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Materials and articles are constantly increasing in their complexity, promoted by demand for functionality, appearance and cost of consumer and industrial products. To satisfy these demands, a variety of chemicals and combinations of materials are used in products. On the other hand, material recycling has been recognised as a backbone of circular economy, with constant measures and initiatives being proposed in order to increase the recycling rates of materials being consumed. Material cycles are complex and dynamic systems where chemicals are added and removed in production, manufacturing, consumption and waste management stages within a product's lifecycle (Figure 1). Hence, waste materials contain potentially hazardous chemicals that are unwanted in the new products made of the recycled raw materials. So far, the presence of such chemicals in materials for recycling has not been systematically investigated. This PhD project provided detailed quantitative data following a consistent approach to assess potential limitations for the presence of chemicals in relation to material recycling. Paper and plastics were used as illustrative examples of materials with well-established recycling schemes and great potential for increase in recycling, respectively.

The approach followed in the present work was developed and performed in four distinct steps. As step one, fractional composition of waste paper (30 fractions) and plastics (9 fractions) from households in Åbenrå municipality (Southern Denmark) was provided. In step two, a literature review concerning presence of chemicals in paper was performed. It was shown that approx. 10,000 individual chemicals may be present in paper products. Among the chemicals identified, approx. 150 were considered hazardous and approx. 50 were identified as particularly relevant with respect to paper recycling. Potential sources for chemicals in paper were evaluated. Printing and conversion were identified as the most important steps in relation to paper cycle, but chemicals added non-intentionally (NIAS) in a variety of steps (Figure 1) may also play a role.

Figure 1 Schematic representation of generic material and chemical cycles for a defined geographical boundary (e.g., Europe). Chemical loss implies evaporation, degradation, migration, etc., as well as removal through material (re)processing. NIAS: Non-Intentionally Added Substances [1].

Following, chemical analyses for quantification of a range of potential contaminants in paper (mineral oils, phenols, phthalates, polychlorinated biphenyls and toxic metals) and plastics (phthalates and brominated flame retardants) were done. The results indicated large variations in presence of chemical contaminants (from μg/kg to g/kg), depending on the contaminant in focus or the sub-fraction (e.g., books) of the material fraction being analysed (e.g., paper). Certain material fractions showed higher content of chemicals (e.g., bisphenols in thermal paper and flame retardants in polystyrene plastics), potentially detrimental to their recycling. Finally, a material flow analysis (MFA) approach revealed the potential for accumulation and spreading of contaminants in material recycling, on the example of the European paper cycle. Assessment of potential mitigation measures indicated that prevention of chemical use, removal of chemicals in recycling and constrain chemicals to specific product flows were in decreasing order of effectiveness. The assessment also pointed out the potential trade-offs between material quantity (i.e. recycling rates) and quality (i.e. presence of contaminants) when mitigation measures are applied.

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