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Torrefaction of textile waste for production of energy-dense biochar using mass loss as a synthetic indicator

Yogeshwari Pooja Rago*, Dinesh Surroop, Romeela Mohee

Department of Chemical & Environmental Engineering, Faculty of Engineering, University of Mauritius, Réduit 80837, Mauritius

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ABSTRACT

Textile waste torrefaction was investigated as a novel means to assist in waste valorization and energy management practices. This study analyzed the thermal behavior and fuel properties of textile waste subjected to torrefaction at 225, 250, 275 and 300 °C for 1 and 3 h at a constant heating rate of 15 °C/min. The energy and carbon contents of torrefied textiles were greatly enhanced whilst unusually high energy yields above 100% were recorded due to the energy densification process. Reduced atomic H/C and O/C ratios revealed that the fuel characteristics and reactivity of torrefied textiles converged towards those of coal. FTIR analysis indicated that torrefaction altered the chemical structure of textile waste with respect to its hemicellulose and cellulose contents. A strong linear correlation was observed between mass loss and the energy properties of torrefied textile biochar. This demonstrated the effectiveness of mass loss as a synthetic indicator of the degree of torrefaction. The analytical expressions derived experimentally represent essential tools that can be used in the optimization of the torrefaction process. Torrefied textiles can eventually assist in the displacement of important fractions of coal in thermal conversion systems in the long run.

1. Introduction

Growing concerns about climate change, greenhouse gas (GHG) emissions, energy instability and the lack of space for new landfills have led to increased interest in waste valorization practices in line with the UN Sustainable Development Goals (SDG) 2030. Energy recovery from wastes via thermochemical techniques provide important avenues for the sustainable management of both energy and wastes. Considering the high cellulosic composition of textile waste and its fairly high calorific value (~17 MJ/kg), textile waste constitutes an important source of bioenergy that can be tapped for power production purposes [1]. However, the tenacious fibrous structures of textile waste may render the energy conversion process more complex and less effective as shredding and grinding become difficult and energy intensive [2].

As part of the Small Island Developing States (SIDS), Mauritius is highly susceptible to various challenges including waste management, energy instability and climate change concerns. Solid wastes are conventionally disposed of in the sole sanitary landfill of the island whilst a minor fraction is rerouted for composting and recycling [3]. Textile waste accounts for roughly 4.9% of the Mauritian municipal solid wastes (MSW) composition, of which only 31% is recycled [4]. The remaining non-recycled fractions are landfilled, contributing to GHG emissions and leachate formation. On average 58.8 tons of textile waste are generated daily, out of which 40.6 tons are landfilled. The discharge of harmful and hazardous compounds due to reactions caused by chemicals and dyes in the fabric materials are additional deleterious impacts of landfilling textile waste. On the other hand, the nonexistence of oil, coal and gas reserves in Mauritius justifies the island's total reliance on imported sources of energy. With a peak energy demand of 459.9 MW in 2015, the energy requirements in Mauritius have been continuously rising [5]. The main objective of the Mauritian government is to diversify the energy regime while curbing dependence on fossil fuels, especially coal. As such, combustion of textile waste is rather complex and thermally less energy efficient due to its relatively low calorific value compared to coal. Additionally, the cost of handling and disposing of textile waste is increasing proportionally with the rising amount of wastes. Thus, the thermochemical conversion of textile waste to marketable biofuels can be highly advantageous from an energy, environmental and economic perspective. Kosov et al. [6] stated that torrefaction generates solid products whose thermo-technical characteristics are comparable to coal. These torrefied solids are preferable than coal energy due to their less harmful components and can therefore be applied as coal substitutes in various energy sectors.

Recently, waste valorization through torrefaction is being viewed as a low environmental impact technique for the sustainable management of both energy and wastes [7,8]. Indeed, torrefaction has emerged as a

* Corresponding author.
E-mail address: yogeshwari.rago@umail.uom.ac.mu (Y.P. Rago).

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promising biomass pre-treatment that generates energy-dense biochar at low operating temperatures of 200–300 °C under inert conditions [8,9,10,11,12]. Torrefaction offers several benefits: the tenacious fibers in biomass are destroyed and the energy density of the biofuel is enhanced [13]. Increased hydrophobicity of torrefied products, on account of their lower affinity for moisture, facilitates handling, storage and transportation of the treated biomass [7,12,14]. Based on their lowered O/C and H/C ratios and their high carbon contents, torrefied solids are comparable to coal [2,8,15,16,17]. Torrefaction lowers the mechanical resilience in torrefied solids as compared to the parent feedstock [11] such that the grindability [18] and particle size distribution of the resulting biochar are upgraded. This reduces the energy requirement for comminuting untreated biomass by 50–85% and lowers power consumption in pyrolysis, gasification and co-firing systems [7,8,12,13,15,16].

Although numerous research works have been conducted on torrefaction of a wide array of biomass namely, bamboo, willow, coconut shell [16], eucalyptus [14,19], reed canary grass [17], sawdust and agricultural wastes such as coffee residue and rice husk [9], there are limited studies on the torrefaction of solid wastes. Unlike biomass species, wastes are highly heterogeneous in nature such that their thermal treatment becomes more challenging. Torrefaction of wastes is presently limited to laboratory scale only as the process is complex due to the heterogeneous nature of the wastes compared to biomass torrefaction. It therefore requires technical and economic clarity. The thermal behavior of each component in waste undergoing torrefaction has not been fully investigated. So far, fast pyrolysis of specific textile waste has been examined, with emphasis on bio-oil production. Miranda et al. [1] studied the thermal degradation and kinetics of pyrolysis of textile in a temperature range of 400–700 °C and obtained a yield of 72 wt% of bio-oil, 12.5 wt% of residual solid and 13.5 wt% of non-condensable gases at 700 °C. The kinetics of pyrolysis of ramie textile waste were investigated through thermogravimetric analysis (TGA) at different heating rates by Zhu et al. [20]. Zhu et al. [21] probed into the pyrolysis reactions and thermal behavior of cotton and flame-retardant cotton fabrics at 600 °C using TGA and obtained a higher share of condensable products in contrast to a smaller amount of biosolid.

Interestingly, the thermal behavior and biochar yield of mixed textile waste subjected to torrefaction (within a low temperature range of 200–300 °C) have not been fully explored. Recently, only Lin et al. [22] examined the hydrothermal carbonization (wet torrefaction) of waste textile at 230 and 280 °C from 30 min to 90 min and obtained an energy dense (22 MJ/kg) and carbon-rich hydrochar. The thermal conversion of textile waste during dry torrefaction is relatively unknown. Mass loss denotes an important indicator for evaluating the progress of the torrefaction process and is being acknowledged as a significant tool for assessing the energy properties of torrefaction [15,19]. In an attempt to bridge the above-mentioned research gaps, this work was initiated to explore the potential of textile waste torrefaction as a novel means to generate high-quality biochar compared to untreated waste. The present study assessed the thermal behavior of textile waste when subjected to torrefaction, to produce energy-rich biochar at increasing torrefaction temperatures between 225 and 300 °C at a residence time of 1 and 3 h. This paper simultaneously determined the effectiveness of mass loss as a synthetic indicator of the severity of textile waste torrefaction. Emphasis was put on mass loss measurement, energy and mass yields and enhancement in the physicochemical properties of torrefied textile waste. The main functional groups in treated and untreated textile waste were characterized through Fourier Transform Infrared (FTIR) spectroscopy.

2. Materials and methods

The main experimental plan adopted for this study is illustrated in Fig. 1.

2.1. Feedstock material preparation

Reject and defective fabric materials from different textile factories in Mauritius were collected. The samples included a mix of various types of textile fabrics of different colors and sizes although cotton fabric was predominant. The composition of textile waste was roughly estimated to: cotton (~70%), viscose (~10%), polyamide (~10%) and polyester (~10%). To obtain a homogenous mixture, the mixed textile waste was first cut into small pieces of approximately 2 cm × 2 cm and shredded using a cutting mill pulverisette having an average mesh size of 9 mm. All untreated samples were oven-dried at 105 °C for 24 h until constant mass was obtained. The dried, shredded untreated textile waste was kept in hermetically sealed polyethylene bags in a desiccator until torrefaction.

2.2. Torrefaction process

Torrefaction experiments were conducted in a stainless steel lab-scale reactor vessel. The reactor consisted of a 220 mm long cylindrical body having an internal diameter of 70 mm, an inlet-feed aperture and a gas outlet. The gas outlet of the reactor was connected to a 400 mm tube having an internal diameter of 10 mm. The methodology adopted for textile waste torrefaction was based on the experimental set-up implemented by Sadaka and Negi [11]. For efficient production of torrefaction gas, the waste samples occupied over 60% of the reactor volume.

65.0 ± 5 g of dried and shredded textile waste was fed into the pre-weighed reactor vessel and the inlet feed point was tightly sealed. Nitrogen gas (pressure: 200 kPa) was flushed into the reactor vessel for a duration of 10 min, before each torrefaction experiment to purge any traces of oxygen from the system as per the experimental work of Sadaka and Negi [11]. The reactor containing the waste sample was loaded into the muffle furnace as shown in Fig. 2 (Type Carbolite model GSM 11/8; power: 3.05 kW). The furnace was preheated from room temperature to the desired torrefaction temperature at a fixed heating rate of 15° C/min to cater for energy losses in the system. Upon reaching the set-point temperature, the waste was allowed to torrefy for a minimum residence time of 1 h.

The condensable fractions produced were collected through a condenser unit while the volume of torrefaction gas produced was estimated through liquid displacement method before being vented to the atmosphere. Tap water (at 20 °C) was pumped into the condenser unit to promote cooling of the hot gaseous stream of condensable and non-condensable components. At the end of the torrefaction process, the reactor was removed from the furnace and allowed to cool down at ambient temperatures. All cooled solid and liquid products formed were measured, collected and preserved for further analysis. The solid samples were kept in air-tight plastic bags in a desiccator. Torrefaction was conducted at four different temperatures: 225, 250, 275 and 300 °C and each experiment was repeated at a residence time of 3 h. Every experiment was repeated thrice under the same operating condition to ensure reproducibility of results.

2.3. Product analysis

The untreated and torrefied textile solids were evaluated through proximate and ultimate analyses, determination of calorific value, bulk density and flowability, mass and energy yields and FTIR analysis respectively. The proximate analysis, elemental composition and calorific value of torrefied solids were compared to those of coal derived from the works of Chiang et al. [23].

2.3.1. Proximate analysis

The moisture content, ash content and volatile matter content of the untreated and torrefied textile waste were determined through proximate analysis as per ASTM E790, E871, E830 and E897. The fixed