Chemical Engineering Journal 298 (2016) 162–182

Contents lists available at ScienceDirect

Chemical Engineering Journal

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

Review

# Anaerobic digestion of pulp and paper mill wastes – An overview of the developments and improvement opportunities

Mohammadreza Kamali [a,b,*], Tânia Gameiro [a], Maria Elisabete V. Costa [b], Isabel Capela [a]

[a] Department of Environment and Planning, Center for Environmental and Marine Studies, CESAM, University of Aveiro, 3810-193 Aveiro, Portugal
[b] Department of Materials and Ceramics Engineering, Aveiro Institute of Materials, CICECO, University of Aveiro, 3810-193 Aveiro, Portugal

## HIGHLIGHTS

- Historical perspective of P&P mill wastes anaerobic digestion is critically reviewed.
- Recent progress in anaerobic digestion of P&P mill wastes is reviewed and discussed.
- Combined methods are proposed as promising technologies for P&P wastes treatment.

## GRAPHICAL ABSTRACT


## ARTICLE INFO

*Article history:*
Received 8 October 2015
Received in revised form 19 March 2016
Accepted 22 March 2016
Available online 30 March 2016

*Keywords:*
Pulp and paper industry
Wastewater
Sludge
Anaerobic digestion
Methane production

## ABSTRACT

Various organic and inorganic hazardous substances are commonly originated during the processing of virgin or recovered fibers (RCFs), when the pulp and paper (P&P) are produced. Hence, pulp and paper industry (PPI) strongly need to employ advanced waste treatment processes as a powerful tool to comply with the stringent environmental regulations in one hand, and to increase their profitability in the current declining P&P markets, on the other hand. Among the treatment alternatives, anaerobic digestion (AD), is an interesting cost-effective alternative with a small environmental footprint and has been increasingly adopted by the PPI to reach this goal. However, the application of AD to deal with wastes generated in P&P mills has been restricted due to a number of limitations, regarding the anaerobic reactor design and the operating conditions. Hence, the optimization of the AD performance would be a crucial step in order to increase the economic benefits, and also to satisfy the strict environmental protection standards. To this end, this paper presents an overview on the current state of the developments associated with AD treatment of P&P mill wastes to assess the applicability of this treatment process for the management of this type of complex wastes. In this context, suggestions are provided to maximize both biogas production and removal efficiency, focusing on the relationship between waste composition and reactor design and operational conditions, which will enhance methane capture and contribute to prevent global warming.



**Contents**



* Corresponding author at: Department of Environment and Planning, Center for Environmental and Marine Studies, CESAM, Department of Materials and Ceramics Engineering, Aveiro Institute of Materials, CICECO, University of Aveiro, 3810-193 Aveiro, Portugal.
*E-mail address:* Kamali@ua.pt (M. Kamali).

http://dx.doi.org/10.1016/j.cej.2016.03.119
1385-8947/

**Nomenclature**

| | |
|---|---|
| ABR | anaerobic baffled reactor |
| AD | anaerobic digestion |
| AFs | anaerobic filters |
| AOPs | advanced oxidative processes |
| AOXs | adsorbable organic halogens |
| AnMBRs | anaerobic membrane bioreactor |
| BI | biodegradability index |
| BOD | biochemical oxygen demand |
| COD | chemical oxygen demand |
| CP | chemical pulping |
| CTMP | chemical thermo-mechanical pulping |
| DCP | dichlorophenol |
| ECF | elemental chlorine free |
| ENMs | engineered nanomaterials |
| FBRs | fluidized bed reactors |
| HRT | hydraulic retention time |
| KP | kraft pulp |
| LTAD | low temperature anaerobic digestion |
| MP | mechanical pulping |
| NPs | nanoparticles |
| OLR | organic loading rate |
| P&P | pulp and paper |
| PPI | pulp and paper industry |
| PPMW | pulp and paper mill wastewater |
| PPMS | pulp and paper mill sludge |
| PPS | pulp and paper sludge |
| PVDF | polyvinylidine fluoride |
| RCF | recovered fiber |
| SAnMBRs | submerged anaerobic membrane bioreactors |
| SBR | sequencing batch reactor |
| SCOD | soluble chemical oxygen demand |
| SCP | semi-chemical pulping |
| SRT | solids retention time |
| SGBR | static granular bed reactor |
| SPC | sulfonated polycarbonate |
| TCF | total chlorine free |
| TCOD | total chemical oxygen demand |
| TDS | total dissolved solids |
| TSS | total suspended solids |
| TMP | thermomechanical pulping |
| UASB | upflow anaerobic sludge blanket |
| UAF | upflow anaerobic filter |
| UAPBR | upflow anaerobic packed bed reactor |
| VFAs | volatile fatty acids |



## 1. Introduction

Various wood or non-wood materials are the main raw materials for the production of pulp and paper (P&P) in many countries through the world (Fig. 1). Moreover, P&P manufacturing from recovered fibers (RCFs) has been increased during recent years [1]. After preparation of stock materials, steps including pulping, bleaching, and P&P making are applied, respectively, to yield pulp or paper as final products (Fig. 2). Based on the raw materials used and the manufacturing process adopted, P&P industry (PPI) produce relatively large amounts of both wastewater and solid wastes [2]. On-site, reuse and recycling, and also modifications in the technology [3] are among the most efficient economic and environmental options dealing with the produced residues. In this regard, measures for minimizing the produced wastes, and recovery of energy and unavoidable wastes have been introduced [4] and adopted by PPI [5]. However, the external waste treatments are still the main ways to deal with the residues from PPIs, especially for small and medium size units which generally do not benefit of infrastructures for the recovery of chemicals [6]. So far, various types of treatments (primary, secondary, and tertiary) have been developed and applied in order to enhance the treatment efficiency of both pulp and paper mill wastewater (PPMW) and sludge (PPMS) with the aim of reducing the amount of the produced final wastes, and also to prevent the probable subsequent toxic effects induced by the presence of hazardous compounds when released into the receiving environment [7].

Anaerobic digestion (AD), defined as the biological degradation of organic compounds into different end products, including methane (50–75%), carbon dioxide (25–50%), hydrogen (5–10%), and nitrogen (1–2%) [8] by a microbial consortium in the absence of air [9], has been widely employed for primary or secondary treatment of various industrial residues. The development of methods for the AD process control and monitoring [10] as well as the operational conditions set-up has raised a large interest in recent studies. This is mainly due to the advantages of AD over conventional biological P&P waste treatment, such as a significant reduction of the produced wastes and the production of biogas, mainly composed by methane. Despite these advantages, some improvements in the stability of the process, in methane yields,