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Material flow and sustainability analyses of biorefining of municipal solid waste

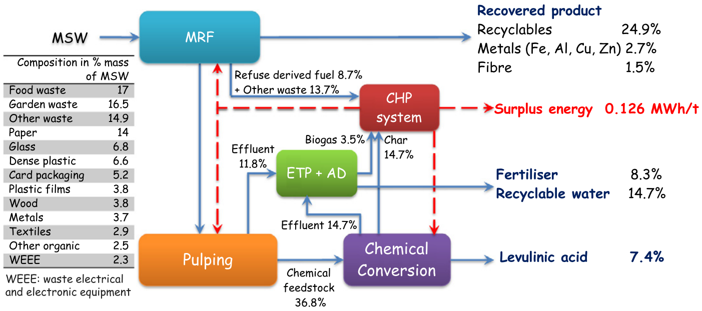
Jhuma Sadhukhan[a],*, Elias Martinez-Hernandez[b]

[a] Centre for Environmental and Sustainability, University of Surrey, GU2 7XH, UK
[b] Department of Chemical Engineering, University of Bath, Bath BA2 7AY, UK

HIGHLIGHTS

- MRF and biorefinery integration for resource recovery from waste (RRfW).
- Integrated system produces levulinic acid, fertiliser and electricity.
- 7.4% mass yield of levulinic acid produced from MSW gives 204 Euro/t net margin.
- Global warming potential (GWP) saving is 2.4 kg CO_2-eq per kg levulinic acid.
- Process integration, essential for achieving the estimated benefits from MSW.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper presents material flow and sustainability analyses of novel mechanical biological chemical treatment system for complete valorization of municipal solid waste (MSW). It integrates material recovery facility (MRF); pulping, chemical conversion; effluent treatment plant (ETP), anaerobic digestion (AD); and combined heat and power (CHP) systems producing end products: recyclables (24.9% by mass of MSW), metals (2.7%), fibre (1.5%); levulinic acid (7.4%); recyclable water (14.7%), fertiliser (8.3%); and electricity (0.126 MWh/t MSW), respectively. Refuse derived fuel (RDF) and non-recyclable other waste, char and biogas from MRF, chemical conversion and AD systems, respectively, are energy recovered in the CHP system. Levulinic acid gives profitability independent of subsidies; MSW priced at 50 Euro/t gives a margin of 204 Euro/t. Global warming potential savings are 2.4 and 1.3 kg CO_2 equivalent per kg of levulinic acid and fertiliser, and 0.17 kg CO_2 equivalent per MJ of grid electricity offset, respectively.

1. Introduction

The world needs to urgently deploy eco-innovative integrated solutions for resource recovery from urban or municipal solid waste (MSW) in the form of biorefinery for the realization of a circular economy resulting into zero-waste urban systems. According to the European Commission department responsible for EU policy on the environment, in 2010, a total of 2.5 billion tonnes of waste was produced (European Commission, Environment, 2017). Only, 40% were reused or recycled, while some countries sent 80% of the waste to landfill. According to the estimation by the World Bank, at the current pace, MSW generation would exceed 11 million tonnes per day by 2100 (World Bank, 2013). The rate of waste generation would increase from 1.2 to 1.42 kg per person per day in the next fifteen years. Wastes are the main cause of pollution posing threat to health, and the natural, and living envrionment. The world is faced with resource constraints, and increased waste

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* Corresponding author.
E-mail address: jhumasadhukhan@gmail.com (J. Sadhukhan).

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generation and demands for products. An approach/opportunity to deal with these challenges is using lesser amount of virgin resources, and reusing waste as resources.

Technologies for bulk conversion of MSW are mature, but have disadvantages such as generation of toxic wastes and emissions, requiring disposal via costly routes (Cheng and Hu, 2010). The state-of-the-art treatment technologies of MSW include incineration, and anaerobic digestion (AD) and compost like output (CLO) generation, broadly fall into two categories, thermochemical (Bhaskar and Steele, 2015; Emun et al., 2010) and biochemical (Walker et al., 2009; Peralta-Yahya et al., 2012) processing, respectively. Incineration of MSW, a mean of energy recovery from waste supported by numerous waste legislations (e.g. European Commission, Environment, 2017), produces three main types of residues, bottom ash considered as non-hazardous waste, fly ash contains metals, heavy metals, metal oxides, chlorides and organic compounds, and air pollution control residue contains chlorides (Margallo et al., 2015). Life cycle assessment (LCA) studies have revealed high environmental impacts due to air pollutant emissions, and fly ash disposal, in addition to high capital and operational costs, and equipment corrosion, etc. as the main bottlenecks of these technologies (Cherubini et al., 2009), for the consideration of policy makers (Finnveden et al., 2005). Some post-combustion or end-of-pipe clean-up technologies exist, however, are not particularly effective in mitigating pollution to the environment or lowering the cost of processing (McKay, 2002; Buekens and Huang, 1998). Thermal degradation of MSW in a progressive manner, e.g. first decomposition of biomass then polymers using enhanced gasification with CO_2 recycling, has been effective in generating a clean fuel gas (Kwon and Castaldi, 2012). Mechanical biological treatment (MBT) is the main alternative to thermochemical processing of MSW. A recent work shows that MBT facilities incorporating composting with AD have a higher waste treatment performance efficiency than the MBT facilities relying on composting (Colón et al., 2017). However, leaching of heavy metals and other elements from the use of CLO as soil amendment has remained as a consistent problem, if not removed before AD, and poses a high risk to the environment (Page et al., 2014).

As waste resources are a heterogeneous mixture of many components, which if unrecovered pose the greatest environmental impacts, recovery of every pollutant as an added value resource is essential for sustainability. It is critical to recover recyclables and metals at the beginning of the processing chain of MSW before fuel production, such as refuse derived fuel (RDF), a coal like fuel, and the facility to achieve so, is coined as material recovery facility (MRF) (Chang et al., 2005). Resource recovery from waste (RRfW) coined by the Natural Environment Research Council (2012) infers by definition, recovery of every potential pollutant to the environment, as added value resources from waste streams and putting the added value resources back into value chains for a zero waste circular economy and better health of the environment (Sadhukhan, 2017). Since the introduction of the concept, process integration between RRfW and biorefinery is being researched (Sadhukhan et al., 2016a,b). Metallurgical, and microbial electrosynthesis are the main secondary mining technologies that can play a key role RRfW (Ng et al., 2016). RRfW can be designed and configured to recover metals, heavy metals, metal oxides, elements, inorganics, etc. prior to valorisation of biodegradable components of MSW, thus mitigating the in-process and end-of-pipe environmental emissions. Furthermore, pollutant-free biodegradable component of MSW opens up a plethora of product choices. Plausible processes, products, and pathways in biorefinery have been investigated in Sadhukhan et al. (2014). The conversion of this organic fraction into value added chemicals has been studied for the production of polyhydroxyalkanoates (Amulya et al., 2015), volatile fatty acids (Bonk et al., 2015; Karthikeyan et al., 2016) and lactic acid (Kwan et al., 2016). A biorefinery combining anaerobic fermentation and hydrothermal liquefaction for production of volatile fatty acids and bio-oil has also been conceptualised (Coma et al., 2017). Other potential pathways for valorisation of the organic biodegradable fraction of MSW have been reviewed elsewhere (Arancon et al., 2013; Bastidas-Oyanedel et al., 2016; Mohan et al., 2016; Chen et al., 2016).

Extraction of C1–C6 molecules from the biodegradable or biomass or lignocellulose or organic components of MSW is the key to determine economic feasibility and sustainability of the system. Presently, there is only one study on valorisation of biodegradable fraction of MSW into the production of levulinic acid (Sadhukhan et al., 2016a). Levulinic acid is a platform or building block chemical precursor to many added value products (Sadhukhan et al., 2014). Ethyl valerate, an ester derived from levulinic acid, is a drop-in biofuel, which can be blended upto 45% by volume and have a demand as high as 22 million barrel a day (GF Biochemicals, 2015). Derivatives of levulinic acid have applications as pharmaceutical, specialty chemical, agricultural, solvent, platform chemical and fuel additive products. Levulinic acid is one of few molecules referred as 'sleeping giants' owing to their vast potentials in the emerging bio-based economy due to their key positions in the production of biomass-derived intermediates and transition from fossil based economy to bio- renewable- based circular economy. GF Biochemicals to date is the main producer of levulinic acid at their plant in Caserta, Italy (GF Biochemicals, 2015). Levulinic acid has emerged as a niche platform chemical in production of pharmaceutical and agrochemical derivatives: δ-aminolevulinic acid, specialty chemical: γ-valerolactone, polymers and resins: diphenolic acid, platform chemical: pyrrolidones, succinic acid and fuel additive: levulinate esters, 2-methyltetrahydrofuran with addressable petrochemical replacement potential of over 25×10^6 t by 2020 (GF Biochemicals, 2015).

As discussed, there is only one comprehensive study on valorisation of biodegradable fraction of MSW into the production of functional chemicals such as levulinic acid (Sadhukhan et al., 2016a). A paradigm shift in MSW processing systems is thus the need of the hour not only to eliminate losses of value-added products to landfills, save virgin resources and increase resource recovery efficiency, but also to close the loop for a circular economy. This paper, thus to fill the gap, presents eco-innovative, efficient, cleanest, and sustainable options for recovering high-grade valuable materials and chemicals that are not currently recovered from MSW. These have been systematically derived using the following tools:

1. Analysis of MSW mass flows into products via Sankey diagrams.
2. Economic value analysis for finding profitable and non-profitable products and integrated biorefinery configurations of MSW for highest economic benefit.
3. Assessment of avoided global warming potential over 100 years (GWP) impact for relative benefits by delivering new products with respect to current use of waste feedstocks, and by replacing one by the other in order to be able to move towards a more circular economy paradigm.

Section 2 discusses the above methods for deriving sustainable biorefinery systems recovering resources from MSW, Section 3 results and discussions, and Section 4 conclusions.

2. Materials and methods

MSW consists of paper and cardboard packaging; glass; dense plastic and plastic films (container, plastic packaging); wood, garden and food waste; textiles; WEEE (waste electrical and electronic