Prospective dynamic probabilistic material flow analysis of advanced (nano)materials in Europe: moving forward to a Circular Economy scenario

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1. Introduction

Climate change, chemical pollution, and circular economy are currently key points in the European policy agenda, for instance, in the EU Green Deal [1], the Circular Economy Action Plan [2], the Chemicals Strategy for Sustainability [3], and the Zero Pollution Action Plan [4]. Therefore, industry needs to ensure that the production and consumption of innovative materials are safe and sustainable along the value chain.

“Advanced materials” (AdMa) is a term broadly used by many researchers since years [5]. The term AdMa usually refers to innovative materials that are rationally designed through the control of their composition and structure or materials that are produced or transformed through advanced manufacturing techniques, in order to fulfil new functional requirements [5-9]. Implementing AdMa in different industrial sectors can be an alternative to achieve the European policy goals [9]. For example, in aeronautics, making lightweight airplanes; in construction, implementing technologies to improve energy efficiency and increase circularity; and, in semiconductor manufacturing, producing smaller and faster integrated circuits [6]. Additionally, advances in science and technology are leading to complex materials [10], such as hybrid materials. One group of such advanced materials are multicomponent nanomaterials (MCNMs), a subgroup of engineered nanomaterials (ENM), which will be referred to as “advanced nanomaterials”.

New materials not only present great opportunities but could also have unintended consequences, for example they could disturb the recycling process or lead to the accumulation of problematic substances [9]. This could become more challenging in the future if European countries move forward a circular economy, because a circular economy requires pollutant-free material flows [9]. Although the Circular Economy Action Plan mentions sectors where ENM are applied (or intended to be) [11], only linear life cycles have been studied, from production to the End-of-Life (EoL) of the products.

For instance, nowadays, the recycling techniques are usually not used intentionally to recover ENM but other materials from the nano-enabled products [12, 13]. However, ENM can also enter into recycling and reprocessing processes when there are available techniques to treat products in the geographical boundary [12, 14]. Thus, it is essential to

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evaluate what could happen in the future due to the long-lasting products involved (in-use stocks), the intention to close the loops, and if advanced (nano)materials can impede the recycling process of economically interesting parts of the product (secondary materials).

The goal of this study is to evaluate possible flows of advanced (nano)materials in the context of a circular economy, principally during the EoL stage of solid mixed waste, considering the outflows of the recycling compartment. Thus, in this study, we used prospective scenario formation and dynamic probabilistic material flow analysis (DPMFA) to explore the potential releases of advanced (nano)materials in a future circular economy context in Europe.

2. Methods

First, we created a tool to guide what could happen with the advanced (nano)material and where it could go during different recycling processes, based on the matrix in which the advanced (nano)material could be embedded, the recycling conditions (e.g., temperature, presence of water, mechanical forces), and the advanced (nano)material's properties (size, surface functionalization, melting point, etc.).

Second, we created three prospective scenarios which represent the dynamics of the system over the years, such as the production development, solid waste collection and sorting, recycling capacity, and circularity. We used DPMFA [15] of ENM to model the flows of advanced (nano)materials across the European Union (EU-27), Norway, Switzerland, and the United Kingdom (referred as EU) from 2025 to 2050 (Figure 1). The code was written in Python and will be publicly available in Zenodo.

The technosphere includes the production of the material under study, manufacturing of the products in which the material is embedded, consumption stage, wastewater treatment systems, and the EoL of the municipal solid mixed waste compartment. While the ecosphere includes environmental compartments, such as the atmosphere, natural and urban soil, sludge-treated soil, subsurface, and surface water. It is important to highlight, that in case the secondary material goes to a product not allocated in the product categories, this flow goes out of the system, mentioned as products "out of the loop" in Fig. 1 (red arrow).

We then evaluated what could happen in Europe according to the EU waste-policy targets, i.e., reducing landfilling and improving recyclability, promoting circular life cycles, and closing-the-loop (red- dashed arrow in Fig. 1, from reprocessing to manufacturing).

The end-of-life (EoL) scenarios are:

- S1 - "Business-As-Usual (BAU)": solid waste collection, recycling, landfilling, and incineration are constant according to the current situation, and linear life cycles are mostly studied;
- S2 - "Exploring circularity": represents the development of recycling techniques, the reduction of landfilling, and the implementation of circular product life cycles within the system;

- S3 - "Closing-the-loop": represents an ideal scenario in which EU waste-policy targets are reached by 2050 and circularity is implemented in most of the product life cycles.

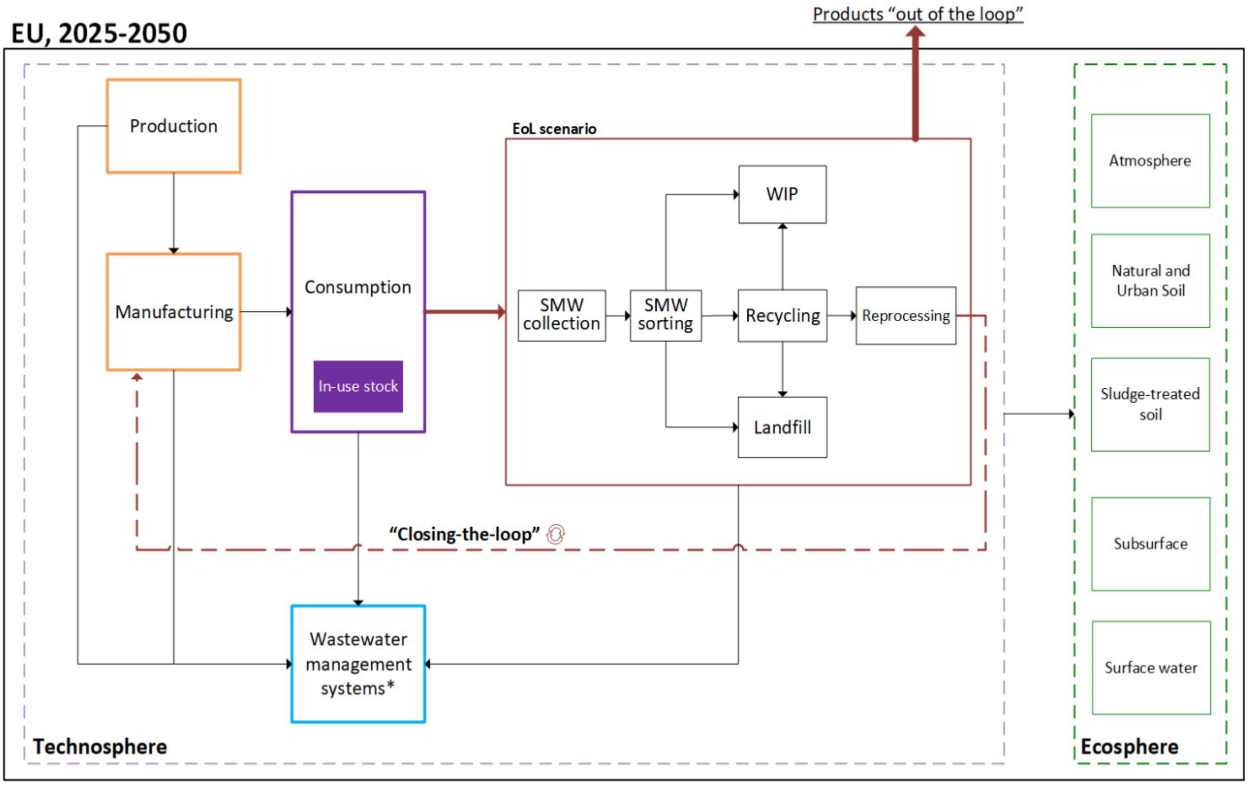

Figure 1. Representation of the material flows. The technosphere, purple-dashed rectangle, includes the technical compartments, such as production, manufacturing, consumption, wastewater management systems, and the EoL management of municipal solid mixed waste, this last section (red rectangle) serves to emphasize that the scenarios consider the SMW collection, sorting, and subsequent compartments where the material could go. The ecosphere, green-dashed rectangle, includes the environmental compartments, such as the atmosphere, natural and urban soil, sludge-treated soil, subsurface, and surface water. Arrows represent flows. EoL stands for End-of-Life, SMW for Solid Mixed Waste.

3. Results and discussion

The scenario are depicted in Figure 2 serve as the possible outflow from the collection and sorting stage of solid mixed waste, which can represent potential circularity of one of the product categories where the advanced (nano)material is embedded, and show the last dynamic layer of the model in which one of more of these pathways might apply depending on the product, matrix, material, recycling technique(s), and so on.

We investigated the available recycling techniques to recover economically interesting parts of the products, in order to analyze if the advanced (nano)material might "pollute" secondary materials and re-enter the life cycle of the product (scenario 3 in Fig. 2). Advanded (nano)materials might therefore end up in other products unintentionally, mainly when there are no industrial techniques to recover those materials, such as in the case of ENM.

The procedure will be first applied in a case study of products containing graphene-based materials [16] with the possible recycling processes from the corresponding products, such as wind turbines, electronics, batteries, among others.

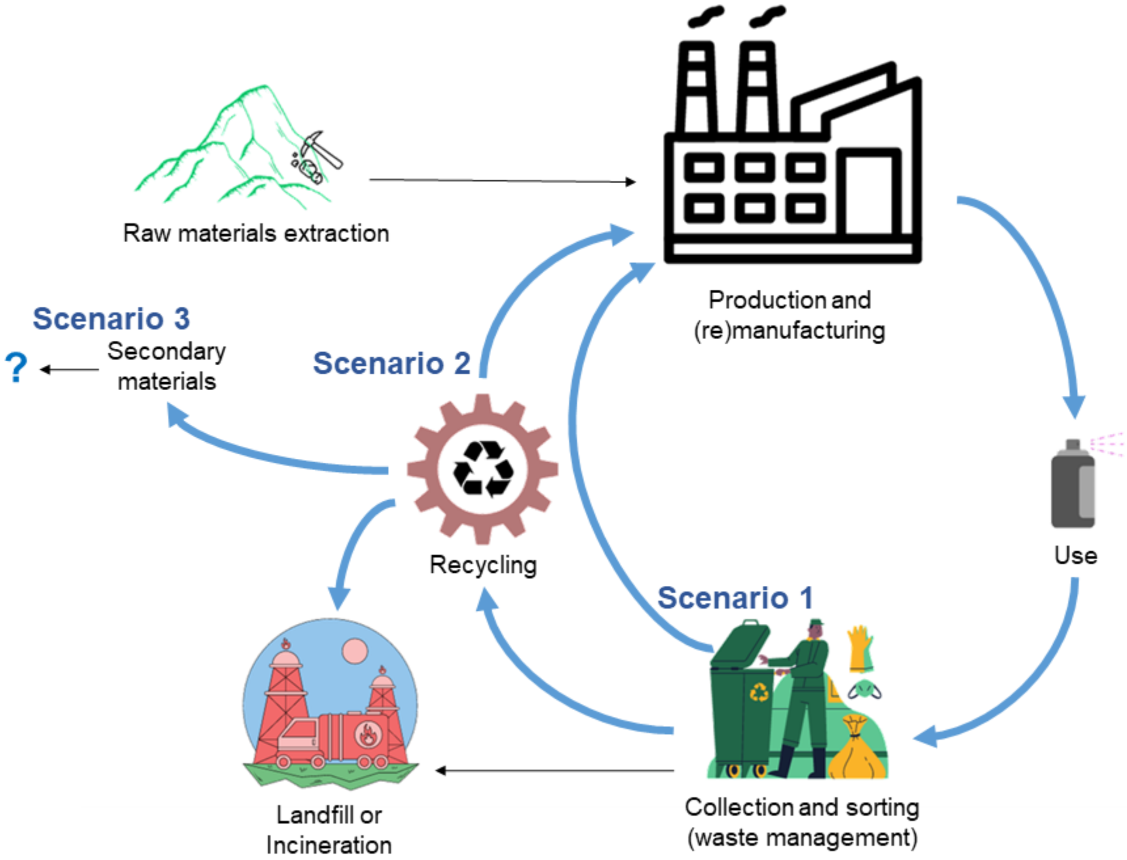

Figure 2. Scenarios to study the flows of the releases of the advanced (nano)materials in the context a circular economy. Life cycle stages under study are represented as blue arrows. Scenario in this figure means possible outflows from the collection and sorting stage of solid waste, as part of the last layer of the model. Created on Canva.

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5. Acknowledgements

The MACRAMÉ project has received funding from the European Union's Horizon Europe Research and Innovation programme under grant agreement No. 101092686. Associated Partners (i.e. (a) Swiss Partners and (b) UK Partners) have received national funding from (a) the Swiss State Secretariat for Education, Research and Innovation (SERI), and (b) Innovate UK.

Lora Dameska acknowledges the opportunity and financial support provided by the Erasmus Mundus Joint Master's Degree Program in Advanced Materials and Innovative