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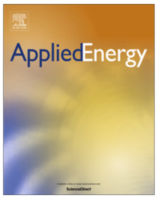

Bioenergy, material, and nutrients recovery from household waste: Advanced material, substance, energy, and cost flow analysis of a waste refinery process

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HIGHLIGHTS

- We modeled material, substance, energy, and cost flows of a waste refinery process.
- Ca. 56% of 1 Mg dry waste input can be recovered as bioliquid yielding 6.2 GJ biogas.
- Nutrients and carbon recovery in the bioliquid was estimated to 81–89%.
- The biogenic carbon in the input waste was 63% of total carbon based on ^{14}C analyses.
- The quality of the digestate may be critical with respect to use on land.

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ABSTRACT

Energy, materials, and resource recovery from mixed household waste may contribute to reductions in fossil fuel and resource consumption. For this purpose, legislation has been enforced to promote energy recovery and recycling. Potential solutions for separating biogenic and recyclable materials are offered by waste refineries where a bioliquid is produced from enzymatic treatment of mixed waste. In this study, potential flows of materials, energy, and substances within a waste refinery were investigated by combining sampling, analyses, and modeling. Existing material, substance, and energy flow analysis was further advanced by development of a mathematical optimization model for determination of the theoretical recovery potential. The results highlighted that the waste refinery may recover ca. 56% of the dry matter input as bioliquid, yielding 6.2 GJ biogas-energy. The potential for nitrogen, phosphorous, potassium, and biogenic carbon recovery was estimated to be between 81% and 89% of the input. Biogenic and fossil carbon in the mixed household waste input was determined to 63% and 37% of total carbon based on ^{14}C analyses. Additional recovery of metals and plastic was possible based on further process optimization. A challenge for the process may be digestate quality, as digestate may represent an emission pathway when applied on land. Considering the potential variability of local revenues for energy outputs, the costs for the waste refinery solution appeared comparable with alternatives such as direct incineration.

1. Introduction

Within the recent decade, focus on recovery of materials, resources, and energy from solid waste has increased significantly in the endeavor of reducing fossil fuel consumptions and resources depletion [1,2]. Particularly, separation and recovery of the biodegradable fraction of municipal solid waste (MSW) is encouraged in [1,2] as a mean to produce bioenergy and recycle the nutrients (phosphorous, nitrogen, and potassium as organic fertilizers) on land. In addition, in the regions where landfilling (instead of, for example, incineration) is the most common disposal method, separation of the biodegradable organics (e.g. kitchen waste, tissues, etc.) becomes a necessary priority in order to minimize landfilling and comply with political targets (e.g. [3]). However, although technologies exist for sorting selected waste material fractions, an efficient separation of organic materials, for bioenergy and nutrients recovery, and recyclables,

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to reduce resource consumption, is difficult with mixed household waste.

Organic waste source-segregation at the household may contribute to this goal; yet, recent studies have highlighted that such a strategy may end up being inefficient (mass- and energy-wise) as a consequence of the losses occurring at the household and during the pre-treatments [4]. Therefore, the development of technologies for separating the biodegradable fraction of the municipal waste and optimizing its energy conversion becomes very important. For instance, mechanical–biological treatment (MBT) plants typically use a combination of mechanical operations to separate the organic fraction of the incoming mixed waste from the remaining materials (e.g. plastic, metals, and paper), which are partly recovered (and sent for recycling) and partly mixed to produce refuse-derived fuel (RDF). The separated organic fraction could be anaerobically digested to produce biogas-energy or aerobically stabilized and landfilled [5].

Emerging waste refining technologies provide potential solutions for organic separation and promise improved energy and materials recovery [6,7]. For example, the waste refinery investigated in [6,7] uses enzymatic treatment to produce two outputs from the incoming waste: a bioliquid (liquefied paper, cardboard, and organics) and a solid fraction (undegraded materials). Many of these plants are, however, still in the pilot testing stage, and obtaining a sufficiently high quality of recovered materials is difficult. For instance, in the pilot plant described in [6,7] the post-treatment to separate recyclables needs further development. The post-treatment aims at maximizing the recovery of bioliquid and at sorting recyclables from the solid fraction ex-enzymatic treatment. In the ideal post-treatment all the biomass (and associated biogenic carbon) would be diverted to the bioliquid flow; in other words, all the biomass would be recovered. A number of unit processes may be useful for this purpose; for example, washing, pressing, and sieving with recirculation of the washing liquid into the enzymatic vessel. However, 100% efficiency is not realistic and some biomass would still be found in the solid fraction as undegraded organics (e.g. shells), paper, and textiles.

With regard to documenting the development potential, simple sampling at such preliminary facilities cannot provide data appropriate for full-scale implementation of the technologies. From this perspective, material-, substance-, and energy-flow analysis (MFA, SFA, and EFA) are useful techniques to assess mass, energy, and substance flows in a range of different urban systems (e.g. waste management, bioenergy, urban metabolism, etc.), including evaluation of the quality of the recovered resources [8]. In the specific context of waste management, MFA and SFA are often utilized to highlight the fate of valuable materials and substances and to further suggest system improvements on the basis of the results. Further, the results of MFA and SFA are often used as a basis for life-cycle assessment (LCA). From this perspective, MFA, SFA, and LCA represent complementary tools for environmental management [9]. For instance, [10] used MFA to identify the relevant waste flows in a waste-emergency area and to suggest management solutions; [11] combined MFA and LCA to assess the performance of a garden waste composting plant; [12,13] used MFA and SFA to estimate flows and recycling efficiencies for electronic waste; [14] modeled the energy content of solid recovered fuel (SRF) based on MFA. [15] combined SFA and LCA to assess the performance of bioenergy scenarios. However, in addition to mass and substance flow analyses, in order to address the theoretical performance of pilot-scale waste refineries, mathematical modeling needs to be applied to determine the potential optimum recovery of bioliquid, materials, and nutrients, thereby providing a target for further technological development. Mathematical optimization has been extensively used in studies about waste, bioenergy, and waste-to-energy in order to evaluate potential technology performances, limitations, and associated improvement potentials. Among the others, mathematical optimization modeling was applied to evaluate potential performances and limitations of waste- and biomass-to-energy systems (both thermal and biological) [16–23] and also to evaluate potential optimal solutions for maximizing energy and environmental savings in wastewater treatment [24,25], industrial production [26–28] and waste management strategies [29–31].

This study used an advanced MFA, SFA, and EFA approach based on a mathematical optimization model to evaluate the potential flows of materials, substances (e.g. carbon, nutrients, and selected metals), and energy within a waste refinery including downstream energy conversion processes. The objectives of the study were: (i) a detailed sampling and characterization of the outputs of a pilot-scale waste refinery process (materials flow and chemical composition) with particular focus on the bioliquid; (ii) the development of a mathematical optimization model to evaluate the potential for recovery of bioliquid, materials, and nutrients with a ‘virtual’ post-treatment phase; (iii) the development of MFA, SFA, and EFA models based on the mathematical model outputs to illustrate the potential flows of materials, energy, carbon (including fossil carbon, i.e. C_{foss}), nutrients, and selected metals (Al and Fe); (iv) the evaluation of the quality of the digestate left after anaerobic digestion of the bioliquid in order to assess the load of nutrients and metals in the scenario of application on land; (v) the estimation of the costs of the waste refinery solution compared with alternative waste management systems.

2. Materials and methods

The study involved five major phases: (1) On-field sampling of the pilot-scale waste refinery outputs (bioliquid, fluff, and solid fraction ex-enzymatic treatment); hand-sorting of the solid fraction was also performed at this point: six individual waste material fractions were sorted and separated (see Section 2.2). Thus, in total, eight waste material fractions were collected (six from the solid fraction ex-enzymatic treatment plus bioliquid and fluff). (2) Preparation of the eight individual samples for chemical analyses (shredding, mixing, splitting, etc.). (3) Chemical composition analyses (including calorific value). (4) Elaboration of a mathematical optimization model to estimate the potential for bioliquid, materials, and nutrients recovery with a ‘virtual’ post-treatment. (5) Elaboration of MFA, SFA, and EFA to illustrate material, substance, and energy flows within the waste refinery process including virtual post-treatment and downstream energy and materials recovery processes. These flows were also used as basis for the cost analysis. Table 1 summarizes the five phases of the study with the associated methods applied.

2.1. The waste refinery process

The study was based on the operation of a pilot-scale plant (0.5–1 Mg wet waste (ww) h^{-1}), where the waste was processed (heating and enzymatic treatment) without further post-treatment. The pilot-scale plant treated residual municipal solid waste (rMSW) collected from a residential district of Copenhagen (Denmark) where a vacuum-collection system is established. The waste was sampled and characterized within this study (as the output of the waste refining process; see Section 3).

The waste refinery aims at producing two products from the incoming MSW: (i) a bioliquid (i.e. slurry composed of enzymatically liquefied organics, paper, and cardboard) and a solid fraction (i.e. non-degradable waste materials). The refinery process consisted of two reactors: in the first reactor the waste was heated to about 75 °C for approximately 0.5–1 h and then cooled to about