Renewable and Sustainable Energy Reviews 96 (2018) 253–261

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Energy and carbon coupled water footprint analysis for Kraft wood pulp paper production

Xiaotian Ma, Xiaoxu Shen, Congcong Qi, Liping Ye, Donglu Yang, Jinglan Hong*

Shandong Provincial Key Laboratory of Water Pollution Control and Resource Reuse, School of Environmental Science and Engineering, Shandong University, Jinan 250100, PR China

ARTICLE INFO

Keywords:
Pulp and paper
Energy consumption and recovery
Carbon emissions
Water footprint
Wastewater treatment

ABSTRACT

Although paper production demonstrates high energy and water sensitivity in their life cycles, only a few systematic analyses have focused on these issues. Therefore, an energy and carbon coupled water footprint analysis of five types of Kraft wood pulp-based paper (i.e., specialty-, art-, household-, light coated-, and tissue paper) is conducted in this study to help improve the environmental performance of the paper industry. All investigations are conducted with an impact-oriented approach based on ISO standards. Results show that elemental-chlorine-free bleaching is more environmentally friendly than chlorination-alkaline extraction-hypochlorite bleaching, specifically for global warming, aquatic eutrophication, and human health (i.e., carcinogens and non-carcinogens). Gray water footprint along whole life cycles of each product is approximately twice of blue water footprint. Direct processes contribute approximately 50% to water scarcity, while their impact on aquatic eutrophication ranges from 0.002% to 50.72%. For other midpoints, indirect processes dominate the influences. Meanwhile, COD, BOD_5, CO_2, TP, Cr (VI), Ti, Hg, and As are key contributors. Finally, reusing sludge by direct burning in the recovery furnace, reclaiming organic compounds in black liquor before alkali recycling, and integrating black liquor gasification technology are expected to provide substantial environmental benefits. Amelioration of wastewater treatment, optimization of the national energy structure, and improvement of the efficiency of chemicals and freshwater are recommended.

1. Introduction

The pulp and paper industry is well known as its high energy and water sensitivity [1,2], contributing about 3% of global end uses of energy [3] and 40% of global industrial wastewater [1]. Meanwhile, its wastewater contains various pollutants (e.g., COD, BOD, chlorinated organic compounds, and absorbable organic halides) [4] and approximately 90% of pollutants originate from cooking stage during Kraft pulping process (i.e., black liquor) [5]. Meanwhile, approximately half of the energy is consumed in cooking stage [6]. Thus, Kraft wood pulp, which accounts for about half of the world's total pulp output in 2016, is analyzed in this study to help improving the environmental performance of paper industry [7]. China's Kraft wood pulp production ranked the fifth place in the world and accounted for 5.76% of the total global output of 136.2 million tons in 2016 [7]. In China, wastewater emitted by pulp and paper industry accounted for 18% of the total industrial wastewater emissions [8]. However, the amount of wastewater, which ranks the first in all industries, does not match its production value of 1.5% of China's total value [9]. Therefore, a systematic assessment of water discharge and consumption during China's Kraft wood pulp paper production is highly necessary. Water footprint (WF) is a comprehensive indicator in geographical and temporal dimensions for evaluating water pollution and consumption derived from anthropogenic activities which includes both direct and indirect processes [10]. Furthermore, energy consumption and carbon emissions are combined in WF analysis for their high value during paper production in China [2]. Various methods, such as the IPCC report for carbon emissions [11], ReCiPe model for energy consumption [12], and four-step WFA methodology [10], have been proposed to reply these issues. These methods are widely used. However, traditional WF analysis methods cannot analyze complex industrial processes during a product's entire life cycle [13]. They also do not consider environmental burdens (e.g., toxic effects) [14], are incomparable when used for different products [15], and do not assess air and soil emissions which affect water quality [16]. To address these problems, International Organization for Standardization (ISO) prescribed life cycle assessment (LCA) as the normative WF analysis method [16]. However, direct application of the international model to China's WF analyses may lead

* Corresponding author.
E-mail address: hongjing@sdu.edu.cn (J. Hong).

https://doi.org/10.1016/j.rser.2018.07.054
Received 11 December 2017; Received in revised form 14 July 2018; Accepted 29 July 2018
1364-0321/

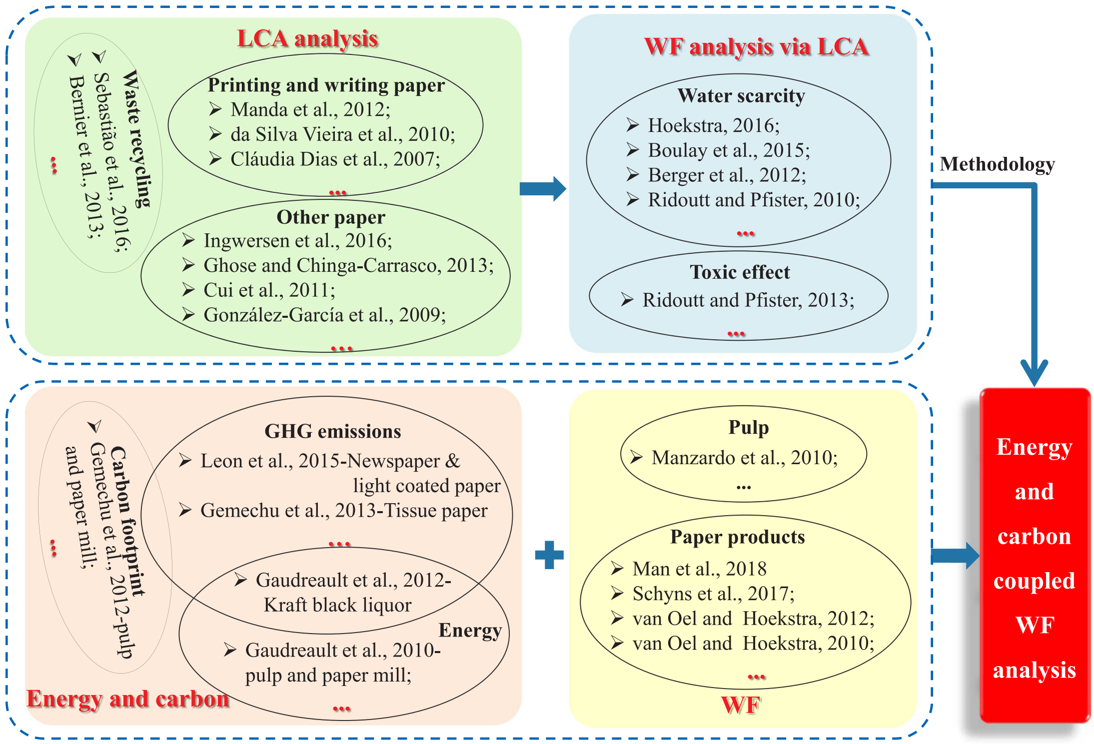

Fig. 1. Literature review.

to inaccurate results [14,17]. Thus, an LCA-based WF analysis that uses China's own information and toxic effects related only to water quality needs to be conducted.

Accordingly, this study aims to 1) evaluate the WF of five Kraft wood pulp paper (i.e., specialty-, art-, household-, light coated-, and tissue paper) via an energy and carbon coupled WF analysis approach which includes the toxic effects of pollutants enter into water through various ways; 2) perform a comparative analysis of pulping processes, various papers production, and wastewater treatment scenarios; 3) analyze the key factors during whole paper production stages; 4) provide useful suggestions for reducing energy consumption, carbon emissions, and WF during Kraft wood pulp paper production. The rest of this paper is organized as follow. A review of existing studies on the pulp and paper industry that used WF and LCA method is presented in Section 2. Accordingly, reasonable system boundary and impact categories are established in Section 3. An energy and carbon coupled WF analysis of Kraft wood pulp paper production is conducted in Section 4. Key factors, studies on black liquor recovery, and comparisons of different wastewater treatment scenarios are also explored in this section. Furthermore, an uncertainty analysis is performed for the comparison of pulping technologies. Section 5 presents an evaluation of the footprint analysis results and discusses the key unit (i.e., black liquor recovery system) comprehensively to determine the reduction potential of the Kraft wood pulp paper industry.

2. Review of literatures

Studies on WF analysis of the pulp and paper industry are limited, and the only exception is the study of Manzardo et al. [18], Man et al. [19], Schyns et al. [20], and van Oel and Hoekstra [21,22]. Nevertheless, the key factors during a product's entire life cycle and detailed information on gray WF in paper production have generally been ignored. Thus, in this study, LCA is combined with WF analysis to deal with these problems [23]. LCA can trace the potential to improve the environmental performance of products during their life cycle, inform decision-makers, and promote marketing by addressing environmental burdens during a product's life cycle [24]. LCA methodology is also applied in the analyses of carbon emissions and energy consumption. For the wood pulp and paper industry, most studies related to LCA focused on the analysis of different paper products and greenhouse gas (GHG) emissions [25]. Ingwersen et al. [26], Ghose and Chinga-Carrasco [27], Manda et al. [28], Cui et al. [29], da Silva Vieira et al. [30], González-García et al. [31], Dias et al. [32], and Sun et al. [33] presented LCA analysis results for paper towel, Norwegian newsprint, printing and writing paper, coated white board, Portuguese writing paper from different pulp, hardboard, Portuguese printing and writing paper produced with Kraft pulp, and straw-based pulp, respectively. These studies all indicated that energy consumption plays an active role in pulp and paper production, and a similar finding can be observed in GHG [34,35] and carbon emissions [36,37] analysis via LCA. Gaudreault et al. [38] analyzed different options for the reduction of electricity consumption during pulp and paper production. LCA has also been applied in the analyses of waste recycling which aims to alleviate environmental burdens caused by energy consumption and water pollution, such as bioethanol production from sludge [39], Kraft lignin recovery [40], Kraft black liquor recovery [6], and recovery of global wastepaper [41]. However, no WF analysis of the pulp and paper industry has been conducted with the LCA methods. Furthermore, most current methodologies for WF analysis via LCA method, such as the models reported by Hoekstra [42], Boulay et al. [43], Berger et al. [44], and Ridoutt and Pfister [45], pertain to water scarcity which can further affect agricultural irrigation, food production, and ecosystem diversity. The toxic effect has been generally disregarded by researchers, expect for Ridoutt and Pfister [15], who carried out a WF analysis by multiplying water emissions with the characterization factor of the ReCiPe method. However, neither that the air and soil emissions which impact water quality are ignored nor that the intake routes via soil and air were excluded. Accordingly, the results reported by Ridoutt and Pfister [15] are inaccurate [14]. Additionally, most presented studies focused on newsprint and writing paper according to aforementioned reviews, whereas other types (e.g., specialty paper, kitchen paper, and art paper) were rarely noticed Fig. 1.