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From linear to circular integrated waste management systems: A review of methodological approaches

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ABSTRACT

The continuous depletion of natural resources related to our lifestyle cannot be sustained indefinitely. Two major lines of action can be taken to overcome this challenge: the application of waste prevention policies and the shift from the classical linear Integrated Waste Management Systems (IWMSs) that focus solely on the treatment of Municipal Solid Waste (MSW) to circular IWMSs (CIWMSs) that combine waste and materials management, incentivizing the circularity of resources. The system analysis tools applied to design and assess the performance of linear IWMSs were reviewed in order to identify the weak spots of these methodologies, the difficulties of applying them to CIWMSs, and the topics that could benefit from further research and standardization. The findings of the literature review provided the basis to develop a methodological framework for the analysis of CIWMSs that relies on the expansion of the typical IWMS boundaries to include the upstream subsystems that reflect the transformation of resources and its interconnections with the waste management subsystems.

1. Introduction

Resources within planet Earth are finite by nature. Natural resources whose formation roots in other geologic periods, like mineral deposits, cannot be renewed in human timescales and thus their reservoirs are bound to eventually become depleted if their consumption continues (Prior et al., 2012; Shafiee and Topal, 2009). On the other hand, natural stocks subject to biological cycles (a population of trees for example) yield a sustainable flow of valuable goods and services (such as wood and CO_2 removal from the atmosphere) on a continuous basis (Costanza and Daly, 1992). Nonetheless, since the early 1970s some renewable natural resources are being exploited faster than they can be renewed (Borucke et al., 2013). As a matter of fact, it would take 1.64 planets to regenerate in one year the natural resources consumed in 2016 (Global Footprint Network, 2016). This figure is expected to worsen because of the projected population increase and the improved acquisition levels of the emerging economies (Foley et al., 2011; Karak et al., 2012).

If the consumption of raw materials rises, so does waste generation (Shahbazi et al., 2016). Around 1.3 billion tons of MSW are annually produced in cities all over the world (Hoornweg and Bhada-Tata, 2012), and a significant amount of the waste produced in low and lower-middle income countries is disposed of in open dumps (Hoornweg and Bhada-Tata, 2012) lacking measures to prevent safety and environmental hazards. Under the assumption that every ton of MSW generated in cities worldwide could be stored in 1 m^3 of sanitary landfill (Li et al., 2013), a landfill volume equivalent to that of 347,000 Olympic swimming pools would be required every year. Accordingly, policies against landfills are mostly motivated by a lack of space, particularly in the highly populated areas of Europe and Asia, where landfills are more likely to interfere with other land uses like agriculture (Moh and Abd Manaf, 2014).

In fact, waste valorization might help to overcome one of the most pressing global challenges: securing the food supply. Waste has been suggested as a plausible source to recover phosphorus (Reijnders, 2014; Tarayre et al., 2016; Withers et al., 2015), an essential nutrient to the metabolism of plants and by extension to agriculture, whose remaining accessible reserves could run out as soon as 50 years from now (Gilbert, 2009).

Hence, as the principles of industrial ecology dictate, resources and waste management are key to meeting the future needs of society in a sustainable manner. Waste prevention activities or policies such as restricting planned obsolescence in electronic products and measures like minimizing product weight or design for disassembly (Li et al., 2015) will contribute to tackle these issues.

A reduction in the consumption of natural resources and the amount

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Abbreviations: CIWMS, circular integrated waste management system; EFA, energy flow analysis; IWMS, integrated waste management system; LCA, life cycle assessment; LCC, life cycle costing; MFA, material flow analysis; MCDM, multi-criteria decision-making; MSW, municipal solid waste; SFA, substance flow analysis

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of waste generated would also be accomplished if a shift to circular economic and production systems, mimicking the self-sustaining closed loop systems found in nature, such as the water cycle, was put into practice. A circular economy aims at transforming waste back into a resource, by reversing the dominant linear trend of extracting, processing, consuming or using and then disposing of raw materials, with the ultimate goal of preserving natural resources while maintaining the economic growth and minimizing the environmental impacts (Ghisellini et al., 2016; Lieder and Rashid, 2016).

In a circular economy the reduction in the environmental impacts, such as global warming, is due to the improvement in resource and energy efficiencies. For instance, it has been demonstrated that the production of secondary aluminum from scrap consumes less than 5% of the energy needed in the production of primary aluminum (JRC, 2014); this entails that the emission of up to 19 tons of equivalent CO_2 to the atmosphere could be avoided per ton of aluminum that is recycled instead of produced from the mineral ore (Damgaard et al., 2009).

Given all the benefits that the circularity of resources has to offer, the reasonable question to pose is how society and industry can successfully transition to a circular economy. The straightforward answer from an engineering point of view is through the design of efficient CIWMSs that link resource processing and waste treatment, and allow the potential of waste to be fully exploited. A CIWMS is expected to produce not only materials, but also energy and nutrients; additionally, it could deliver certain chemicals.

Therefore, a trade-off between the functions of a CIWMS is unavoidable. A thorough analysis must be carried out prior to the design stage of a CIWMS so that it can assist in the decision-making process. As the analytical framework supported by systems thinking can provide a holistic view on the sustainability challenges that arise from the interconnections between the components of an IWMS (Chang et al., 2011; Singh et al., 2014), so far manifold papers applying a systems-oriented approach to waste management have been published.

That is the reason only the most recent papers focusing on the analysis of IWMSs have been addressed in this study. The aim of this paper is to conduct a critical and comprehensive review of the studies published since 2011 that analyze IWMSs whose input is MSW, in order to gain insight into the strengths and shortcomings of the methodologies currently being applied, and to identify their applicability to a sustainable CIWMS targeting resource recovery. To the best of the authors' knowledge, an IWMS has never been analyzed from the perspective of a circular economy before. The novelty of this review is that the characteristics of a CIWMS are defined, the potential pitfalls of applying the current methodologies deployed in the analysis of linear IWMSs to a CIWMS are identified and possible methodological improvements are proposed.

This review is structured as follows: first, the methodology applied in the selection of the reviewed papers is described. Second, the state-of-the-art technologies and processes for IWMSs are outlined, along with their potential restraints to the development of a circular economy. Third, the characteristics of a CIWMS are defined. Next, the methodologies currently applied to analyze IWMSs are briefly described and the hottest topics regarding the methodological aspects of the analysis of IMWSs are subsequently identified. Finally, the conclusions drawn from the findings of the study are summarized, with special emphasis on the Life Cycle Assessment (LCA) methodology.

2. Method

77 papers analyzing IWMSs that treat MSW and published after 2010 were identified by means of the Scopus database (Scopus Website, 2016). They are listed in Appendix A. The systematic review method was conducted applying four different keyword strings: i) *municipal solid waste*; *integrated*; *system* and *analysis*; ii) *municipal solid waste*; *integrated*; *system* and *methodology*; iii) *municipal solid waste*; *integrated*; *system* and *(sustainable* or *sustainability)*. The papers focusing on the analysis of scenarios regarding alternative waste treatment technologies or processes were excluded from the review.

Once the technological obstacles faced by CIWMSs and the limitations of the methodologies applied for the analysis of IWMSs were detected in the reviewed studies, the search criteria were expanded to cover the specific topics of interest. Those additional papers are listed throughout the document.

3. Technological background

Prior to the proposal of guidelines for the analysis of CIWMSs that enhance the circularity of resources and enable the transition to a circular economy, it is mandatory to recognize the technological restrictions to the implementation of such a system. They are outlined in this section.

3.1. Quality and value of recycled materials

The market penetration of recycled materials is highly dependent on their physical and chemical characteristics, which will determine their price. However, not all the existing recycling technologies enable a fair competition between virgin and secondary materials, because their quality might differ.

Recycling technologies either downgrade or upgrade the materials in respect to the quality of the virgin materials. Downgrading implies that the properties of the recycled material are not as good as those of the virgin material. Instead, upgrading technologies improve the quality of the waste materials at least up to the quality of the virgin materials.

In closed-loop recycling, the material is recycled into the same product system and the inherent properties of the recycled material are maintained virtually identical to those of the virgin material. Oppositely, in open-loop recycling the material is recycled into a different product system and its inherent properties may or may not differ to those of the virgin material (ISO 14044, 2006). Closed-loop recycling is not equivalent to infinite recycling; materials can be used and later recycled within a closed-loop system for a number of times, until microstructural changes in the material or the accumulation of chemical elements and compounds hamper its further reuse (Gaustad et al., 2011).

A case of closed-loop recycling occurs when a glass bottle is recycled into a glass jar, because the glass jar could be recycled back into a glass bottle with the same functionality as the original one (Haupt et al., 2017a), whereas recycling PET bottles into PET fibers is an example of open-loop recycling (Shen et al., 2010); it is an irreversible process.

Recycling processes can be further classified as downcycling or upcycling processes. Downcycling has been defined as the recycling of materials into lower value products (Gaustad et al., 2012). The use of wrought scrap in cast products, due to their ability to accommodate higher silicon contamination, is considered downcycling. On the contrary, if the waste materials are recycled into products of higher value, the recycling process is called upcycling (Pol, 2010). Upcycling involves a change in the fundamental properties of the material, like its physical structure or its chemical composition. Novel approaches to upcycling described in the literature entail chemical (Pol, 2010; Zhuo et al., 2012) or biological transformation (Kenny et al., 2008). Fig. 1 compiles the types of recycling processes according to the quality of the recycled materials and the value of the resulting recycled products in respect to the original materials and products.

Although downgrading and upgrading are often used as synonyms of downcycling and upcycling, Fig. 1 shows that is not necessarily true: a waste material may be upgraded to maintain its original function, and later used to manufacture a product of lower value than the original one. The confusion regarding the terminology has recently been intensified by Geyer et al. (2016), who question the usefulness of making