Life Cycle Assessment of Novel Ceramic Pastes Incorporating Secondary Raw Materials

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The ceramic industry is a vital sector in the European economy, contributing significantly to energy consumption, CO_2 emissions, and the depletion of mineral resources. Aligning this industry with the European Green Deal's objectives demands ambitious efforts to enhance decarbonization and circularity by reducing primary raw material use and increasing material re-utilization (Monteiro, Cruz, & Moura, 2022). The mobilizing Agenda ECP, comprising ceramic and glass industries alongside research institutions, is focused on developing innovative ceramic blends and products that integrate reprocessed ceramic and glass waste. These novel ceramic pastes hold the potential to improve circularity and decrease the environmental impact of ceramic production. However, a comprehensive assessment of their sustainability requires a life cycle perspective to ensure that improvements in one impact category do not result in problem shifting elsewhere, and industrial development results in more sustainable solutions.

This study presents a life cycle assessment (LCA) of an innovative ceramic paste incorporating recycled waste, comparing its environmental footprint to that of conventional ceramic production. The research evaluates different production steps and life cycle stages to quantify the potential benefits and trade-offs associated with this new material.

A standardized LCA methodology was applied to assess the environmental performance of producing one ton of ceramic material using these novel compositions. The study follows ISO 14040 and ISO 14044 standards and EN15804+A2 and applies a cradle-to-cradle system boundary, including production stage, end-of-life stage, and potential benefits and loads. Primary data from ceramic industry partners was collected to model industrial production scenarios, and it was supplemented by secondary background environmental data from the ecoinvent database to account for upstream and auxiliary processes.

The LCA study encompasses all major steps in ceramic production, including raw material extraction and processing, formulation of ceramic pastes, shaping and drying, firing, and finishing. For the novel ceramic formulations, the incorporation of reprocessed ceramic and glass waste is modeled to account for its impact on resource conservation and energy consumption. The energy-intensive nature of the firing process makes it a key focus, as reductions in firing temperature could substantially influence the overall environmental profile. The environmental impact categories analyzed follow the EN15804+A2 norm, including Climate Change, abiotic depletion for fossil fuels, abiotic depletion for minerals and metals, acidification and eutrophication, among others.

To ensure robust comparisons, two scenarios are evaluated: i) Baseline Scenario: Conventional ceramic production using virgin raw materials and standard process conditions. ii) Recycled Scenario: Production of ceramics incorporating different proportions of recycled ceramic and glass waste, with potential process optimizations such as reduced firing temperatures. The study also evaluates end-of-life scenarios, including landfill disposal and closed-loop recycling, to understand the long-term sustainability implications of the new ceramic compositions.

Preliminary results indicate that energy consumption is a dominant contributor to the environmental impact of ceramic production. The energy required for firing ceramics at high temperatures leads to significant CO_2 emissions, reinforcing the need for process improvements that enable lower-temperature firing. Recycling solutions that achieve this reduction hold considerable potential for lowering the industry's carbon footprint. Additionally, incorporating recycled ceramic and glass waste can reduce the demand for virgin raw materials, thereby decreasing resource depletion and related impacts such as land degradation and biodiversity loss.

The ongoing comparative analysis between the baseline and recycled scenarios for different environmental impact categories suggests the following findings: i) Climate Change: the recycled scenario has the potential to reduce embodied CO_2 emissions due to lower raw material extraction and the possibility of decreasing firing temperatures. However, the extent of improvement depends on the availability and quality of recycled materials, transportation distances, as well as process optimizations. ii) Abiotic depletion potential for fossil fuels: Energy consumption, namely natural gas and electricity use remain critical factors, with kiln operations being the most energy-intensive stage. If recycling strategies can lead to lower firing temperatures while maintaining product quality, fossil energy savings can be achieved. The gradual incorporation of local renewable energy generation from PVs can also reduce the environmental impacts associated with electric consumption. iv) Abiotic depletion potential for minerals and metals: The integration of recycled materials directly reduces the extraction of virgin minerals (such as feldspar and kaolin), contributing to a more circular production system. Regarding eutrophication and acidification, the reduction of mining activities for raw materials indirectly lessens soil and water pollution, but potential trade-offs related to waste collection and processing must be carefully managed.This aligns with findings from previous studies on sustainable ceramics, which have demonstrated that recycling industrial by-products can lead to environmental benefits without compromising product performance (Gonzalez-Garcia et al., 2017; Vieira et al., 2020). Similar LCA research on glass recycling has also highlighted the importance of reducing melting and firing temperatures to optimize sustainability gains (Faraca et al., 2019).

This study underscores the importance of integrating LCA early in the development of innovative ceramic materials to ensure informed decision-making. The ongoing work highlight that incorporating recycled ceramic and glass waste into ceramic pastes can significantly enhance circularity and reduce environmental impact, particularly in terms of resource conservation and CO_2 emissions. However, achieving optimal benefits may require further process refinements, particularly in reducing the firing temperature without compromising product quality. For industrial stakeholders, these findings provide valuable insights into the feasibility and benefits of adopting more sustainable ceramic production practices. Manufacturers can leverage these results to inform investment in energy-efficient kiln technologies, improve waste management strategies, and refine ceramic formulations to maximize circular economy principles. Additionally, policymakers can use this evidence to support regulations that incentivize industrial waste reutilization and energy-efficient processes in the ceramics sector.

Future research should focus on optimizing recycling techniques, logistics of ceramic waste collection, evaluating alternative low-carbon energy sources, and assessing the long-term durability of ceramics made with recycled content. By continuing to align ceramic production with sustainability goals, the industry can play a crucial role in Europe's transition to a greener, more circular economy.

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