_3) (Wang et al., 2025). Paper sludge ash (PSA) offers a low-carbon alternative to conventional alkali activators (Mengasini et al., 2021). This study included different slags such as an electric arc furnace and ladle furnace mixed slag (S1), ground granulated blast furnace slag (S2), both activated with PSA, and conventionally activated ladle furnace slag (S3) to assess whether PSA can serve as a replacement for conventional activators. The raw materials used were characterised for their chemical composition and mineral composition. Their environmental acceptability was assessed by leaching tests on raw materials and on 28 day old PSA activated samples. Paste prisms were prepared, to analyse the

strength properties and measured after 3, 7, 14 and 28 days. X-ray diffraction was adopted to monitor the phase changes. After 28 days, PSA-activated S2 developed a flexural strength (3.45 MPa) approaching that of conventionally activated S3 (4.52 MPa), while S1 and PSA alone remained below 1 MPa. This reflected the composition of the raw materials: S2 was highly amorphous with a high SiO_2 content, and S3 was rich in Al_2O_3 (23%), whereas S1 already contained hydration products of AFt and AFm as a result collected from the open-air stockpile, resulting in a low reactive capacity. The leaching results showed a contrasting trend in the mobility of trace elements. Fresh S1 exceeded the prescribed limits for Cr, Mo and Ba, but these elements were immobilised when the material was activated with PSA. S2 showed the opposite behaviour. The fresh, amorphous material did not exceed any limits, but after activation with 10% PSA, the pellets exceeded the limits for Cr, Mo and Ba, indicating that activation can mobilise trace elements that were stable in fresh S2, partly due to the added PSA. For S3, only Ba exceeded the limit, and its concentration decreased after activation. These results indicate that PSA can activate reactive, amorphous slags such as GGBFS to strengths approaching those of conventional activation, but activation can immobilise or mobilise trace elements, depending on the type of recycled material. This highlights the need to assess the environmental safety of raw industrial by-products and the activated product, and to determine the origin of the mobilised trace elements.

Keywords: industrial by-products, trace elements mobility, alkali activation, phase evolution, mechanical strengths

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Modified Tessier Sequential Extraction for Reliable Assessment of Trace Element Mobility in Alkaline Industrial By-Products

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The importance of using recycled materials is promoted by the 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, which also limits landfilling by 2030. Reusing those materials reduces CO_2 emissions and supports the transition to a more sustainable economy (Li et al., 2024; Liang et al., 2024). However, the reliable valorisation of industrial by-products requires a comprehensive assessment of the leaching behaviour, origin, and environmental risk associated with the trace elements present in these materials. The Tessier sequential extraction and the Community Bureau of Reference (BCR) extraction schemes were established for this purpose but are not yet well validated for alkaline industrial by-products with high buffering capacity due to its primal use for soils. This study therefore compares the original Tessier sequential extraction scheme (Tessier et al., 1979) with a modified version to assess how trace element mobility varies between industrial by-products with different mineralogy and buffering capacity, and to verify whether the standard scheme captures the mobility of trace and major elements in

these materials. Four by-products with different mineral composition and buffering capacities were investigated: coal fly ash (CFA), white steel slag (WSS), paper sludge ash (PSA) and wood fly ash (WFA). The bulk chemical composition was determined by inductively coupled plasma mass spectrometry (ICP-MS) and Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES), and element mobility was assessed using both extraction schemes, with pH measured after each step, while X-ray diffraction (XRD), Scanning Electron Microscopy-Energy Dispersive X-ray Spectrometry (SEM-EDS) and Fourier-transform infrared spectroscopy (FTIR) were used to characterise phase formation and dissolution, and to evaluate the efficiency of the extraction schemes. The original Tessier scheme worked as designed only for CFA, where Mo was the most mobile element, released in the first extraction step. For WSS, PSA and WFA, it was insufficient: the hydration products of ettringite (AFt) and monocarboaluminate, hydrocalumite, and hydrotalcite (AFm), and carbonate phases, were preserved throughout steps II and III, so the scheme was modified with acetic acid (CH_3COOH) to dissolve them. Using the modified scheme, WSS showed the lowest total mobility of trace elements. PSA, however, had Ba as the most mobile element and, in WFA, the most mobile elements after the first step were Cr and Mo, both exceeding the limit values set by Slovenian legislation (Official Gazette, 2022). These results show that the applicability of the Tessier scheme beside on soils strongly depends on the mineralogical composition and buffering capacity of the industrial by-product. The original scheme under-represents the mobility of elements, and a modification is required for a reliable assessment. Exceeding regulatory limits for CFA, WSS, PSA, and WFA highlights the need for careful, trace elements mobility assessment before these by-products are used.

Keywords: industrial by-products, trace elements mobility, tessier sequential extraction, phase composition

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Stochastic Optimization of Food Self-Sufficiency under Extreme Weather Conditions

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The food supply chain is a complex system exposed to numerous risks and uncertainties, particularly extreme weather events and natural disasters that can substantially reduce agricultural production. As climate change is expected to increase the frequency and intensity of some weather extremes (ARSO, 2025), uncertainty in future crop yields must be incorporated into agricultural planning. This study developed an optimization model for allocating agricultural land to maximize Slovenia's long-term expected overall food self-sufficiency under different weather conditions while maintaining predefined minimum self-sufficiency levels for individual products.

To develop realistic scenarios, per-hectare yields of key Slovenian crops were analysed for 1991–2024. Five-year moving averages and annual deviations from the corresponding averages were calculated for each crop. Yields for 2050 were then estimated by linear extrapolation of historical trends. Using data on natural disasters, scenarios of agricultural drought, frost, hailstorms, floods, an average season, and an above-average season were defined and calibrated using historical yield deviations. Hailstorm and flood scenarios were excluded from further optimization because their effects were less pronounced in nationally aggregated data and spatially limited.

The baseline linear optimization model for maximizing the overall self-sufficiency rate (Drofenik et al., 2023) was supplemented with constraints defining minimum allowable self-sufficiency rates for individual products and adapted to uncertainty. Four approaches were applied: (i) scenario-specific optimization under perfect information, providing a theoretical benchmark because cropping decisions must be made before weather conditions are known; (ii) deterministic optimization using average yields, followed by evaluation of the fixed land allocation under the remaining scenarios; (iii) stochastic optimization considering all scenarios simultaneously and maximizing expected overall self-sufficiency; and (iv) a pessimistic stochastic case assuming continued agricultural land loss in line with the current trend and more frequent drought and frost.

The results show that agricultural drought causes the greatest reductions in the yields of maize, vegetables, green forage crops grown on arable land, and hay, whereas frost most strongly affects permanent crops, particularly fruit. The baseline stochastic approach achieved an expected overall self-sufficiency rate approximately 2 percentage points higher than that obtained with the deterministic approach. Comparison with the current self-sufficiency rates for individual agricultural products indicates that these rates could be improved in the long term primarily by strengthening the production of cereals, potatoes, vegetables, and fruit, while maintaining livestock farming in permanent grassland areas and ensuring an adequate domestic feed base. Under the pessimistic scenario, the expected overall self-sufficiency rate decreases by approximately 20 percentage points compared with the baseline stochastic approach. Cereals, particularly wheat, as well as fruit, vegetables, and certain animal products dependent on the feed base, emerge as the most vulnerable. The model calculations therefore quantify the consequences of agricultural land loss and more frequent droughts and frosts, providing a concrete basis for the timely implementation of agricultural land preservation measures and for directing investments towards irrigation systems, crop protection against weather extremes, more resilient varieties, and storage and processing capacity.

Keywords: food self-sufficiency, stochastic optimization, agricultural land allocation, extreme weather events, climate change

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AI-Assisted Innovations in the Twinning of Bioreactors and the Synthesis of Industrial Biocatalysts

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The presentation outlines trends and challenges in the development of digital twins, highlighting opportunities and the scope to define and refine the digital twin concept in the context of specific applications. The presentation further focuses on bioreactors and specific incentives to promote the digital twin concept in industrial biotechnology, an application domain very fragmented but also extremely rich in data and knowledge. Bioreactor digital twins are discussed in general terms and then, in relation to Bioindustry 4.0, a collective research effort to formulate generic and systematic approaches that are suitable to explore twinning for use in a wide range of biotechnology services. The presentation shares recent results that explain the bioreactor digital twin concept, the potential of technology to shadow and twin real-life processes, as well as the scope to the digital replica for optimization and control.

Building on this foundation, the presentation explains recent results demonstrating the use of Physics-Informed Neural Networks (PINNs) to create high-fidelity digital twins by integrating first-principle dynamic models (ODEs) with sparse experimental data.

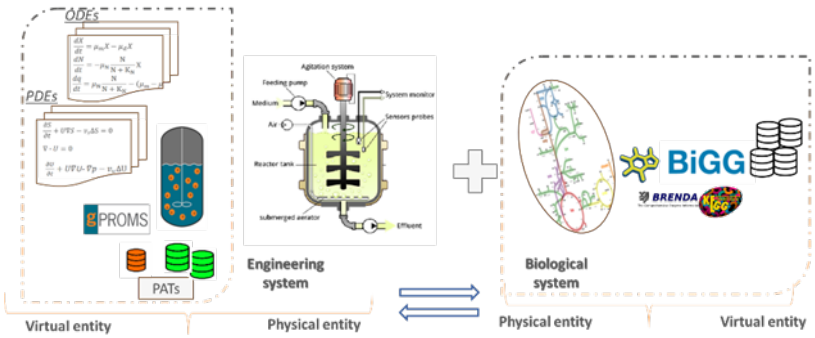

Figure 1: Bioreactor Digital Twins

In a pilot study involving recombinant nanobody production with E. coli, PINNs were applied to both batch and fed-batch bioreactor phases. Digital shadows proved successful to accurately replicate system dynamics and enable real-time state estimation and kinetic parameter inference. Even with a limited dataset, digital twins remarkably provide excellent short-term predictions, significantly outperforming conventional regression approaches. The framework supports continuous model refinement as new measurements become available, making it extremely attractive for adaptive process control and dynamic optimization. In most fed-batch applications, digital twins demonstrated strong adaptability by dynamically handling discontinuous inlet flow changes – a major challenge in bioprocess modeling. Despite the complexity introduced by variable feed rates, PINN-based models consistently delivered robust short- and long-term predictions. Additionally, kinetic parameters can be estimated without prior knowledge, highlighting an ability to generalize across phases. The presentation concludes with the integration of process twins with biochemical and metabolomics, supporting strain engineering and retrosynthesis as curated kinetic parameters can be combined with digital threads pointing to options for overexpressing or downregulating paths of the metabolic networks for better reaction and process efficiency.

Keywords: bioreactor digital twins, Physics-Informed Neural Networks (PINNs), industrial biotechnology, adaptive process control, metabolic engineering

Sorption Performance and Hydrothermal Stability of Ionic Liquids for Biogenic CO_2-to-Methanol Conversion at Wastewater Treatment Plants

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Closing industrial carbon loops requires technologies that convert dispersed biogenic CO_2 into transportable and storable products. The Horizon Europe ILIMITED project is developing a sorption-enhanced process for decentralized CO_2 conversion to methanol, with wastewater treatment plants envisioned as prospective biorefineries. The process targets methanol yields above 80% through the in-situ removal of methanol and water using a selective liquid sorbent. Continuous product removal shifts the reaction equilibrium, potentially increasing CO_2 conversion while reducing downstream separation requirements and enabling lower-pressure operation. A metal additively manufactured, fluid-guiding reactor will support process intensification through improved flow distribution and heat and mass transfer.

A major challenge is identifying a liquid sorbent that retains affinity for methanol and water at temperatures up to 513 K while exhibiting low volatility, manageable viscosity, and sufficient thermal, chemical, and hydrothermal stability. Temperature-programmed thermogravimetric analysis was used to screen phosphonium- and ammonium-based ionic liquids with different cations, anions, functional groups, and additives. Molecular sieve 3A, TEGDME, and Santovac 5 were included as reference materials.

The preliminary results identify $[NTf_2]^-$-based ionic liquids as the most thermally robust platform. $LiNTf_2$-containing $[P_{1444}][NTf_2]$ additionally exhibited low-temperature sorption, whereas dicyanamide- and dimethyl-phosphate-based liquids showed reduced stability. TEGDME reference was limited by its high volatility.
These findings guide the selection of stable liquid sorbents for the ILIMITED process and support CO_2 utilization through decentralized renewable-methanol production and long-term chemical energy storage.

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Digital Product Passports for Circular Construction: a LIFE IP RESTART Pilot Implementation

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The construction sector depends on complex supply chains and generates large volumes of materials whose potential for reuse and recycling is often reduced by fragmented documentation, inconsistent traceability and limited access to verified technical data. Regulations (EU) 2024/1781 and (EU) 2024/3110 establish the general digital product passport framework and introduce a dedicated construction digital product passport system (European Parliament and Council, 2024a; 2024b). Practical implementation nevertheless requires data models that connect product regulation, mining and processing or/and waste legislation, quality assurance and real material flows.

This contribution presents the development and pilot implementation of SloDPLgp, a Slovenian digital product and material passport platform combined with an urban construction materials bank and marketplace. The platform was developed within Action C9 of the LIFE IP RESTART project by the Slovenian National Building and Civil Engineering Institute (ZAG) in cooperation with Infordata and tested with material/product cases of NIGRAD company. Its objective is to provide structured and accessible information on the origin, processing, properties, conformity and circular use potential of construction products containing secondary raw materials.

The development followed an evidence-based approach. Data requirements were obtained from European and Slovenian legislation and documentation generated through processing, testing and factory production control at the NIGRAD Dogoše demonstration site. The resulting data model covers material origin and waste acceptance, processing, transport and storage events, product composition, declared uses, performance characteristics, laboratory tests, certificates, environmental information and direction for reuse, recycling and end-of-life treatment. The workflow assigns data responsibilities to producers, transporters, laboratories, processors, notified bodies, users and regulators. Public passport data are accessible through product links and QR codes, while permissions based on roles protect sensitive information. The model was tested using three representative NIGRAD products, NIGBET-1, NIGBIT-1 and NIGIZA-1, allowing the proposed structure to be assessed against actual production and compliance records.

The pilot resulted in three structured digital product passports and a functional platform prototype. The prototype includes public, administrative and mobile interfaces connected to a shared backend. It links passport records with secondary raw material (SRM) stock information, supporting documentation and marketplace listings. Testing confirmed that operational, laboratory and regulatory data can be consolidated into a consistent digital record and made available to different actors across the value chain. It also identified the main implementation challenges: the availability and quality of verified data, alignment between waste and product classifications, consistent national terminology, and future interoperability with external registries, application programming interfaces (APIs) and Building Information Modelling (BIM)/Industry Foundation Classes (IFC) environments. Additional export, translation and interoperability functions remain under development.

The results show that digital product passports can provide a link between traceability, technical evidence and market exchange of SRM-based construction products and materials along with primary ones. Their effective use depends on clearly assigned data responsibilities, verified evidence and interoperable data structures. This approach provides a basis for extending digital passports to additional products and for supporting broader implementation of circular construction practices in Slovenia.

Keywords: digital product passport, circular construction, secondary raw materials, traceability, construction products, digitalization

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From Laboratory to Semi-Industrial Scale: Challenges in Upscaling Bioleaching of Waste Electrical and Electronic Equipment (WEEE)

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Waste electrical and electronic equipment (WEEE) is one of the fastest-growing waste streams. It is a metal-rich secondary resource containing base and critical raw materials including precious metals, often at concentrations exceeding those found in primary ores (Baldé et al., 2024; Arya and Kumar, 2020). Recovering these metals supports the European Union's efforts to ensure a secure and sustainable supply of critical raw materials (European Parliament and Council, 2024). Conventional extraction methods, including pyro- and hydrometallurgical processes, are energy- and reagent-intensive. Bioleaching using acidophilic bacteria such as *Acidithiobacillus thiooxidans* and *Acidithiobacillus ferrooxidans* offers a lower-energy and lower-emission alternative. However, its application has so far been demonstrated mainly at a small bench scale, with the transition to pilot scale operation remaining a main barrier to industrial adoption.

This work investigates the feasibility and challenges of upscaling the bioleaching of waste printed circuit boards from bench-scale (5 L) to semi-industrial (100 L) and industrial (1000 L) bioreactors. Metal mobilisation is driven by acidolysis with biogenic sulfuric acid (H_2SO_4) and by oxidative dissolution mediated by the Fe^{3+}/Fe^{2+} redox cycle. pH, oxidation–reduction potential, conductivity, dissolved oxygen and elemental composition are monitored throughout the process, while a deliberate microbial strategy is applied to support efficient and stable bioleaching performance.

Scaling shifts the rate-limiting factors from microbiological process toward reactor engineering and solution chemistry. Pulp density acts as the coupling variable that links the key controls – material composition, acid demand and dissolved-metal concentration. The principal challenges include sustaining microbial activity and the generation of acid- and ferric ions as the working volume increases. This requires maintaining the generation of sulfuric acid and ferric ions at sufficient levels. Another challenge is ensuring sufficient oxygen transfer and keeping dense particles in suspension without generating shear that damages attached cells. Excessive foaming should also be prevented, as it may wash out cells from the reactor. In addition, inhibition by dissolved metals, notably Cu and Zn must be mitigated. The formation of secondary iron precipitates, such as jarosite, which lower efficiency and complicate downstream processing, also needs to be controlled (Awasthi et al., 2016; Vera et al., 2022).

Overall, bioleaching of WEEE is technically transferable from laboratory to semi-industrial scale. Its viability depends more on engineering and solution-chemistry factors than on microbiological limitations. The main factors are aeration and mixing, iron-speciation management, sterility and metal-toxicity mitigation. Identifying and controlling these factors is essential for translating microbial urban mining into a practical circular route for recovering critical raw materials from electronic waste.

Keywords: bioleaching, WEEE, printed circuit boards (PCBs), scale-up, Acidithiobacillus thiooxidans, Acidithiobacillus ferrooxidans

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A Common Strategy for Circular and Digital Construction in Central Europe: Approach and Results of the Interreg ReBuilt Project

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The construction sector is the Europe's largest consumer of raw materials and one of its largest sources of waste, with construction and demolition waste (CDW) representing a substantial share of total waste generated and the sector contributing significantly to energy-related emissions. Addressing this impact requires a coordinated shift from a linear to a circular model, supported by digital tools that make material flows visible and traceable. This abstract paper presents the Common Strategy for Circular and Digital Construction in Central Europe, developed within the Interreg Central Europe project ReBuilt by a transnational partnership of fourteen organisations from nine countries, with the Slovenian National Building and Civil Engineering Institute (ZAG) acting as central coordinating hub.

The strategy is organised around six interconnected pillars: circular development and design; digitalisation and data interoperability; circular value chains, markets and business models; governance and public procurement; skills, capacity building and knowledge; and a regional network of circular and digital construction hubs. Building on these pillars, the project has delivered a set of concrete outputs, including a circular design methodology and standard, a digital product passport platform for material traceability, an upgraded CinderoSS digital marketplace connecting

suppliers of secondary construction materials with demolition companies and contractors, a massive open online course (MOOC) on circular and digital construction for professionals, public authorities, investors and architects, and students, and a network of circular and digital construction hubs anchored by ZAG and extending across the partner regions in Central Europe.

The strategy developed outlines the governance and monitoring approach underpinning the strategy, including a country-differentiated indicator framework with 2035 targets, and reflects on the conditions needed to scale circular and digital construction practices beyond the project's duration. It concludes that closing the region's persistent gaps in circularity, digitalisation and skills requires sustained institutional commitment and cross-border cooperation and highlights the role of public research institutions as ZAG as connectors between policy, industry, academia and civil society in accelerating the transition of the built environment.

Keywords: circular economy, digital construction, construction and demolition waste, BIM, circular construction hubs

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Food Waste Prevention for More Efficient Household Food Resource Use

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Introduction

Food waste prevention is a key strategy for improving the efficiency of food resource use because discarded food also embodies the unnecessary use of raw materials, water, energy, land, labour and financial resources. In 2022, 1.05 billion tonnes of food waste were generated globally, with households accounting for 60% (United Nations Environment Programme, 2024). Although numerous household interventions have been developed, evidence of their effectiveness and durability remains inconsistent (Jobson, 2024).

This review aimed to identify the behavioural and psychological factors contributing to household food waste and to assess which communication strategies, behavioural interventions and nudges can support food waste prevention and more efficient household food resource use.

Methods

A multi-stage literature search was conducted between November 2025 and January 2026 across Scopus, Web of Science, GreenFILE, Google Scholar, Springer Nature Link and PubMed. English- and Slovenian-language records were considered, and the study selection process was structured according to PRISMA 2020. The searches identified 12,009 records; 7,125 remained after duplicate removal, and 601 reports were assessed for eligibility in full text. The final review corpus comprised 59 scientific articles; one book chapter was retained separately as a supplementary conceptual source. Evidence was synthesised thematically across behavioural and psychological foundations, communication strategies, nudges and behavioural interventions, mechanisms of effectiveness, and research limitations.

Results

The thematic synthesis showed that household food waste is a practice-based and context-dependent outcome of repeated decisions across meal planning, purchasing, storage, preparation, portioning, consumption and leftover use, rather than merely a consequence of insufficient awareness. Awareness and knowledge were necessary but insufficient for sustained behavioural change, as established household routines, convenience, time constraints, food-safety concerns, family preferences, social norms and limited perceived behavioural control frequently weakened the translation of intentions into action (Cheng et al., 2025; Jobson et al., 2024; van der Werf, P., Seabrook, J. A., & Gilliland, 2021). More promising approaches combined actionable food-literacy communication with practical household food-management tools, timely prompts and reminders, feedback, carefully designed social-norm messages and digital support delivered at relevant decision points (Laila et al., 2024; van der Werf et al., 2021). However, no single intervention type appeared consistently effective across all households and consumer groups (Jobson et al., 2024; Kansal et al., 2025). The household evidence base remained heterogeneous and was limited by reliance on self-reported outcomes, short follow-up periods, context-specific samples and insufficient testing of the mechanisms underlying behavioural change (Jobson et al., 2024). Food waste prevention and food safety should therefore be treated as complementary goals, particularly when addressing date-label interpretation, food storage, perceived edibility and the safe use of leftovers (Cheng, 2025).

Conclusions

Household food waste prevention requires an integrated behavioural approach rather than stand-alone awareness campaigns. More efficient household food resource use can be supported by combining food-literacy communication with practical planning, storage and leftover-management tools, timely prompts, feedback and context-sensitive behavioural interventions. These approaches should be adapted to different household routines, capabilities and barriers. Future research should employ objective household food waste measurements, controlled longitudinal designs and explicit evaluation of behavioural mechanisms to determine which interventions work, for which households and whether their effects persist over time.

Keywords: household food waste, consumer behaviour, food resource efficiency, food literacy, behavioural interventions, nudges

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Cross-Border Cooperation: Circular Construction Value Chains: Potential and Barriers in the Slovenia-Austria Region

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The transition from linear to circular production and consumption models requires a systemic transformation of value chains. Circularity in the construction sector goes beyond the recycling of construction and demolition waste: it seeks to retain the functional, technical, and economic value of construction products and materials through reuse, recovery, refurbishment, and recycling. Achieving this requires reconfiguring material, information, and economic flows, and closer coordination among the actors involved across the construction value chain (European Commission, 2020; European Environment Agency, 2024).

This paper analyses the potential and barriers for the development of cross-border circular construction value chains between Slovenia and Austria. The research applies value chain analysis to identify the main actors, activities, relationships, and material flows relevant to the circulation of secondary and reused construction materials and products in this region. The analysis is complemented by a comparative examination of relevant European Union and national regulatory frameworks, with particular attention to requirements that influence the cross-border movement, assessment, acceptance, and use of secondary materials, as well

as to the region's existing cross-border cooperation infrastructure, including Interreg co-funded initiatives.

The analysis indicates significant potential for developing regional value chain and circular material loops between Slovenia and Austria, supported by geographical proximity, economic integration, and interconnected construction markets. This potential is, however, constrained by fragmentation along the value chain and by differences in regulatory and technical requirements (Huovila et al.,2022). Key barriers include divergences in waste management practices, environmental permitting and end-of-waste criteria decisions, national technical standards and product specifications, logistical and cross-border shipment requirements, and insufficient information on the origin, composition, quality, and performance of secondary materials. These barriers limit the marketability and cross-border acceptance of recovered materials and contribute to downcycling rather than reintegration into higher-value applications (Ferriz-Papi et al., 2024; Idir et al., 2025; Bato et al., 2025). The relatively low EU circular material use rate of 12.2% in 2024 further indicates the limited substitution of primary resources by secondary materials at the economy-wide level (Eurostat, 2025).

The findings demonstrate that circularity must be addressed across the entire value chain rather than primarily at the waste-management stage. Product design, design for disassembly and deconstruction, modularity, appropriate material selection, and early planning for reuse and recovery are important prerequisites for preserving material value across use cycles. Effective cross-border circulation additionally requires reliable, standardised, and interoperable information on material characteristics and provenance; digital technologies, including Building Information Modelling, material passports, and interoperable data systems, can support material identification, traceability, assessment, and decision-making across successive use cycles (Banihashemi et al., 2024; Keles et al., 2025).

Keywords: circular construction, value chain, cross-border value chain, secondary raw materials, regulatory framework, digitalisation

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Circular Economy and Life-Cycle Innovation: From Microalgae to Outer Space

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New data-intensive technologies are changing the way we perceive natural environment and shape economic systems. Be it climate change, new materials or natural capital management, systems thinking through data is today at the heart of life-cycle innovation and circural economy entrepreneurship. In this talk, we will examine some of the main trends in Data-Driven Innovation, showcasing experimental projects ranging from using microalgae for decarbonisation, developing new concepts for in-situ resource utilisation (ISRU) in Outer Space, and how Earth Observation is shaping the future of our (trans)planetary ecology. We will also look at tools and strategies that can support a growing circular economy by characterising locally-situated opportunities for responding to global societal challenges.

Keywords: circular economy, life-cycle innovation, data-driven innovation, microalgae, decarbonization

Machine Learning-Assisted Modelling and Optimisation of an Integrated Process for Synthetic Liquid Fuel Production via Co-Electrolysis and Fischer–Tropsch Synthesis

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The production of synthetic liquid fuels from captured CO_2 and renewable electricity represents a promising pathway for reducing fossil-resource consumption and recycling CO_2 into energy carriers. In this study, integrated modelling and optimisation are performed for a process combining CO_2 capture, high-temperature co-electrolysis in a solid oxide electrolysis cell (SOEC), and Fischer-Tropsch (FT) synthesis. CO_2 capture is modelled in Aspen HYSYS, while the remaining process units are simulated in Aspen Plus to obtain mass and energy balances, perform heat integration, and generate inventory data required for the subsequent Life Cycle Assessment (LCA). Machine learning surrogate models are used to represent the outputs of the SOEC and FT reactors under varying operating conditions.

The SOEC surrogate model is developed using experimental data obtained from the literature (Inuzuka et al., 2025). Temperature, current density and the inlet CO_2/H_2O molar ratio are selected as input variables, while the cathode-outlet mole fractions of CO_2, H_2O, H_2 and CO are used as model outputs. Symbolic regression is applied to derive mathematical relationships between the operating conditions and outlet composition. The validated symbolic regression derived model is then used in a genetic algorithm (GA)-based optimization of the operating conditions. Sobol sampling (Sobol, 1967) is applied to obtain a well-distributed initial GA population. The objectives are to maximise the combined H_2 and CO fraction, minimise residual CO_2, and achieve an H_2/CO ratio close to 2. A one-factor-at-a-time analysis is also performed to evaluate the individual effects of temperature, current density, and inlet composition on the predicted outlet composition. The optimised operating conditions, selected to satisfy the specified SOEC outlet-composition requirements, are subsequently used in the Aspen Plus process simulation.

For the FT reactor, custom reaction kinetics are implemented in Aspen Plus using an inlet stream determined by the SOEC cathode outlet, and a simulation dataset is generated by varying reactor temperature and pressure (Gimpelj, 2023). Separate symbolic regression models are developed to predict the outlet composition of gaseous products, paraffins, and olefins. The validated models are then used to identify favourable operating conditions through GA-based optimisation with a Sobol-initialized population. The optimisation maximises the production of C_5–C_9 and C_{10+} paraffin fractions, minimises net CO_2 formation per kg of product, and maintaines high CO conversion. The individual effects of temperature and pressure are additionally assessed using one-factor-at-a-time analysis.

This work encompasses process simulation, interpretable machine learning models, and multi-objective optimisation for integrated synthetic liquid-fuel production. It provides a computationally efficient approach for linking SOEC and FT operation, identifying favourable operating conditions, and generating consistent process data for heat integration and LCA.

Keywords: solid electrolysis cell, Fischer-Tropsch synthesis, symbolic regression, genethic algorithm, synthetic liquid fuels

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Optimal Design and Economic Viability of Regional Bio-Based Polyethylene Production

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Bio-based polyethylene (bio-PE) represents a promising route towards reducing the dependence of polymer production on fossil resources. Its economic viability, however, is strongly influenced by the spatial availability and cost of biomass as well as by economies of scale in capital investment.

This work presents a framework for the economic optimization of regional bio-PE production systems. A mixed-integer linear programming (MILP) model was formulated in Python using the Pyomo modelling framework and solved with the HiGHS solver. The model simultaneously determines the optimal number, location and capacity of production facilities together with regional biomass allocation by maximizing Net Present Value (NPV) over a 20-year lifetime.

The model was applied to 198 NUTS3 regions in Slovenia, Croatia, Italy, Austria and Hungary. Eight biomass feedstocks were considered: wheat straw, rapeseed straw, maize stover, barley straw, sunflower straw, hardwood and softwood forest residues, and oilseed press cake. The process flowsheet consists of biomass-to-ethanol production, ethanol-to-ethylene conversion, and ethylene polymerisation to high-density polyethylene (HDPE). Process performance and cost data were obtained from techno-economic studies (Humbird et al., 2011; Haro et al., 2013; Ding et al., 2026) and converted to a 2024 cost basis using the Chemical Engineering

Plant Cost Index. The nonlinear relationship between plant capacity and investment cost was represented by a piecewise-linear approximation. The NPV objective accounts for the initial capital investment and discounted net cash flows, including revenues, feedstock and transportation costs, operating and labour costs, and country-specific taxation.

A parametric analysis of the bio-PE selling price was performed to identify the minimum price required to achieve a non-negative NPV. Under the assumed parameter values, this threshold was approximately 1,275 EUR/t, at which a single plant was selected in southern Hungary with a capacity of 252 kt/a, meeting approximately 46% of the modelled HDPE demand across the five countries.

The results suggest that, within the assumptions considered, supplying a larger share of regional HDPE demand with bio-PE requires higher selling prices, indicating that the economically viable extent of regional deployment is strongly influenced by the achievable product selling price.

Keywords: biomass, bio-based polyethylene, supply chain optimization, mixed-integer linear programming, techno-economic analysis

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Economic and Environmental Optimization of Hydrogen Supply Network for Industry and Road Transport in Slovenia

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Hydrogen is increasingly considered as a key energy carrier for decarbonizing hard-to-abate sectors, yet the design of hydrogen supply networks requires a comprehensive approach that simultaneously considers energy supply, production technology, storage, transport, and spatial deployment. In this study, an integrated optimization framework for the synthesis of a hydrogen supply network in Slovenia was developed. A multi-objective, multi-period mixed-integer linear programming (MILP) model was formulated as a three-layer superstructure comprising: i) electricity supply sites, ii) hydrogen production, storage and conditioning plants, and iii) demand sites. The model considers a longer-term development scenario with hydrogen demand from both industry and road transport.

The superstructure includes electricity generation from photovoltaic systems and wind power plants, as well as electricity from the Slovenian power grid, while considering the spatial and temporal variability of renewable energy availability. Hydrogen could be produced using alkaline electrolysis (AEL) or proton exchange membrane (PEM) electrolysis, stored and conditioned by compression or liquefaction, and distributed to industrial consumers and hydrogen refuelling stations by truck or pipeline.

Life cycle assessment (LCA) was used to quantify environmental impacts, with global warming potential (GWP) incorporated into the multi-objective optimization. The optimization was performed using three objective functions: an economic objective minimizing total annual cost (TAC), an environmental objective minimizing GWP, and a composite economic-environmental objective incorporating monetized GWP.

The solution obtained under the composite criterion was close to the economic extreme of the Pareto curve. Compared with economic optimization, TAC increased by only 0.35%, while GWP decreased by 2.45%. The lowest levelized cost of hydrogen (LCOH), 5.288 €/kg H_2, was obtained by minimizing the composite criterion at hydrogen production of 55.6 kt H_2/a. Solutions obtained under the economic and composite criteria favored hydrogen production at demand sites, supplemented by road transport where necessary, electricity generation predominantly from wind power, and AEL technology. In contrast, minimizing GWP resulted in more spatially distributed production, pipeline distribution, and PEM electrolysis.

The integrated multi-objective optimization model identifies system-level trade-offs and provides a basis for designing economically competitive hydrogen supply networks with reduced environmental impact.

Keywords: hydrogen supply network, renewable hydrogen production, multi-objective optimization, life cycle assessment global warming potential

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Multi-Period Optimisation of Aluminium Slug Production and Supply Networks with Low-Carbon Energy Integration

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Material circularity and low-carbon energy integration represent two important pathways towards more sustainable aluminium manufacturing. This work presents a superstructure-based mixed-integer nonlinear programming (MINLP) framework for the multi-period optimisation of aluminium slug production and its associated material and energy supply network, with particular emphasis on low-carbon electricity and hydrogen integration.

The model simultaneously considers the sourcing of aluminium scrap and alloying materials, aluminium slug production subject to product-quality constraints and demand requirements, and on-site electricity and hydrogen production. The energy superstructure includes electricity supply from the Slovenian grid, on-site generation from newly installed photovoltaic panels and a small modular reactor (SMR), and electricity storage for temporal balancing between generation and consumption. Temporal variations in solar irradiation are also considered. Hydrogen can be produced through water electrolysis or from aluminium-containing residues via alkaline hydrolysis. The produced hydrogen can be compressed and stored, and used as a partial substitute for natural gas in industrial thermal processes, or as a full

substitute with necessary process modifications, or sold to external consumers. The model ensures that the company's internal electricity requirements are satisfied in each time period, while surplus electricity can be sold and hydrogen can be supplied to external consumers when economically advantageous.

The objective is to maximise the overall economic performance of the company by accounting for revenues from aluminium slugs, electricity and hydrogen sales, raw-material and utility costs, operating and transportation costs, and annualised investment costs. The results show that the optimal energy configuration strongly depends on the market demand for hydrogen. At low external demand, investment in the SMR is not selected, and electricity requirements within the company are met by newly installed photovoltaic capacity and electricity purchased from the Slovenian grid. In scenarios with high external hydrogen demand, increased hydrogen production through water electrolysis raises electricity requirements to a level at which SMR investment is selected in addition to increased photovoltaic capacity. At higher hydrogen production levels, part of the hydrogen is utilised internally in existing industrial burners as a blend with natural gas up to 10 vol.%, whereas investment in dedicated pure-hydrogen burners is not economically favourable. These results demonstrate the importance of jointly optimising the production process, supply network, and on-site low-carbon energy systems to identify economically favourable pathways towards more circular and sustainable aluminium manufacturing.

Keywords: mixed-integer nonlinear programming (MINLP), low-carbon energy, supply network, hydrogen production, aluminium slug production

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9TH INTERNATIONAL CONFERENCE ON TECHNOLOGIES & BUSINESS MODELS FOR CIRCULAR ECONOMY (TBMCE): BOOK OF ABSTRACTS

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The 9th 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 9 to 11 September 2026 at the Grand Hotel Bernardin in Portorož. TBMCE 2026 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 programme 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.

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