Upcycling Cellulosic Waste Streams into Construction Materials – Life cycle assessment under ICARUS project

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The circular economy has emerged as a solution to linear economy by enhancing resource efficiency and reducing waste, offering a more sustainable alternative (Islam et al., 2024). The European Commission highlights that, in the context of climate and digitalisation goals, European supply chains must be organised to ensure efficient extraction, processing, and recycling of critical raw materials (Burinskienė et al., 2025). Secondary raw materials (SRMs) are increasingly recognised as a key element of sustainability strategies, as economies seek to reduce dependence on virgin resources. The trade of recycled materials is a key component of the circular economy, contributing to resource efficiency, keeping materials in circulation while reducing environmental impacts and primary resource consumption. It is particularly important for countries with limited natural resources, where recycling can reduce dependence on raw material imports and stabilise product prices. Different end-of-life treatment practices can benefit cities and regions by valorising waste streams, generating SRMs at low or no cost, while reducing both demand for primary raw materials and waste management expenses (OECD, 2025).

The construction industry plays a relevant role in the global economy, accounting for 10–12% of global economic output, while simultaneously consuming approximately 50% of total raw materials and 36% of global final energy use, highlighting its massive resource demand. The significant associated environmental footprint has driven a growing transition towards circular economy (CE) principles, particularly through the valorisation of waste streams such as cellulose, mining tailings, and metallurgy slags (SRM), which are generated in considerably high volumes (Hidalgo & Verdugo, 2025). However, the complexity of construction products and limited level of digitalisation of the sector create significant barriers to the implementation of CE practices, making this transition challenging and requiring coordinated efforts to develop the necessary knowledge and tools for broader industrial adoption (Illankoon & Vithanage, 2023).

Within this context, the ICARUS project aims to demonstrate how high-impact industrial waste can be transformed into valuable construction materials by validating innovative upcycling solutions through three real-scale demonstration cases across Europe, contributing to a more circular and digital industry. The three demo cases included in the project are: Demo case 1- Upcycling of waste from the Lithium extraction and refinery, Demo case 2- Upcycling of industrial and urban cellulosic waste and Demo case 3- Steelmaking slag upgrading and valorisation through different stabilization methods. For each demo case, the environmental evaluation is divided into two stages: the upcycling process, which transforms industrial or urban waste into high-quality secondary raw materials (SRMs) and the production of construction materials using those SRMs.

This present study focuses specifically on the environmental assessment of the Demo Case 2. This process (DC2) addresses the recovery and upcycling of cellulose-containing SRMs from two waste streams available at significant scale across Europe: post-consumer Absorbent Hygiene Products (AHPs) and municipal wastewater treatment plants (WWTPs). By fostering Urban-Industrial Symbiosis, DC2 aims to valorise these previously underutilised residues for application in the construction sector. To this end, a rotatory belt filter (RBF) was implemented at a specific WWTP facility operated by the partner company Acciona to allow for cellulose recovery. An addicional innovative engineered pre-treatment system was also developed by i-Foria, integrating sterilisation, optimised particle size reduction, and an additive system for the removal of pharmaceutical residues, thereby ensuring high-quality SRM outputs. The recovered materials, primarily cellulose fibres and superabsorbent polymers (SAP), are foreseen to be subsequently incorporated into concrete mixes as replacement of virgin cellulose use, targeting large-volume applications such as slabs and pavements, which are particularly susceptible to cracking due to drying shrinkage. While cellulose fibres act mechanically to reduce crack width or prevent crack formation, SAP retains moisture within the cement paste, mitigating differential drying stresses between the core and surface of the structure.

Within the framework of DC2, a Life Cycle Assessment (LCA) will be conducted to comprehensively evaluate the environmental performance of the cellulose and SAP recovery and upcycling system, following the principles established in ISO 14040 and ISO 14044. The system boundary will adopt a cradle-to-gate with options approach, encompassing modules A1–A3 (manufacture), C1–C4 (disposal), and module D (reuse, recovery or recycling potential), thereby capturing upstream waste sourcing, upcycling operations, transport, product manufacturing, and selected end-of-life scenarios. The assessment adheres to the modular structure defined in EN 15804:2012+A2:2020 and the Product Category Rules for Construction Products (PCR 2019:14), ensuring comparability with European sustainability standards, while impact characterisation will be performed using the Environmental Footprint (EF) method. For the analysis, two functional units are defined to reflect the two distinct stages of the value chain under assessment: 1 kg of high-quality recovered cellulose, which serves as the reference unit for evaluating the environmental impacts associated with the recovery and upcycling process itself, and 1 m^3 of concrete slab or pavement incorporating the upcycled materials, which captures the environmental performance of the final construction application. This dual approach ensures that both the production of SRMs and their end-use contribution are independently assessed and comparable with the respective baseline scenarios. The baseline scenarios selected for comparison reflect the most widespread current practices: biodigestion for WWTP cellulosic sludge and landfilling or incineration for post-consumer AHP waste. At the concrete application level, two reference mixes are considered: a control mix without fibres and an equivalent mix incorporating conventional polypropylene microfibres. This comparative approach aims to quantify the environmental gains associated with material substitution and circularity, while also identifying process hotspots to inform future scale-up decisions.

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