

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/263324783>

Review on recent developments on pulp and paper mill wastewater treatment

Article in *Ecotoxicology and Environmental Safety* · June 2015

DOI: 10.1016/j.ecoenv.2014.05.005 · Source: PubMed

CITATIONS

461

READS

6,544

2 authors:



Mohammadreza Kamali

KU Leuven

139 PUBLICATIONS 4,562 CITATIONS

SEE PROFILE



Zahra Khodaparast

University of Aveiro

35 PUBLICATIONS 1,309 CITATIONS

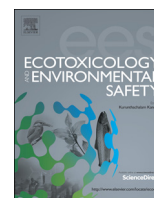
SEE PROFILE



ELSEVIER

Contents lists available at ScienceDirect

Ecotoxicology and Environmental Safety

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

Review

Review on recent developments on pulp and paper mill wastewater treatment

Mohammadreza Kamali ^a, Zahra Khodaparast ^{b,*}

^a University of Aveiro, Department of Environment and Planning, Portugal

^b University of Aveiro, Department of Biology, Campus Universitario de Santiago, 3810-193 Aveiro, Portugal

ARTICLE INFO

Article history:

Received 17 January 2014

Received in revised form

7 May 2014

Accepted 9 May 2014

Available online 18 June 2014

Keywords:

Pulp and paper industry

Physicochemical treatment methods

Aerobic digestion

Anaerobic digestion

ABSTRACT

Economic benefits of the pulp and paper industry have led it to be one of the most important industrial sections in the world. Nevertheless, in recent years, pulp and paper mills are facing challenges with the energy efficiency mechanisms and management of the resulting pollutants, considering the environmental feedbacks and ongoing legal requirements. This study reviews and discusses the recent developments of affordable methods dealing with pulp and paper mill wastewaters. To this end, the current state of the various processes used for pulp and paper production from virgin or recovered fibers has been briefly reviewed. Also, the relevant contaminants have been investigated, considering the used raw materials and applied techniques as the subject for further discussion about the relevant suitable wastewater treatment methods. The results of the present study indicated that adopting the integrated methods, alongside a combination of biological (e.g., anaerobic digestion) and physicochemical (e.g., novel Fenton reactions) treatment methods, can be environmentally and economically preferable to minimize environmental contaminants and energy recycling.

© 2014 Elsevier Inc. All rights reserved.

Contents

1. Introduction	327
2. P&P production techniques and key pollutants	327
2.1. P&P from virgin fiber	327
2.1.1. P&P from virgin fiber – production techniques	327
2.1.2. P&P from virgin fiber – key pollutants	328
2.2. P&P from RCF	330
2.2.1. P&P from RCF – production techniques	330
2.2.2. P&P from RCF – key pollutants	330
3. Advances in P&P wastewater treatments	330
3.1. Physicochemical methods	331
3.1.1. Sedimentation and floatation	331
3.1.2. Coagulation and precipitation	331
3.1.3. Membrane technologies	331
3.1.4. Adsorption	332
3.1.5. Oxidation	332
3.2. Biological techniques	334
3.2.1. Fungal treatment	334
3.2.2. Aerobic treatment	335
3.2.3. Anaerobic digestion	337
4. Conclusion	339
References	340

* Corresponding author.

E-mail address: Khodaparast@ua.pt (Z. Khodaparast).

1. Introduction

Pulp and paper (P&P) industry is considered a large user and producer of biomass based energy and materials (Svensson and Berntsson, 2014). To maintain their profitability and overcome the declining (Machani et al., 2014) and competitive (Karikallio et al., 2011) markets, P&P mills are no longer limited to production of pulp and/or paper; rather, they may adopt additional measures including waste heat delivery to district heating systems (e.g., Ericsson et al., 2011; Klugman et al., 2009) and production of the electricity, wood pellets, and dried bark as well as valuable chemicals such as ethanol (e.g., Fornell et al., 2012; Phillips et al., 2013) and materials like carbon fiber (see e.g., Maradur et al., 2012), biofuels, etc. (Jonsson et al., 2011).

However, the pulp and paper (P&P) industry is now facing challenges to comply with stringent environmental regulations. These factories commonly produce considerable amounts of wastewaters, especially from virgin raw materials processing. Such effluents have the potential to adversely affect the receiving aquatic environment through, for instance, slime production by microorganisms such as *Sphaerotilus sp.* (Pellegrin et al., 1999) and formation of scum, as well as toxicity to the exposed communities, thermal impacts, color problems, and aesthetical issues (Pokhrel and Viraraghavan, 2004), in case of incomplete treatment. The generated effluents, based on factors such as raw materials used and employed production process, commonly have a high COD (Table 1) and a low biodegradability (defined as the ratio of BOD₅/COD) and more than 200–300 different organic compounds and approximately 700 organic and inorganic compounds (Karrasch et al., 2006). Such substrates may include non-biodegradable organic materials, adsorbable organic halogens (AOX), color, phenolic compounds, etc. (Buyukkamaci and Koken, 2010), depending upon the applied pulping process, additive chemicals, and the amount of water consumed. Accordingly, in both traditional and emerging P&P producers (e.g., Chen et al., 2012) such as United States (Schneider, 2011), China (Zhu et al., 2012), and India (Afroz and Singh, 2014), P&P mills are considered a major source of environmental pollutants.

Pollutants which are released during several parts of P&P production process can be reduced by adopting several internal process improvements, especially in combination with management measures. In this regard, European Commission (2001) has described the best available techniques (BAT) to be adopted by P&P mills. Moreover, several studies have been carried out with the final purpose of reduction in the pollution load during the P&P making process (Martín-Sampedro et al., 2011). However, the external processes, including the primary clarification, secondary treatment, and/or tertiary processes have remained the main remediation ways used in P&P mills which can be simply divided

into physicochemical and biological processes. In order to contribute to more development of these technologies, it is beneficial to demonstrate their current status. Hence, through a brief review of P&P manufacturing techniques and key pollutants released directly into the wastewater contents, recent and advanced P&P wastewater treatment methods have been reviewed and discussed in the present paper.

2. P&P production techniques and key pollutants

P&P are produced from virgin or recovered fibers (RCFs) as raw materials. Chemical, mechanical, or a combination of them are common pulp producing processes from virgin raw materials while recovered pulp is produced from fiber recovering processes. Produced pulp is further processed using additional non fiber materials, such as fillers, to obtain the paper web.

2.1. P&P from virgin fiber

2.1.1. P&P from virgin fiber – production techniques

Manufacturing processes of paper and paperboard can be generally divided into three steps: pulp making, pulp processing, and paper-making (Avsar and Demirel, 2008). Pulping is the process generally started by debarking which removes soil, dirt, and bark from the wood raw materials and converts the plant fiber into smaller pieces (chips) (Ali and Sreerishnan, 2001). Resulting wood pieces are cooked at high temperature and under high pressure. Also, chemical techniques can be used to separate lignin and hemicelluloses from cellulose, used for making paper. This process is usually carried out by means of wet processes, which is responsible for removing large amounts of organic compounds from the processing wood (Vepsäläinen et al., 2011).

The yield of the mechanical pulping (MP), compared with chemical-based processes, is generally high (90–95%), but the quality of the products is significantly low (Pokhrel and Viraraghavan, 2004). Improvement of MP can be achieved by several techniques, such as thermo-mechanical pulping (TMP), chemo-mechanical pulping (CMP), and chemical thermo-mechanical pulping (CTMP). In TMP, the raw materials are exposed to pressurized steam for a short period of time, followed by refining. Chemical treatments (e.g., by using hydrogen sulfite (HSO₃)) can also be applied to TMP during the steaming stage for further modifications to form CTMP (Ekstrand et al., 2013). In recent years, some studies have been carried out to optimize the CTMP which produces fibers by biological (e.g., Lei et al., 2012) or chemical pre-treatment (e.g., Pan et al., 2013) of wood chips prior to refining. Chemical pre-processing of the raw materials, before exposing to mechanical pulping, is another common way to increase the efficiency of the process which is called CMP. Kraft pulp

Table 1

Typical characteristics of effluents from P&P production processes.

Unit operations	pH	COD (mg/L)	BOD ₅ (mg/L)	BOD ₅ /COD	TSS (mg/L)	Reference
Wood yard and chipping ^a	7	1275	556	–	7150	Avsar and Demirel (2008)
Thermo-mechanical pulping	4.0–4.2	3343–4250	–	–	330–510	Qu et al. (2012)
Chemical thermo-mechanical pulping ^b	7.43	7521	3000	–	350	Liu et al. (2011)
Kraft cooking section	13.5	1669.7	460	0.27	40	Wang et al. (2007)
Pulping process operations ^c	5.5	9065	2440	–	1309	Avsar and Demirel (2008)
Bleaching ^d	8.2	3680	352	–	950	Kansal et al. (2008)
Paper machine	6.5	1116	641	–	645	Avsar and Demirel (2008)
Integrated pulp and paper mill	6.5	3791	1197	–	1241	Avsar and Demirel (2008)
Recycled paper mill	6.2–7.8	3380–4930	1650–2565	0.488–0.52	1900–3138	Zwain et al. (2013)

^a Pulpwood storage, debarking, and chipping.

^b Alkaline peroxide mechanical pulping (APMP).

^c Pulping, pulp screening, pulp washing and thickening, bleaching, and kraft repulping.

^d A combination of chlorination and alkaline extraction stages.

(KP) is a widely used type of chemical pulping (CP) which is an alkaline process to produce chemical pulp. The wood chips are cooked in a solution of sodium hydroxide (NaOH) and sodium sulfide (Na_2S), called white liquor, to remove the lignin (Sainlez and Heyen, 2013). Moreover, some other inorganic compounds, such as Na_2CO_3 , Na_2SO_4 , Na_2SO_3 , and $\text{Na}_2\text{S}_2\text{O}_3$, can be presented in the liquor (Ekstrand et al., 2013). The resulting black liquor can be concentrated and burned in a recovery furnace to yield an inorganic smelt of Na_2CO_3 and Na_2S to reproduce the needed chemicals for cooking (Sainlez and Heyen, 2013). So far, some studies have been done with the aim of increasing the produced pulp and decreasing the amount of the related pollutants. The results of a recent study revealed that partial substitution of MgO for NaOH could lead to a lower dissolution of chemical components in pulp fibers. As a result, the pulp yield can be improved while decreasing the effluent load (Ye et al., 2012). The neutral sulfite semi-chemical (NSSC) is a traditional CP which uses a mixture of Na_2SO_3 and NaHCO_3 in order to dissolve the lignin (Ekstrand et al., 2013). Bleaching process is the next step which may be applied to brown pulp in order to improve brightness and to make it appropriate for paper making operations. In this regard, several bleaching agents can be used, such as chlorine, chlorine dioxide, hydrogen peroxide, oxygen, ozone, etc., through elemental chlorine free (ECF) or total chlorine free (TCF) bleaching processes. ECF is mainly conducted by using ClO_2 and H_2SO_4 in an acidic environment or NaOH, which is often combined with O_2 , and hydrogen peroxide in an alkaline phase are used to enhance the extraction stage of the lignin oxidation. In TCF, different combination patterns of bleaching acid (H_2SO_4), ozone, O, chelating agents, and/or hydrogen peroxide (P) steps are used (Ekstrand et al., 2013). P is an oxidant compound which has been widely applied for pre-delignification of chemically produced pulps, in bleaching sequences. This process is mainly used to decrease the kappa number and increase the brightness and stability of the produced pulps. Also, P can become more effective in combination with the tetraacetyl-ethylene-diamine (Requejo et al., 2012). Washing the produced pulps (e.g., by using an alkali caustic soda) is then applied to remove the bleaching agents and hardly biodegradable compounds (Ali and Sreekrishnan, 2001).

The final stage of P&P production is paper-making, in which the processed pulp is combined with some materials including dyes, resins, fillers such as clay, titanium dioxide, calcium carbonate, and sizing agents like rosin and starch, to form the paper (Ali and Sreekrishnan, 2001; Avsar and Demirel, 2008). Afterwards, the mixture is dewatered by pressing and the resulting sheets are dried, using air or heat (Santos and Almada-Lobo, 2012). In this regard, paper-making industry is especially interested in increasing the filler content of paper. This is mainly because they are relatively cheap materials that improve the paper optical and bulk properties and also its smoothness (Gamelas et al., in press). However, the application of mineral fillers can affect the paper strength properties. To overcome this problem, some measures have been proposed such as complexation of fillers with cellulose fines (Subramanian et al., 2008), surface modification of fillers (Shen et al., 2009), and filler pre-flocculation (Sang and Englezos, 2012). It must be stated that particle size of these minerals are in the colloidal range. As a result, they are difficult to settle during wastewater treatment (Nasser et al., 2013).

Paper making normally consumes a large amount of energy. Chen et al. (2012), by analyzing the energy flow for three major energy consuming P&P mills in Taiwan, concluded that paper making consumes 47.2% of electricity and 94% of thermal energy, compared with that for pulping process (41.7% and 4.5%, respectively). Saving in energy and raw materials as well as low environmental impacts can be achieved through employing new methods and using new materials in paper making process. Holmberg et al. (2013) stated that 32% of the electrical energy and 9.6% of the total energy consumption goes to overcome the

friction in paper machines which is in the range of 15–25% in the entire paper mill. They concluded that friction losses can be reduced by 11% in the short term (about 10 years) and by 23.6% in the long term (20–25 years) by adopting some measures such as the use of low-friction coatings, surface engineering, appropriate lubricants and fluids, novel additives, new materials in seals, doctorblades, foam forming technology, and new designs. Manda et al. (2012) illustrated that 60% and 35% wood saving for the nanoparticle coated recovered fiber and micro TiO_2 coated CTMP paper can be achieved, respectively. Moreover, the nanoparticle coated recovered fiber paper offered up to 100% and 75% savings in non-renewable energy use and greenhouse gases emission, respectively, compared with conventional paper making processes by using ECF bleaching of kraft pulp.

2.1.2. P&P from virgin fiber – key pollutants

The volume and properties of P&P wastewater and related pollutants depend upon several factors, such as production scale, the raw materials used, and applied production technologies (Tiku et al., 2007). Long time ago (beginning of 20th century), production of a ton of paper would require consumption of 500–1000 m^3 of water (Holik, 2006). Thanks to technological advances, the amount of water needed for different parts of paper making processes has been significantly decreased, e.g., by using wet processes (Bajpai, 2010). For instance, in German pulp and paper industry, it has been decreased down to 13 m^3 per ton of produced paper (Holik, 2006). Although small and medium pulp and paper mills (< 100t/d) normally generate smaller quantities of wastewater, compared with large mills (> 100t/d), they produce a higher pollution load (Garg, 2012). This is mainly due to the fact that most of small and some of medium scale P&P mills do not have an infrastructure for chemical recovery and they discharge them directly into the produced effluents (Tewari et al., 2009; Tiku et al., 2007).

In recent years, wood species have been the most widely used raw materials for P&P manufacturing throughout the world (Wanrosli et al., 2007). For instance, *Pinus radiata* is the main raw wood material in some countries such as New Zealand. The effluents produced from these raw materials usually include high amount of resin acids, which are naturally occurring in conifer species (Fraser et al., 2009). The predominant key raw material in south eastern European countries (such as Spain and Portugal), Brazil, and other regions of the world is *Eucalyptus*, and in particular *Eucalyptus globulus*, which provides the highest yield with the best pulp quality in kraft pulping and TCF (Martinez-Inigo et al., 2000). Sterols (mainly β -sitosterol), waxes, and β -sitosterol esters are the main compounds in the deposits after kraft cooking and oxygen pre-bleaching of such raw materials (Del Rio et al., 1998).

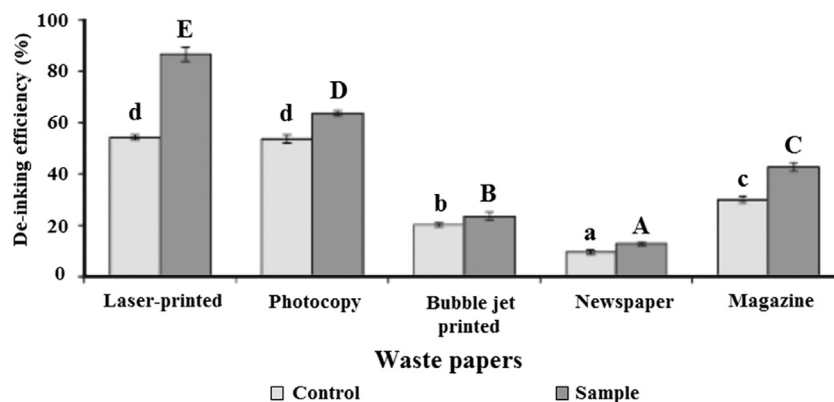
In addition to the wood-based fibers, the production of cellulose pulp from non-wood fibers has risen in recent years. Alternative materials mainly include agricultural residues such as canola straw (Hosseinpour et al., 2010), residual vine shoots (Jiménez et al., 2009), rice straw (Rodríguez et al., 2010), wheat straw (Hedjazi et al., 2009), sunflower stalks (Khristova et al., 1998), and sugar cane bagasse (Andrade and Colodette, 2014). The ratio of the cellulose and other substances in such raw material contents is considered an important factor to estimate the potential for production of waste materials during pulping process. This variable is also very significant to assess the selected raw material suitability for production of cellulose P&P (Rodríguez et al., 2010).

Cellulose pulp production is responsible for generation of large amounts of wastewater resulting from cooking the raw materials, especially when some sulphur-containing reagent is used (e.g., in the kraft pulping processes). During wood preparation, soil, dirt

Table 2

Major pollutants released from P&P making process (Ali and Sreekrishnan, 2001; Pokhrel and Viraraghavan, 2004; Tewari et al., 2009).

Process stage	Wastewater		
	Volume	Pollution load	Effluent content
Raw material preparation	Low	Low	Suspended solids including bark particles, fiber pigments, dirt, grit, BOD, and COD.
Pulping	Low	High	Color, bark particles, soluble wood materials, resin acids, fatty acids, AOX, VOCs, BOD, COD, and dissolved inorganics.
Bleaching	High	High	Dissolved lignin, color, COD, carbohydrate, inorganic chlorines, AOX, EOX, VOCs, chlorophenols, and halogenated hydrocarbons.
Paper-making	Depends on the extent of the recycling effluents	Low	Particulate wastes, organic and inorganic compounds, COD, and BOD.

**Fig. 1.** Enzymatic de-inking efficiency of different types of waste papers. Arrow bars illustrate means with standard error. Means with the same letter (a, b, c, d, A, B, C, D, and E) showed no significant difference by least significance test at 5% level of probability (Lee et al., 2013).**Table 3**The amount of the consumed raw materials to produce 50 g/m² of printing and writing paper (Hong and Li, 2012).

Materials	Unit	Writing paper	
		With RCF	With wood pulp
Waste paper	kg	1.36	–
Wood chips	m ³	–	3.50 × 10 ⁻³
Chlorine	kg	–	0.07
Sodium hydroxide	g	–	4.49
Starch	g	3.61	3.61
Talcum powder	kg	0.10	–
Fresh water	kg	3.20	84.88
Salt	g	0.56	0.44
Husk	kg	0.71	0.57
Chemicals organic	g	12.14	12.14

and bark are removed from the raw materials. Consequently, the effluents are highly colored, mainly due to their tannin content. Resin acids are also included in debarking waters. Isopimaric, sandacopimaric, levopimaric, abietic, dehydroabietic, neoabietic and palustric acids are resin acids which can be generally found in pulping wastewaters (Vepsäläinen et al., 2011). The pulp produced in the pulping process is brown and, thus, subject to bleaching in order to increase its brightness. Wastewater from this process normally includes wood debris and soluble wood materials. Moreover, depending upon the type of pulping process, various toxic chemicals, such as resin acids (which naturally occur in the resin of tree wood), unsaturated fatty acids (such as oleic acids, linoleic acid, and linolenic acid), diterpene alcohols, juvaniones, chlorinated resin acids, and others, are generated (Ali and Sreekrishnan, 2001; Pokhrel and Viraraghavan, 2004) with high levels of BOD and COD (Freitas et al., 2009). For instance, effluents from TMP

process (white water), which is often responsible for the corrosion problems in paper making machines (Tenno and Paulapuro, 1999), are typically wood-based with normally medium strength and concentrations ranging from 1000 to 6000 mg/L COD, including easy biodegradable material, such as carbohydrates and organic acids (Kortekaas et al., 1998). The lignin fraction causes high concentration of COD in the white water which remains after bleaching in the generated wastewater. It also includes some chemical additives involved in the paper making processes such as soluble silicates (3SiO₂·Na₂O), widely known as water glass (Huuha et al., 2010). In addition to the mentioned compounds, some other contaminants may appear in pulping process effluent. As an example, black liquors, from the kraft process, generally contain aqueous solution of sodium hydroxide and sodium sulfide, which have been used to break up and remove the lignin, and they are known to adversely affect the treatment facilities and aquatic life (Betancur et al., 2009).

Chlorine-based bleaching processes are responsible for majority of environmental problems. Related effluents normally contain a large amount of chlorophenols, adsorbable organic halogens (AOX) (Requejo et al., 2012), and extractable organic halogens (EOXs) as well as a trace of toxic substances such as DDT, polychlorinated biphenyls, and polychlorinated dibenzodioxines (Karrasch et al., 2006). Some halogenated polycyclic aromatic hydrocarbons have been detected in KP mill products and discharges (Koistinen et al., 1994). Also, dioxins, furans, chlorinated lignosulfonic acids, and chlorinated resin acids are found to be produced during the bleaching process (Ali and Sreekrishnan, 2001). Therefore, it is environmentally beneficial to establish and develop alternative technologies, which use non-chlorinated oxidant compounds such as oxygen, ozone or peroxide hydrogen. However, in spite of being more environmentally friendly, compared with ECF, TCF maintains a small niche market less than 5% of

the world bleached chemical pulp production, because of higher production costs and lower strength and brightness of the produced pulp (Bajpai, 2012). Nowadays, sequential ECF can be considered representative of conventional ECF bleaching which includes chlorine dioxide oxidation stage at acidic conditions and alkaline extraction with aqueous sodium hydroxide (Calvo et al., 2007). Table 2 summarizes the main pollutants which are normally produced during several steps of P&P making process.

2.2. P&P from RCF

2.2.1. P&P from RCF – production techniques

Recovering waste papers such as mixed office waste, old newsprint and old corrugated container have been increasingly used during recent decades because of a number of environmental and economic reasons. FAO (2012) reported that the global collection of recovered fibers for recycling purposes between 1970 and 2010 shows a significant increase from 30.8 million tons to 208 million tons in 2010. Natural resources saving and reduction of both emissions and solid waste generation can be stated the main reasons of such ongoing growth (Van Beukering and Bouman, 2001).

Recycling the RCF can be conducted through processes which can be mainly divided into pulping, high density screening and de-inking stages. Pulping is generally applied to convert the waste paper into the RCF dispersed in water and to prepare them for de-inking process, which removes the ink particles from cellulose fibers. Screening is responsible for the removal of large particles with high and medium density, such as paper clips and staples. De-inking can be considered as the main stage of the RCF recycling process which basically consists of separation of ink particles from the cellulose fibers and removal of the detached particles from pulp slurry by washing for ink particles less than 25 μm in diameter (Borchardt et al., 1998) or floatation for larger particles such as toner inks and laser printed papers (Zhenying et al., 2009). Large amount of toxic substances, such as H_2O_2 , NaOH , Na_2SiO_3 , Na_2CO_3 , and other compounds like surfactants, are currently applied as chemical de-inking agents with the aim of improving the brightness of the produced pulp (Zhang et al., 2008). Some of chemical reactive agents can also be applied in floatation process in order to provide efficient COD removal from RCF slurries. In a study conducted by Beneventi et al. (2009), it has been demonstrated that the ozone floatation allowed increasing COD removal from 41% to 63%. However, some particles such as toners usually remain as large, flat, and rigid particles that are very difficult to remove by application of current separation techniques, during de-inking stage. The use of biological agents such as pectinases, hemicellulases, cellulases, and lignolytic enzymes is a possible and suitable option to deal with such persistent compounds, especially in presence of surfactants. They can also be an effective solution for de-inking high quality waste papers, namely mixed office wastes with high contents of non-contact inks (Pala et al., 2004). These methods bear some advantages over common chemical de-inking techniques, such as avoidance of the use of alkali, simplifying the de-inking process, and changing the ink particle size distribution (Bhat, 2000). However, different enzymatic de-inking efficiencies have been observed in de-inking various types of waste papers. For instance, Lee et al. (2013) investigated the enzymatic de-inking efficiency of different types of waste papers using cellulase, hemicellulase, and xylanase. Based on the results of their study, a high efficiency of 86.6% on laser-printed papers was obtained while a relatively low de-inking efficiency of 12.9% was observed with newspaper (Fig. 1).

Enzymatic de-inking by using, for instance, *Celluclast 1.5 L*, *Trichoderma viride* CCMI 84 and *IOGEN celulase* (Pala et al., 2004), can reduce the wastewater treatment cost and make the process

eco-friendly through significant reduction in the produced COD and BOD, as well as the requirements of conventional de-inking chemicals. Zhang et al. (2012) estimated that applying the enzymes to replace 50% de-inking chemicals can potentially reduce COD load by 22–28%. Likewise, Singh et al. (2012) concluded that a decrease of 20.15% and 22.64% in BOD and COD values of effluents can be achieved by 50% replacement of conventional chemicals by enzymatic de-inking agents. Moreover, they observed 10.71%, 7.49%, 10.52%, and 6.25% improvements in viscosity, breaking length, burst factor, and tear factor of hand-sheets, compared with conventional chemical de-inking.

2.2.2. P&P from RCF – key pollutants

The wastewater generated in a RCF mill is quite small compared with those from virgin P&P production process. Table 3 presents the 2009–2010 annual data of a P&P plant in operation processes in China (Hong and Li, 2012) which shows the relatively low amounts of consumed fresh water and chemicals to produce 1 kg of printing and writing paper (50 g/m^2).

Metallic components (e.g., staples and ring binders), sand, glass, plastic, coatings, and fillers are the impurities generally separated from waste papers during recycling process. In addition, high concentrations of compounds such as 2,4,7,9-Tetramethyl-5-decyne-4,7-diol (which is a surfactant in paints and printing ink) can be released into the wastewater during paper recycling process (Guedez and Püttmann, 2014). Moreover, pulping additive chemicals (such as caustic soda, sodium silicate, hydrogen peroxide, and soap), de-inking additives and ink particles, and other impurities such as short fibers, fines and, fillers are pollutants normally generated in RCF mills (Miranda et al., 2009; Monte et al., 2009). The wastes from these factories, which normally contain compounds like Si and Ca (Raut et al., 2012) can be reused in other manufacturing processes such as light weight bricks production (see e.g., Raut et al., 2012) and cement industry (see e.g., Yan et al., 2011).

The types and amounts of the generated pollutants are directly related to the origin of the waste papers. From light-weight coated paper, higher amounts of organics (because of the coating binders) and lower amounts of inorganics (because of different manufacturing process and the used furnish) are released into the resultant effluents compared with newsprint paper (Miranda et al., 2009). In case of laser printing papers, the thermoplastic resins (commonly polystyrene, the copolymerization of ethylene and vinyl acetate, nitro cellulose, polyvinyl chloride (PVC), polyamide and polyester, etc.) in the toner are generally melted and then adhered with carbon black on the paper in printing process. Hence, traces of such materials together with electric-magnetic iron oxide can be found in the produced wastewater contents (Zhenying et al., 2009). A sample characterization of RCF mill wastewater for various physicochemical components, measured by Zwain et al. (2013), is shown in Table 1.

3. Advances in P&P wastewater treatments

Several studies have indicated that P&P mill effluents can potentially induce aquatic toxicity, especially at the reproductive level (see e.g., Costigan et al., 2012; Hewitt et al., 2008; Waye et al., 2014). Thanks to the developments occurred in the P&P treatment methods; toxicity of the final discharged effluents has been greatly decreased. However, such pollutants continue to be found in the final treated effluents (Orrego et al., 2010). This is mainly due to the remaining technical problems which lead to incomplete degradation as well as economic limitations of some effective P&P wastewater treatment methods. Recent studies, reviewed in the present paper, have aimed to overcome such limitations of

currently used P&P treatments to be of cost benefit and to be able to fulfill the environmental protection requirements.

3.1. Physicochemical methods

The application of various physicochemical treatment methods, such as sedimentation and floatation, coagulation and precipitation, filtration, reverse osmosis, adsorption, wet oxidation, ozonation and other advanced oxidation processes for P&P wastewater treatment, has been well documented over the past two decades because of their ability to remove a variety of suspended and floating matters as well as toxic compounds from the produced wastewaters.

3.1.1. Sedimentation and floatation

The effectiveness of sedimentation and floatation for clarification of P&P mill wastewater has been previously reviewed by key references (see Pokhrel and Viraraghavan, 2004; Thompson et al., 2001). However, adoption of such systems seems to be dependent on the employed P&P production process as well as applied secondary treatment methods. Ekstrand et al. (2013), by comparing the methane formation from different P&P production effluents, showed that when the residue fibers contain relatively high cellulose content, which normally occurs in the KP effluents, conducting the anaerobic digestion without primary sedimentation may be more beneficial by producing higher amounts of biogas, compared with dewatering and burning of the fiber residues sediments.

3.1.2. Coagulation and precipitation

The basis of such methods is addition of metal salts to the stream in order to generate larger flocs from small particles. Wang et al., (2011) applied aluminum chloride as coagulant and a modified natural polymer (starch-g-PAM-g-PDMS) as flocculant for treatment of wastewaters from primary sedimentation tank. They concluded that at the optimal condition (coagulant dosage of 871 mg/L, flocculant dosage of 22.3 mg/L and pH 8.35) the efficiency of the turbidity and lignin removals and water recovery were 95.7%, 83.4%, and 72.7%, respectively. Razali et al. (2011) found that utilization of higher molecular weight polydiallyldimethylammonium chloride for P&P mill wastewater treatment is more efficient in the overall performance of flocculation process, compared with low molecular weights. However, they observed that COD reduction by each tested polyDADMAC sample size was more than 90%. Renault et al. (2009) showed the higher performance of chitosan, as flocculant agent, in reduction of COD (above 80%) and turbidity (more than 85%), compared with that for polyaluminium chloride (40–45% and 55–60%, respectively) from

biologically treated cardboard industry wastewater. Eskelinen et al. (2010) achieved up to 90% removal of COD by using chemical precipitation, using 5 g/L CaO, and demonstrated the effectiveness of this method, compared with ultrasonic irradiation in combination with Fenton-like oxidation ($\text{Fe}^{3+}/\text{H}_2\text{O}_2$) (12%), photo-Fenton degradation ($\text{Fe}^{2+}/\text{H}_2\text{O}_2/\text{UV}$) (20%), or electro-oxidation treatment (28%) in reduction of COD, where the Fe(III) and H_2O_2 dose, pH, agitation speed, and contact time were 1 and 3 g/L, 6.9, 200 rpm, and 60 min, respectively.

There has been an increasing interest in application of electrochemical methods, which are more technically and economically feasible in large-scale operation (Soloman et al., 2009), in comparison with other physicochemical treatment techniques. Electrocoagulation treatments can be considered potential electrochemical P&P wastewater treatment ways which are more effective to deal with high molecular weight dissolved organic matters than the low molecular weight compounds (Lewis et al., 2013). Removal of different pollutants, using such methods, is significantly dependent on the operational conditions. Boroski et al. (2008) stated that commercial plates composed of aluminum electrodes and iron electrodes show equal statistical COD reductions from P&P industry effluents. In case of other pollutants such as lignin, phenol, and BOD, Al electrode has shown higher efficiency than Fe (Ugurlyu et al., 2008). In addition, a study to find out optimum conditions for decolorization and total COD reduction in P&P mill wastewater revealed that the polyelectrolytes such as sodium silicate, calcium carbonate, and polyacrylamide can be omitted, saving on operational and environmental costs, as they have no significant effect on the treatment process of wastewaters from the P&P industry (Fig. 2) (Khansorthing and Hunsom, 2009).

3.1.3. Membrane technologies

In recent years, various membrane technologies have been applied for treatment of P&P mill wastewater. Reverse osmosis can be considered one of these methods with the ability of pathogen destruction (Asano and Cotruvo, 2004). However, such systems are now challenging with technical and economical limitations, related to the retentate disposal (Greenlee et al., 2010). In this regard, adoption of proper pre-treatment methods seems to enhance the performance of the RO systems. For instance, Li and Zhang (2011) showed that pre-treatment of P&P mill wastewater by using a composite flocculant (PAFSSB), prior to RO, can efficiently reduce the COD up to 75%.

Chanworrawoot and Hunsom (2012) demonstrated that utilization of a membrane electrochemical reactor can be an economic and effective way for P&P wastewater treatment. It can happen by facilitating the removal of color, BOD, COD, TSS, and TDS, as well as

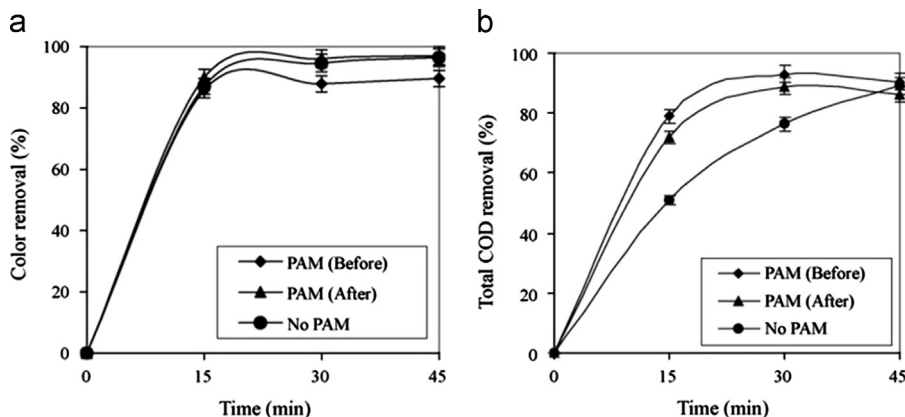


Fig. 2. The effect of polyacrylamide (PAM), as polyelectrolyte on removal percentages of color (a) and total COD (b) by electrocoagulation process (Khansorthing and Hunsom, 2009).

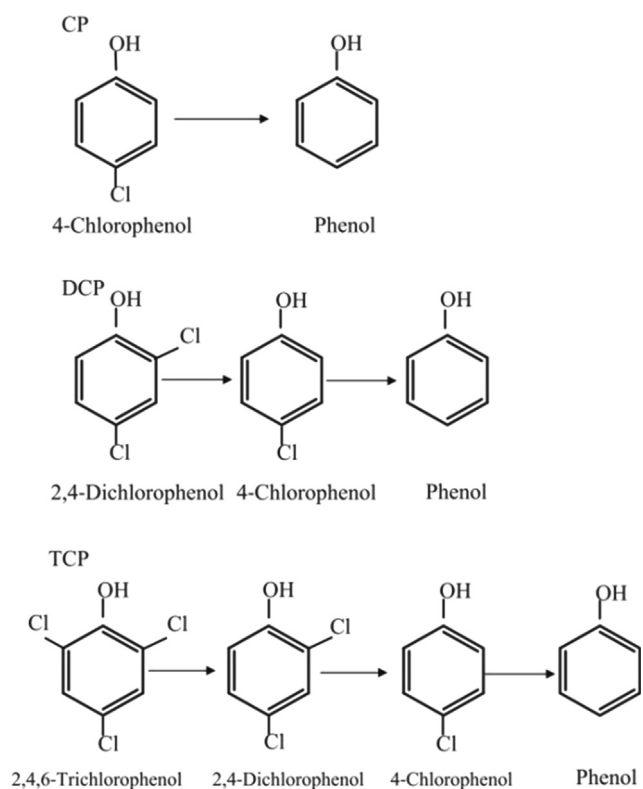


Fig. 3. Dechlorination pathways for 4-CP, 2,4-DCP, and 2,4,6-TCP by Fe⁰ impregnated silica (Dorathi and Kandasamy, 2012).

Table 4
Changes in the AOX and other P&P mill wastewater parameters, before and after the treatment (Dorathi and Kandasamy, 2012).

Parameter	Before treatment	After treatment
pH	8.12	7.42
EC (μS/cm)	5132	5815
TDS (mg/L)	2314	2419
Chloride (mg/L)	151	574
AOX (mg/L)	381	25.2

producing a smaller quantity of the low-density sludge and having a low operating cost per unit quantity of COD, by producing in-situ H⁺ instead of adding large amounts of mineral acids such as H₂SO₄. Ciputra et al. (2010) achieved 91% removal of the dissolved organic carbon from a biologically treated newsprint mill effluent by nanofiltration treatment. Puro et al. (2010) compared fouling of regenerated cellulose (RC) and polyether sulfone (PES) membranes in filtration of softwood and hardwood pulp mill process waters. They concluded that although the process water can affect the performance of the membrane, the fouling of PES was greater than that of RC with both types of process waters, based on their flux recovery.

The factors influencing the treatment efficiency of membrane technologies have been also well studied in recent years. For instance, a study by Gonder et al. (2011), with the purpose of purification of biologically treated P&P wastewater by nanofiltration process, revealed that membrane fouling can be minimized by optimizing operating conditions (pH 10, temperature 25 °C, trans-membrane pressure (TP) 12 bar, volume reduction factor (VRF): 4). In this regard, TP and VRF had the highest and small percentage of contribution respectively, while pH was found to have no significant effect on membrane fouling. Gönder et al. (2012)

investigated the treatment of pulp and paper mill wastewater using ultrafiltration (UF) membranes. They achieved 83%, 97%, 95%, 89%, and 50% removals of total hardness, sulfate, spectral absorption coefficient (SAC254), COD, and conductivity, respectively, by optimizing the operating conditions (pH 10, temperature 25 °C, TP 6 bar, and VRF 3). However, a 35% flux decline caused by fouling was observed, under the optimized conditions.

However, some arrangements such as pre-treatment by enzymes can considerably enhance the performance of the membrane filtration process. For instance, Ko and Fan (2010) reported that by pre-treatment of P&P raw wastewater and secondary effluents through using laccase polymerization prior to filtration by four investigated membranes with different molecular weights, over 60% of COD reduction was achieved. In addition, Krawczyk et al. (2013) recovered high molecular mass hemicelluloses, which is needed for manufacturing value added products, from CTMP process water by using a membrane filtration and enzymatic treatment with laccase.

3.1.4. Adsorption

Various adsorbents such as activated carbon, silica, fuller's earth, coal ash, etc. have been previously tested and they have shown acceptable performances for decolorization and refractory pollutants removals from P&P mill wastewater, as reviewed by Pokhrel and Viraraghavan (2004). Ciputra et al. (2010), by investigating the adsorption mechanisms of ion exchange resin and granular activated carbon, indicated that they preferentially act on the hydrophobic and high molecular weight fractions. Their study reported 72% and 76% reductions in dissolved organic carbon by using ion exchange resin and granular activated carbon, respectively. Xilei et al. (2010) conducted the adsorption followed by coagulation tertiary treatment by using low-cost bentonite as adsorbent and polyaluminum silicate chloride as coagulant. They obtained 60.87% and 41.38% of COD and color removals, respectively, at the optimum conditions for adsorbent (450 mg/L) and coagulant (400 mg/L) dosages.

3.1.5. Oxidation

Various oxidation processes as well as new catalytic materials have been studied as interesting solutions dealing with P&P wastewaters. It has been previously demonstrated by Akolekar et al. (2002) that catalytic wet oxidation using bi-metal catalysis such as Cu/Mn, Cu/Pb, and Mn/Pd can exhibit higher efficiency than single transition (Cu, Mn) or noble metal (Pd) catalysts (with more than 84% removal of TOC). With the aim of making wet oxidation process cost-effective, Garg et al. (2007) conducted a catalytic wet oxidation of thermally pre-treated P&P mill and achieved a maximum COD reduction of 89% using 5% CuO/95% activated carbon as catalyst. Herney-ramirez et al. (2011) investigated the degradation of acid orange 7, which is a typical dye widely used in P&P industry, using a heterogeneous catalytic wet hydrogen peroxide process. They observed that the complete decolorization was achieved using a pillared saponite clay impregnated with Fe (II) acetylacetonate in less than 4 h.

Manttari et al. (2008) studied the ozone treatment of nanofiltered effluents after activated sludge process. They achieved more than 50% reduction in turbidity, color, and lignin (UVA_{280 nm}) when the ozone dosage increased to 800, 900 and 1100 mg/L. Kishimoto et al. (2010) observed that ozonation combined with electrolysis (ozone-electrolysis) is more effective than both ozonation or electrolysis for decolorization and COD removal from treatment of P&P mill wastewater. Moreover, ozone effectivity (the ratio of the COD removed per ozone dose) in ozonation became lower than in ozone-electrolysis after one hour of treatment. Ramos et al. (2009) indicated that fumaric, maleic, malonic, and formic acids were formed as by-products in

ozonation of the filtered residual water of a paper industry, and the biodegradability of the treated water increases during ozonation (0.067–0.29).

Chemical treatments, using advanced oxidation processes (AOPs), have been a widely used technique to deal with a large number of refractory organics pollutants (Babuponnusami and Muthukumar, 2012b). Removal activity is generally carried out via the oxidation of complex compounds by non-selective hydroxyl radicals, which are generated by AOPs through a series of complex reactions. Such AOPs have been successfully applied for treatment of wastewaters with low biodegradability index (BI) (e.g., Babuponnusami and Muthukumar, 2012a, 2012b; Hussain et al., 2013). Lucas et al. (2012) reported that Fenton reactions can be applied successfully for tertiary treatment of P&P industry wastewaters. They stated that solar photo-Fenton ($\text{Fe}^{2+}/\text{H}_2\text{O}_2/\text{UV}$) processes are more effective than dark reaction ($\text{Fe}^{2+}/\text{H}_2\text{O}_2$) under identical experimental conditions. Dorathi and Kandasamy (2012) investigated the degradation of xenobiotic compounds resulting from P&P production processes (namely 4-chlorophenol (4-CP), 2,4-dichlorophenol (2,4-DCP) and 2,4,6-trichlorophenol (2,4,6-TCP)) by uniquely prepared Fe^0 impregnated silica (Fig. 3).

They also performed experiments to investigate the transformation of chlorophenols by varying pH, column height, flow rate and initial chlorophenol concentration in a continuous mode column. The results showed that at neutral pH (6 and 7) and after 4 h almost 93% of each of the three chlorophenols were removed (the decreasing order of dechlorination is 2,4,6-TCP < 2,4-DCP < 4-CP) (Table 4).

In addition to the conventional Fenton reactions, the feasibility of the mechanisms involving the application of other engineered nanoparticles (ENPs) for AOPs has been studied by key references. This is mainly because of their acceptable performance and cost-effectiveness, compared with conventional treatment ways (El-temsah and Joner, 2012). In this regard, several studies have

shown that ENPs are capable of reducing various types of organic pollutants like phenol by $\alpha\text{-Fe}_2\text{O}_3/\text{TiO}_2$ (Cong et al., 2012), p-nitrophenol by nano-magnetite Fe_3O_4 (Sun and Lemley, 2011) and 2,4,6-trichlorophenol by the photo-Fenton-like method (Fe (III) ENPs) (Vinita et al., 2010) and other halogenated compounds at ambient temperatures (Dorathi and Kandasamy, 2012). ENPs seem to have an acceptable performance to deal with persistent pollutants from P&P mill wastewaters. However, there is a limited number of published papers in these areas, probably due to possible subsequent environmental and health risks (e.g., see Gao et al., 2013; Grieger et al., 2010; Melegari et al., 2013). Ghaly et al. (2011) investigated the application of the solar photocatalytic

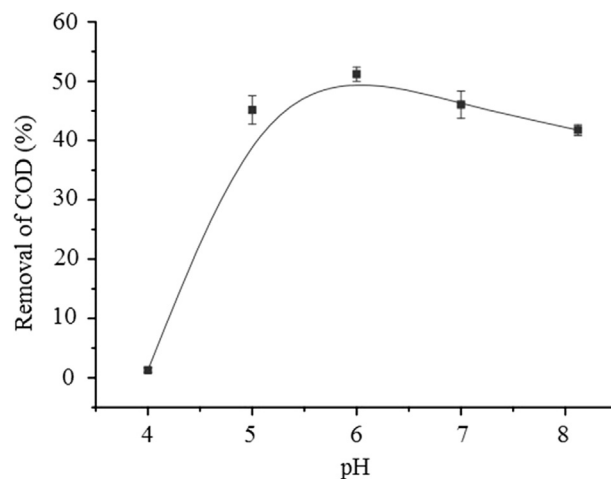


Fig. 4. The role of the initial pH on the COD removal in the biological treatment of the alkaline peroxide mechanical pulping effluent using *A. niger* (Liu et al., 2011).

Table 5

Changes in the P&P mill wastewater parameters after treatment by physicochemical processes.

Process	Parameters					Reference
	COD		Other parameters			
	Initial (mg/L)	Removal (%)	Type	Initial	Removal (%)	
Coagulation (aluminum chloride)+Flocculation (starch-g-PAM-g-PDMC)	1358	–	Turbidity	1209 NTU	95.7	Wang et al. (2011)
Electrocoagulation (Al)	2500	~95	Lignin	–	83.4	Shankar et al. (2013)
Flocculation (polydiallyldimethylammonium) ^a	2900 ± 90	> 90 ^b	TSS	6000 ± 50 mg/L	> 90 ^c	Razali et al. (2011)
Flocculation (Chitosan)	500–1800 ^d	> 80	Turbidity	4585 ± 30 NTU	> 90 ^c	Renault et al. (2009)
Flocculation (polyaluminium chloride)	–	40–45	Turbidity	229–469 NTU	> 85	Renault et al. (2009)
Precipitation (CaO)	1510	Up to 90	Turbidity	229–469 NTU	55–60	Eskelinen et al. (2010)
Electrocoagulation (EC/Fe ⁰)–Flotation+ Solar photocatalytic degradation (UV/TiO ₂ /H ₂ O ₂)	1310	88	–	–	–	Boroski et al. (2008)
Electrocoagulation (Al)	426.03	75%	Lignin	13514 mg/L	80	Ugurlu et al. (2008)
Adsorption (ion exchange resin)	–	–	Phenol	0.535 mg/L	70	
Adsorption (granular activated carbon)	–	–	BOD	25.52 mg/L	70	
Nanofiltration	–	–	DOC	57.4 mg/L	72	Ciputra et al. (2010)
laccase-polymerized membrane filtration	785	> 60	DOC	57.4 mg/L	76	Ciputra et al. (2010)
Ozonation ^e	1315	~20	DOC	57.4 mg/L	91	Ciputra et al. (2010)
Ozonation + electrolysis	1382	> 50	DOC	410 mg/L	> 15	Ko and Fan (2010)
Solar photo-Fenton (Fe ²⁺ /H ₂ O ₂ /UV)	898.9	~90	Color	1580 (Pt–Co)	> 50	Manttari et al. (2008)
Fungi + solar photo-Fenton (Cryptococcus + Fe ²⁺ /H ₂ O ₂)	1802	> 90	DOC	–	–	Kishimoto et al. (2010)
Solar photocatalytic degradation (nTiO ₂ /UV)	2075	75	DOC	348.0 mg/L	> 90	Lucas et al. (2012)
			DOC	820 mg/L	90	Fernandes et al. (2014)
			TSS	1165 mg/L	80	Ghaly et al. (2011)

^a Molecular weight: 15.7×10^4 g/mol

^b At different dosages of polyDADMAC, from 0.2 to 2.2 mg/L.

^c At polyDADMAC dosage of 1.2 mg/L.

^d Depending on the sampling season.

^e After microfiltration and nanofiltration of effluents from an activated sludge process.

degradation of the wastewater from P&P industry, using synthesized nano TiO₂. The results of their study indicated that the degradation rate increases directly with the catalyst loading till the definite concentration of 0.75 g/L. Moreover, the optimum pH was observed to be near 6.5. In these conditions and within 180 min solar irradiation time, 75% removal of COD from the wastewater was achieved. In addition, H₂O₂ was found to be effective in the degradation process, as an electron acceptor. They indicated that solar photocatalytic oxidation can enhance the BI of the wastewater and proved that this method can be applied as an efficient pre-treatment step to biological post-treatment of P&P industry effluents.

In terms of operating cost, designed plants, which include physicochemical treatments, can be usually found to be expensive options for all kinds of P&P effluents, as indicated by Buyukkamaci and Koken (2010), especially for chemical P&P wastewater treatments. Hence, biological treatments can be more attractive, if BI presents an acceptable value by produced wastewaters, which has been defined to be at least 0.3 (Morais and Zamora, 2005). Nevertheless, if the effluent contains persistent toxic pollutants and low BI, chemical treatments would be necessary to apply prior to biological processes to remove the physical barriers from the cellulosic biomass, formed by the strong bonds in the molecules, which may inhibit the degradation of recalcitrant pollutants by biological methods (Bayr et al., 2013). As a result, by giving an appropriate physicochemical pretreatment, biological steps are expected to perform faster and demand smaller reactor volume (see e.g., Soloman et al., 2009). Table 5 summarizes the observed changes in the P&P mill wastewater parameters after treatment by physicochemical processes.

3.2. Biological techniques

Biological treatment methods involve the utilization of microorganisms including fungi, bacteria and algae, and enzymes, as a single step treatment or in combination with other physical and/or

chemical methods (Singhal and Thakur, 2009). Compared with physicochemical ways, biological methods for wastewater treatment are considered to be of cost benefit, eco-friendly, and suitable for reduction of the BOD and COD from the effluents. However, the conventional biological processes have not effectively performed for removal of color and recalcitrant compounds from P&P mill wastewater. Activated sludge process, anaerobic lagoon, stabilization pond, or their modifications, depending on the local conditions, are considered to be the commonly available biological treatment methods adopted in the P&P industry (Tiku et al., 2010).

3.2.1. Fungal treatment

Fungi are common in P&P mill wastewaters (see e.g., Yang et al., 2011). They produce extracellular enzymes and can survive at higher effluent load, compared with bacteria (Singhal and Thakur, 2009; Thakur, 2004). White-rot fungi, such as *Phanerochaete chrysosporium* (Zhang et al., 2012) and *Trametes pubescens* (González et al., 2010), are the microbes that degrade lignin/phenolic compounds through the production of enzymes such as lignin peroxidases, manganese peroxidases (MnP) dependent peroxidases, and laccases (Chandra and Singh, 2012; Freitas et al., 2009).

Malaviya and Rathore (2007) investigated the application of an immobilized fungal consortium consisting of two basidiomycetous fungi (*Merulius aureus* and an unidentified genus) and a deuteromycetous fungus (*Fusarium sambucinum*) for bioremediation of effluents from a kraft P&P mill, using *Eucalyptus* wood and bagasse to manufacture writing and printing paper and rayon grade pulp. The results indicated the 78.6%, 79.0%, and 89.4% reduction of color, lignin, and COD, respectively, during the first 4 days. *Pleurotus sajor caju* (white-rot fungi) and *Rhizopus oryzae* (soft rot fungi) species have been also studied for their reduction potential of color and COD of effluents derived from the secondary treatment of a bleached kraft *Eucalyptus globulus*, and the effective reductions of relative absorbance (25–46% at 250 nm and 72–74% at 465 nm), and COD (74–81%) after 10 days of incubation have been observed (Freitas et al., 2009). Liu et al. (2011)

Table 6
Changes in the P&P mill wastewater parameters after fungal treatment.

Microorganism	COD		Other Parameters/pollutants			Reference
	Initial (mg/L)	Removal (%)	Type	Initial	Removal (%)	
<i>Trametes pubescens</i>	–	–	2-CP ^a	15 mg/L	94.65	González et al. (2010)
			2,4-DCP	15 mg/L	92.41	
			2,4,6-TCP	15 mg/L	37.88	
			PCP ^b	15 mg/L	67.85	
<i>Trametes pubescens</i> ^c + AOP (TiO ₂ /UV)	–	–	2-CP	15 mg/L	100	González et al. (2010)
			2,4-DCP	15 mg/L	100	
			2,4,6-TCP	15 mg/L	100	
			PCP	15 mg/L	100	
A consortium of <i>Merulius aureus</i> , an unidentified genus and <i>Fusarium sambucinum</i>	2013 ± 11.7	89.4	Color	2976.71 ± 7.41 (Pt–Co)	78.6	Malaviya and Rathore (2007)
			Lignin	5301 ± 6.27 mg/L	79.0	
<i>Pleurotussajorcaju</i>	392 ± 2	72	Relative absorbance (465 nm)	0.204 ± 0.001	72	Freitas et al. (2009)
<i>Trametes versicolor</i>	392 ± 2	77	Relative absorbance (465 nm)	0.204 ± 0.001	57	Freitas et al. (2009)
<i>Phanerochaete chrysosporium</i> <i>Rhizopus oryzae</i>	392 ± 2	81	–	–	–	Freitas et al. (2009)
	392 ± 2	82	Relative absorbance (465 nm)	0.204 ± 0.001	74	Freitas et al. (2009)
<i>Aspergillus niger</i>	7521	60	MTBE extracts	147 mg/L	97	Liu et al. (2011)
			Turbidity	510 NTU	77	
			Color	977 CU	43	
<i>Emericella nidulans</i> var. <i>nidulans</i>	–	–	Color	65,475 CU	66.66	Singhal and Thakur (2009)
			Lignin	163,741 mg/L	37	

^a 2-Chlorophenol.

^b Pentachlorophenol.

^c Biological process was supplemented with glucose.

conducted a lab-scale experiment in order to treatment of poplar alkaline peroxide mechanical pulping (APMP) effluent with *Aspergillus niger*. At the optimized conditions (3% inoculum, pH 6 (Fig. 4), shaking at 160 rpm, 60–72 h, and 30 °C), they observed about 97% of the methyl tertiary butyl ether (MTBE) extracts, and 60%, 77% and 43% of the COD, turbidity, and color were removed, respectively, even without a flocculation step (Liu et al., 2011).

The importance of the pH has been also investigated in other studies. Singhal and Thakur (2009) indicated that *Emericella nidulans* var. *nidulans* is able to efficiently decolorize and detoxify the KP effluents, associated with initial pH, as the most influential parameter. After optimization of seven effective parameters (temperature, rpm, dextrose, tryptone, inoculum size, pH, and duration), they achieved 66.66% and 37% reductions in color and lignin, respectively. Moreover, fungal treatment can be combined with other physicochemical methods to provide optimum conditions for degradation of recalcitrant pollutants. For instance, the white-rot fungus *T. pubescens* was used for the biodegradation of chlorophenols followed by TiO₂/UV as AOP agent application. This combination of sequential biological degradation and advanced oxidation process, even at a low amount of catalyst, allowed up to a 100% chlorophenol removal (González et al., 2010).

However, some fungal features may limit their ability for practical treatment under extreme environmental conditions such as high pH and oxygen limitations (Chandra and Singh, 2012). High glucose requirement of the microorganisms (Tarlan et al., 2002a) and the necessity of longer detention time because of the slow metabolism of these organisms can be considered other existing weaknesses (Balcioglu et al., 2007). Hence, there is a need to search for the novel modifications which can tolerate a wide range of pH to survive in extreme environmental conditions and have a capability to produce extracellular ligninolytic enzymes. Table 6 summarizes the observed changes in the P&P mill wastewater parameters after fungal treatment.

Some studies have suggested that algae can replace fungi to remove color and AOX more efficiently. For instance, Tarlan et al. (2002b) observed up to 74% COD and color removals in about 40 days of incubation. They achieved maximum removal efficiencies of 60–85% for COD, 42–75% for color and 82–93% for AOX, for the filling periods of 4–12 days. Their results showed that algae removed both chlorinated and non-chlorinated organics, mainly by metabolism, and degradation of the chlorinated organic

molecules was more rapid than the removal of the non-chlorinated and colored organics. Algae utilize a natural mechanism for the removal of color and recalcitrant pollutants from the P&P mill wastewater. Dilek et al. (1999) stated that the main mechanism for lignin removal by algae is metabolism rather than adsorption. Moreover, Tarlan et al. (2002a) showed that the main mechanism of color and organic removal by algal strains is partially metabolism and partially transformation of color and chlorinated compounds to non-colored and non-chlorinated ones.

3.2.2. Aerobic treatment

Compared with fungi, bacteria have shown enhanced biodegradation capability, mainly due to the broad pH range tolerability, biochemical versatility, and immense environmental adaptability (Chandra and Singh, 2012). Therefore, various biological treatment processes, such as aerated lagoons and activated sludge, have been generally used to treat P&P mill wastewater. However, most of such conventional methods are not effective in degradation of the compounds such as lignin, mainly because of their size and complex structure (Balcioglu et al., 2007), and therefore, complete degradation of such recalcitrant pollutants remains elusive by using these methods (Tiku et al., 2010). Thus, the extended and modified methods have been developed in order to produce less sludge (Mahmood and Elliott, 2006).

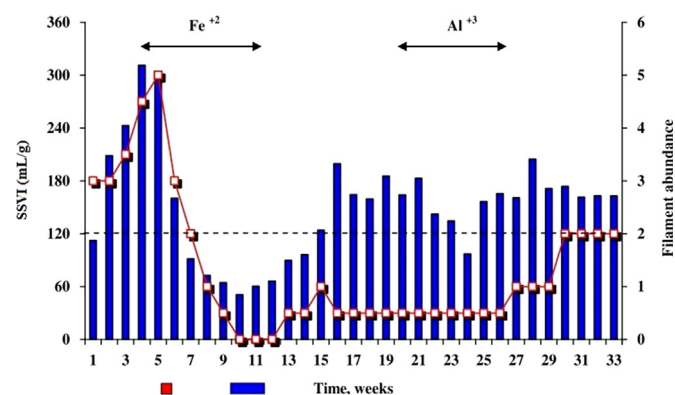


Fig. 6. A comparison of the SSVI (■) with the filament abundance (■) for the lab-scale activated sludge plant (Agridiotis et al., 2007).

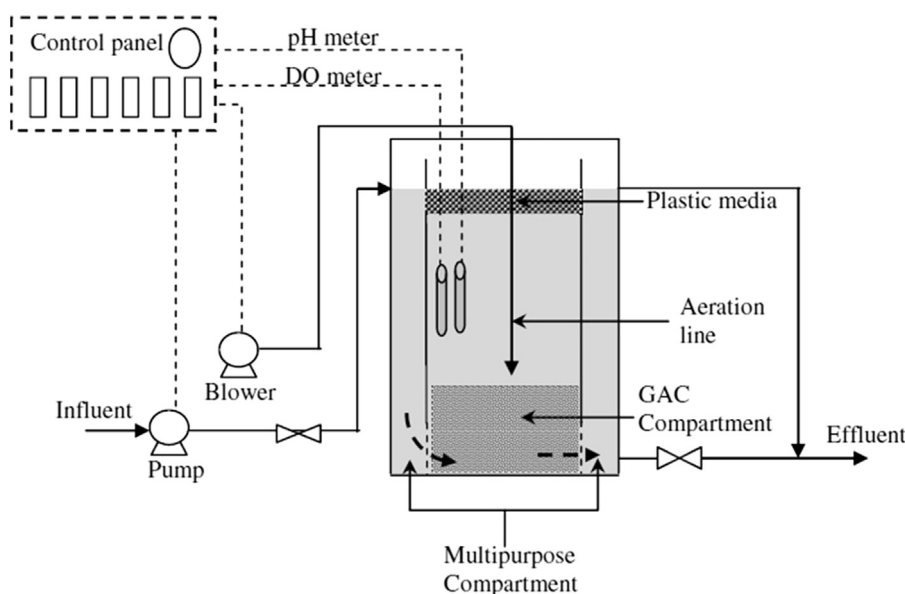


Fig. 5. Schematic of a GAC-SBBR, designed to treat RCF mill wastewater (Muhamad et al., 2013).

Table 7
Conventional aerobic and anaerobic treatment compared with aerobic and anaerobic MBR (Lin et al., 2013).

Feature	Conventional aerobic treatment	Conventional anaerobic treatment	Aerobic MBR	AnMBR
Organic removal efficiency	High	High	High	High
Effluent quality	High	Moderate to poor	Excellent	High
Organic loading rate	Moderate	High	High to moderate	High
Sludge production	High	Low	High	Low
Footprint	High	High to moderate	Low	Low
Biomass retention	Low to moderate	Low	Total	Total
Nutrient requirement alkalinity	High	Low	High	Low
Alkalinity requirement	Low	High for certain industrial stream	Low	High to moderate
Energy requirement	High	Low	High	Low
Temperature sensitivity	Low to moderate	Low to moderate	Low	Low to moderate
Mode of treatment	Total	Essentially pretreatment	Total	Total or pretreatment

Table 8
pH, TOC, COD, COD, TOC⁻¹ and CH₄-yields of different hardwood TMP mill waste-waters samples, adapted from Ekstrand et al. (2013).

Mill	Sampled effluent	pH	TOC (mg/L)	COD (mg/L)	COD TOC ⁻¹	CH ₄ (N mL/g TOC) ^a
A2	Wood room	4.8	1030	3620	3.5	370 ± 15
A5	Rejected screening effluent	5.2	1620	5960	3.7	430 ± 43
A6	TMP-white water	4.4	1510	6030	4.0	510 ± 53
A9	PM/DM white water	7.5	530	3420	6.5	600 ± 44
A12	Before pre-sedimentation	7.0	2110	6870	3.3	370 ± 16
A13	After pre-sedimentation	7.3	1160	3570	3.1	510 ± 18
A41	TMP/CTMP bleaching ^b	7.9	3270	9920	3.0	470 ± 11

^a TOC and COD values are means of triplicates with maximum standard deviation (SD) of 5% and 1% respectively. CH₄-yields are means of triplicates ± SD.

^b Hydrogen peroxide.

Pokhrel and Viraraghavan (2004) reviewed the previous studies on the performance of aerated lagoons for treatment of P&P mill wastewater. They concluded that such methods were efficient in the BOD (over 95%) and chlorinated phenolics (85%) removals. In addition, moderate performance of these facilities for COD (60–70%) and AOX (around 50%) removals was observed in most of the reported results. Later studies have mainly aimed to enhance the ability of stabilization basins for removing recalcitrant compounds as well as color, which normally increases during such treatment processes, probably due to conversion of high molecular weight organic materials to smaller chromophoric substances rather than minerals (Kemeny and Banerjee, 1997). Matafonova et al. (2006) showed that *Bacillus cereus* GN1 isolated from an aeration pond in a P&P mill can degrade 2,4-DCP in concentrations up to 400 μM (59 μg/L). After 2 days, they achieved 77.6%, 64.9%, and 56.0% removals of 2,4-DCP at initial concentrations of 20, 160, and 200 μM, respectively. Abbasi and Abbasi (2010) by monitoring various oxidation ponds for several years, concluded that an 18–23% enhancement in treatment efficiency can be achieved after introducing *Eichhornia crassipes* to existing P&P oxidation ponds. Lewis et al. (2013) observed a potential trend of lower color formation over time (especially in UV_{280 nm}, compared with UV_{260 nm}), where aluminum sludge accumulated in an aerated stabilization pond for treatment of post-coagulated pulp mill wastewater mixed with paper mill wastewater (1:2).

Activated sludge process has been the major treatment method for P&P mill effluents in recent years in its conventional and modified forms, which is capable of meeting secondary treatment effluent limits (Buyukkamaci and Koken, 2010). In activated sludge bioreactors, aerobic heterotrophic communities efficiently remove organic substances and nutrients as well as toxic compounds and

pathogens from the produced wastewater (Wells et al., 2011). In this regard, it has been shown that the application of a consortium of different bacteria could exhibit more efficiency to reduce the BOD and COD from the P&P effluents. For instance, a combination of the three bacteria *Pseudomonas aeruginosa* (DSMZ 03504), *P. aeruginosa* (DSMZ 03505), and *B. megaterium* (MTCC 6544) has been applied successfully to reduce COD (about 76% within 10 h), BOD (to 35 mg/L, within 24 h), and TDS (by 7%) as well as the color, AOX, and the toxicity of the P&P mill effluent within 24 h (Tiku et al., 2010). Ghoreishi and Haghghi (2007) achieved up to 97.5%, 95%, 98%, and 97% reduction of color, COD, BOD, and TSS, respectively, in a pilot scale simulated continuous stirred batch reactor by pre-treatment with NaBH₄ as reducing agent. Mahmood-khan and Hall (2013) achieved over 90% removal of sterols and biodegradation, respectively, using laboratory activated sludge bioreactors after attaining stable operating conditions at pH 6.7 ± 0.2.

A considerable reduction in the major pollutants from a RCF mill wastewater has been reported by Muhamad et al. (2013), using a lab-scale granular activated carbon sequencing batch biofilm reactor (GAC-SBBR). This is a combination of physical and biological methods including adsorption onto granular activated carbon and biodegradation by microorganisms grown on GAC as a biofilm (Fig. 5). They achieved up to 97.2%, 99.4% and 100% removals of COD, NH₃-N, and DCP, respectively, after 3 days hydraulic retention time (HRT), where aeration rate and influent feed concentration were 3.4 m³/min and 750 mg COD/L, respectively. Pilot-scale GAC-SBBR strategy has been also utilized by Osman et al. (2013) to deal with full-scale mill wastewaters from a RCF mill. They concluded that the achieved percentage of COD, 2-CP, 2,4-DCP, and 2,3,4,5-Te CP removals were 92 ± 6, 99 ± 1, 68 ± 1, and 97 ± 6%, respectively, at HRT of 2 days. They stated that the relatively low removal of DCP is related to the thermodynamic stability of this compound.

Recently, production of valuable compounds such as polyhydroxyalkanoates (PHAs) has been significantly developed through acidogenic fermentation of paper mill wastewater followed by the activated sludge process. It has been reported by Bengtsson et al. (2008) that after acidogenic fermentation of a paper mill wastewater, 74% of the soluble COD was present in the form of VFA with potential to accumulate 48% PHA while providing 95% removal of soluble COD. The influencing factors in PHA producing from P&P mill wastewaters, such as suspended solids concentrations, process time, and different operating conditions (batch, fed-batch and continuous feeding strategy) have been investigated by Yan et al. (2008). They found the activated sludge of 15 g/L as the optimum concentration for PHA production and mentioned that the continuous feeding of acetic acid can enhance the PHA content and productivity.

Conventional activated sludge processes usually struggle with difficulties in the sedimentation and the thickening process

occurred due to the sludge filamentous bulking, caused by excessive growth of filamentous bacteria in sludge suspension. Some techniques have been shown to be applicable to solve the problem and decrease the amount of the P&P produced sludge. Agridiotis et al. (2007) indicated that stirred sludge volume index (SSVI) can be reduced, using Fe ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$) by converting the filamentous flocs into a compact structure. As shown in Fig. 6, by adding the AlCl_3 , in a subsequent trial, sludge properties were improved temporarily but then further dosing had an adverse effect on SSVI and floc compactability.

Decrease in the amount of the produced sludge can also be achieved by using membrane bioreactors (MBRs). In addition, MBRs have other advantages, compared with conventional activated sludge systems such as high effluent quality, small footprint as well as flexibility of operation (Table 7). However, membrane fouling can cause an increase in the operational and maintenance costs, which may limit the broad range application of MBRs (Leclech et al., 2006). Hazrati and Shayegan (2011) considered the imposed flux to be the most important factor in the membrane performance of MBRs and based on the optimum retention time (4 h), the overall COD removal efficiency was 98%, reducing the excess sludge by a factor of 10. Qu et al. (2012) stated that, based on the optimum retention time (1.1 ± 0.1 day), the highest COD removal efficiency of a thermophilic submerged aerobic membrane bioreactor (TSMABR) was 88.6 ± 1.9 to $92.3 \pm 0.7\%$.

However, in terms of economic considerations, the extended aeration activated sludge process can be still considered the most economic and technically optimal treatment processes dealing

with low and medium strength P&P effluents, which can be improved in combination with MBR technologies (Table 7), as stated by Buyukkamaci and Koken (2010). The performance of aerobic and anaerobic treatment methods to deal with P&P mill wastewater is presented in Table 9.

3.2.3. Anaerobic digestion

Anaerobic digestion (AD), as a stable biological process to deal with various substrates, is increasingly used for treatment of P&P mill wastewaters in recent years. This is mainly due to its several advantages over other conventional techniques such as the reduction of the produced sludge volume by 30–70%, methane production as an energy carrier, design simplicity and non-sophisticated equipment requirement, cost-effectiveness in terms of low capital and operating cost, applicability in different scales and the rate of pathogen destruction, particularly in the thermophilic process (Ekstrand et al., 2013; Lin et al., 2011; Zwain et al., 2013).

The performance of these methods, in terms of optimizing the biogas yields and minimizing the solid wastes production, is directly influenced by various factors. P&P production process, wastewater composition and reactor operating conditions, available inoculum for anaerobic digestion steps, and the operational costs can be considered the main influencing factors. The type of P&P making process can significantly affect the total yield of the methane production. Ekstrand et al. (2013) investigated the methane potential of 62 Swedish P&P mills wastewater from 10 different processes (including KP, TMP, CTMP and NSSC) at seven

Table 9
Changes in the P&P mill wastewater parameters after treatment by aerobic and anaerobic treatment processes.

Treatment process	COD		Other parameters/pollutants			Reference
	Initial (mg/L)	Removal (%)	Type	Initial	Removal (%)	
Aeration pond	–	–	2,4-DCP	20 μM	77.6	Matafonova et al. (2006)
Aeration pond + longer time coagulation ^a	–	–	2,4-DCP	160 μM	64.9	Lewis et al. (2013)
			2,4-DCP	200 μM	56.0	
			Color formation ^b	1.53 (UV _{280 nm})	–3	
Activated sludge	863	76	Color formation ^c	0.74 (UV _{280 nm})	> 100	Tiku et al. (2010)
			Color formation ^d	0.70 (UV _{280 nm})	82	
			Color	1510 (Pt–Co)	76 (48 h)	
Hydrogenation + NaBH_4 reduction + activated sludge	1231	95	Color	1500 (Pt–Co)	97.5	Ghoreishi and Haghighi (2007)
			BOD	105 mg/L	98	
			TSS	167 mg/L	97	
Activated sludge ^e	–	–	Sterols	4500 $\mu\text{g/L}$	> 90	Mahmood-khan and Hall (2013)
			GAC-SBBR ^f	750	97.2	
GAC-SBBR	1152 \pm 93	92 \pm 6	2,4-DCP	52 \pm 14 $\mu\text{g/L}$	100	Osman et al. (2013)
			2-CP	249 \pm 15 $\mu\text{g/L}$	99 \pm 1	
			2,4-DCP	98 \pm 8 $\mu\text{g/L}$	68 \pm 1	
TSMABR ^g	3650 \pm 289	92.3 \pm 0.7	2,3,4,5-Te CP	42 \pm 6 $\mu\text{g/L}$	97 \pm 6	Qu et al. (2012)
			–	–	–	
			Color	–	100	
TASMBR – EO	3650 \pm 289	98.2 \pm 0.3	AOX	28 mg/L	90.7	Qu et al. (2012)
Upflow anaerobic filter ^h	–	–	AOX	28 mg/L	93.0	Deshmukh et al. (2009)
Upflow anaerobic filter ⁱ	–	–	AOX	28 mg/L	93.0	Deshmukh et al. (2009)
Upflow anaerobic sludge blanket (UASB) + partially recirculation	1410 \pm 10	~78	VFA	11	~73	Buzzini and Pires (2007)
Submerged anaerobic membrane bioreactor (SAnMBR) ^j	2782–3460	~90	–	–	–	Lin et al. (2011)
Modified anaerobic baffled reactor (MABR)	1000	71	BOD	516 mg/L	71	Zwain et al. (2013)
			VFA	92 mg/L	~–32 ^k	

^a By adding Alum floc (2.5 (V/V)) to a simulated aeration pond, containing coagulated wastewater.

^b At HRT of 28 days.

^c At HRT of 56 days.

^d At HRT of 84 days.

^e By using a consortium of *Seudomonas aeruginosa* (DSMZ 03504), *P. aeruginosa* (DSMZ 03505) and *B. megaterium* (MTCC 6544).

^f Granular activated carbon sequencing batch biofilm reactor.

^g Thermophilic submerged aerobic membrane bioreactor.

^h Influent was supplemented with glucose. Average methane content in biogas produced was 51%.

ⁱ Influent was supplemented with glucose and acetate. Average methane content in biogas produced was 60%.

^j Bio-gas production rate was 0.397 ± 0.053 L/g COD with 62–75% methane and 22–30% carbon dioxide in the biogas.

^k The methane yield was 0.003–0.09 L CH₄/g COD day

P&P mills in anaerobic batch digestion conditions. The results of their study illustrated that TMP mill wastewaters samples gave the best average yield (with all six samples) among all studied production methods ranging 40–65% of the theoretical CH_4 -yield potential (Table 8). In terms of raw materials, although alkaline ECF hardwood effluents resulted in higher yields than softwood effluents, however, no significant raw material dependence has been observed in the case of TCF bleaching effluents at the KP mills. Thus, the impact of raw materials on the methane production yield may be influenced by the applied P&P production process (Ekstrand et al., 2013).

The ratio between the required nutrients and the pollutant loads can be considered the main wastewater properties, affecting the yield of the AD process. The optimal range of operating C:N ratio, as an effective factor for anaerobic bacterial growth in an AD system, has been recommended between 20/1 to 30/1 with an optimal ratio of 25/1 (Li et al., 2011). The low C:N ratio may result in higher total ammonia nitrogen release and/or high VFA accumulation in the digester which is an important inhibitor of the AD process. Moreover, the high C:N ratio would be responsible for the rapid consumption of nitrogen by methanogens and lower biogas

production (Zeshan et al., 2012). Thus, some measures may be required to improve the digestibility of the P&P mil wastewater and the biogas yield. Anaerobic co-digestion is one of these improvements which has been efficiently applied to some types of wastewaters such as co-digestion of sugar-beet processing wastewater and beet-pulp (Alkaya and Demirer, 2011) and olive mill wastewater with olive mill solid waste (Boubaker and Ridha, 2008). This is mainly because of AD co-digestion merits such as making a balance between required nutrients ratio, toxic compounds degradation, buffering capacity supplying, and sharing the substrate and equipment between different treatment plants (Alkaya and Demirer, 2011). The results of the study carried out by Yu et al., (2004) revealed that a considerable lignocellulose fraction in thermophilic acidogenesis (approximately 6.6 times more) can be achieved by co-digestion of TMP wastewater and glucose. Yang et al. (2009) investigated the lignocellulosic structural changes of *Spartina alterniflora* co-digested with potato. After batch anaerobic digestion for 60 days, the total cumulative biogas yield of co-digestion process was noticeably higher than that of mono-digestion by *S. alterniflora* (Fig. 7).

However, it should be stated that the number of the published works on the P&P mill residues co-digestion with suitable substrates is scarce and they have mainly focused on the P&P primary and secondary sludge co-digested with substrates such as municipal sewage sludge (Hagelqvist, 2013), food waste (Lin et al. 2012), and monosodium glutamate waste liquor (Lin et al., 2011).

Wastewater properties can also directly affect the biogas production via, for instance, the toxic effects on the microbial inoculum which are responsible for anaerobic digestion through hydrolysis, acidogenic, acetogenesis, and methanogenesis phases (Fig. 8). The results of a recent study indicated that the acidic ECF effluents can significantly reduce the efficiency of the AD process because of the toxic effects on the AD-flora, while most of alkaline ECF bleaching effluents gave positive methane yields (Ekstrand et al., 2013). In addition to the pH adjustment, some measures may enhance the inoculum related performance of AD. For instance, rumen fluid has been studied as an effective anaerobic microbial ecosystem, including a complex microbial population (i.e., bacteria, protozoa, fungi, and archaea) with a high hydrolytic and acidogenic activity when lignocellulosic substrates are used (Yue et al., 2013). Baba et al. (2013) conducted the pre-treatment experiments of the waste paper as a model of cellulosic biomass pre-treatments (composed of cellulose, hemicellulose, and lignin)

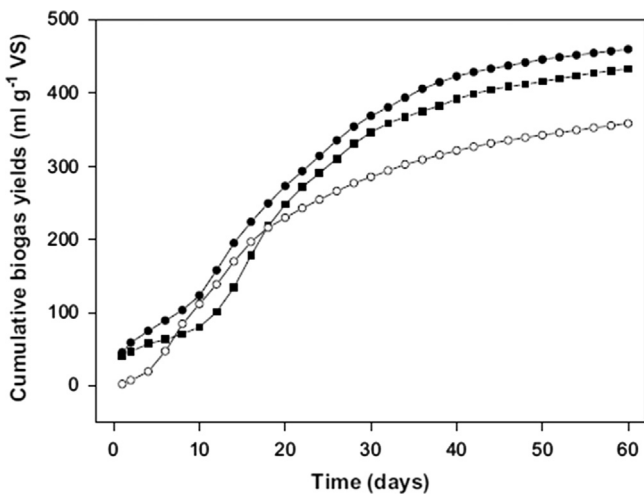


Fig. 7. Differences between cumulative biogas yields of mono-digestion and co-digestion of *S. alterniflora* and potato at 6% of VS at 35 °C. ○: pure *S. alterniflora* to potato (SA:P); ■: SA:P of 4:1; ●: SA:P of 6:1 (Yang et al., 2009).

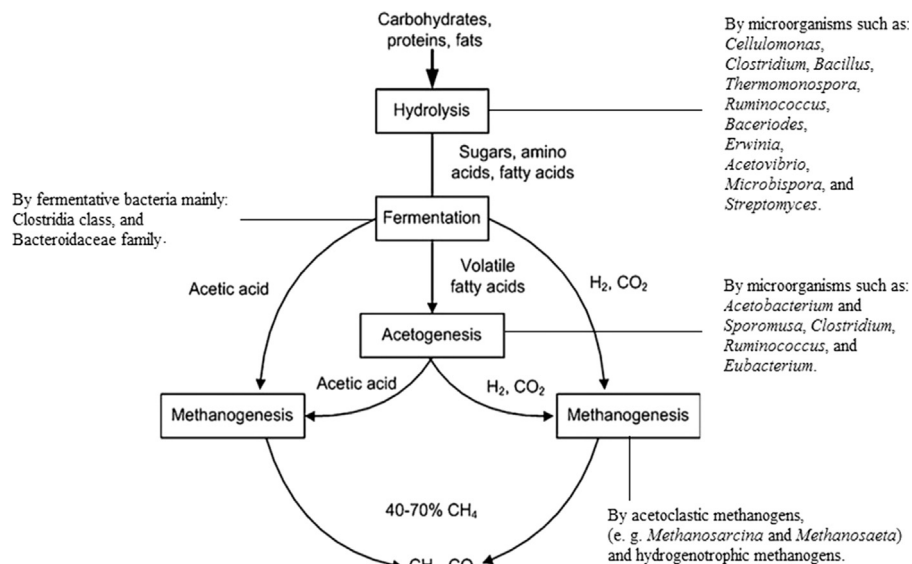


Fig. 8. Process flow of methane production by anaerobic digestion (Li et al., 2011; Traversi et al., 2012).

using rumen fluid prior to methane production. In their study, VFAs, especially acetate, were produced and the best daily methane yield was obtained by the 6 h pre-treatment. The reported amount of produced gas was 2.6 times higher than that of untreated paper, which resulted in 73.4% of the theoretical methane yield.

The total yield of the AD is also directly related to operating conditions such as continuity (batch versus continuous) and operating temperature (psychrophilic (0–20 °C), mesophilic (20–42 °C), and thermophilic (42–75 °C)) (Rajeshwari et al. 2000). Mesophilic AD is more widely used, compared with thermophilic digestion, mainly due to less energy requirements and higher stability of the process (Lin et al., 2011). Deshmukh et al. (2009) achieved 90.2%, 90.7%, and 93.0% average removals of AOX when bleach composite wastewater samples were supplemented with glucose, acetate, and combination of both, respectively, in a mesophilic upflow anaerobic filter at 20 days HRT over a period of 50 days. Buzzini and Pires (2007) investigated the effects of the effluent recirculation in an upflow anaerobic sludge blanket reactor (UASB) on the HRT and COD removal. They observed that with recirculation of the effluent, decrease in HRT (from 30 h to 24 h) led to a slight increase in the COD removal (from 75% to 78%). Without recirculation, the average COD removal efficiency at HRT of 36 h varied from 80% to 86%. Lin et al. (2011) achieved 90% of COD reduction and 0.397 L/g COD biogas production (including 62–75% CH₄) by using a submerged anaerobic membrane bioreactor (SANMBR). They also stated that attachment of small flocs and/or specific bacterial clusters can be considered as the start point of the cake formation process. Sludge cake which is not removable by the back-flush cycles or relaxation, is considered as the dominate cause of the membrane fouling, as stated by Gao et al. (2011). Gao et al. (2010) stated that the performance and membrane fouling of a SANMBR can be adversely affected by the accumulation of substances such as colloids and solutes or biopolymers as a result of sludge flocs breakage induced by elevated pH shocks (pH 8.0, 9.1 and 10.0). Zwain et al. (2013) achieved around 71%, 50%, 45%, 49%, and 45% removals of COD, TDS, TSS, TS, and VSS, respectively, from the RCF mill wastewater during the whole start-up operation of a modified anaerobic baffled reactor (30 days). Moreover, the daily methane yield increased from 0.003 to 0.09 L CH₄/g COD.

However, economic considerations including construction, mechanical and electrical instruments, footprint, piping, transportation, and engineering and consulting costs may be entered during the decision making process (Table 7). Buyukkamaci and Koken (2010) determined optimum treatment processes for different types of P&P industry effluents based on detailed cost analyses. They showed that the most economic and technically optimal treatment processes for medium strength effluents are up-flow anaerobic sludge blanket (UASB) followed by an aeration basin, and for high strength effluents are UASB followed by an aeration basin or by the conventional activated sludge process.

Table 9 summarizes the observed changes in the P&P mill wastewater parameters after treatment by aerobic and anaerobic treatment processes.

4. Conclusion

This study aimed to review the current status of P&P wastewater treatments in order to aid in providing information by which a suitable strategy can be selected and implemented by P&P industry. Nowadays, the pulp and paper industry is facing important reforms in both environmental performances and production processes, in order to satisfy stringent environmental regulations, to maintain their profitability, and to overcome the declining and

competitive markets. In order to overcome the incomplete treatment of P&P mill wastewater and make the treatment process cost effective, several physicochemical and biological methods have been employed. Physicochemical methods have shown the ability to remove a variety of suspended and floating matters as well as recalcitrant pollutants from the produced wastewaters. Sedimentation has been widely adopted by P&P mills for primary clarification. However, more surveys are needed to investigate the effectiveness and necessity of pre-sedimentation when it is conducted prior to anaerobic digestion. Several studies have shown the effectiveness of the coagulation and precipitation methods to remove, especially, COD, turbidity, and lignin from the P&P mill wastewater effluents. Electrocoagulation and adsorption treatments can be efficiently employed to remove high molecular weight dissolved organic matters and they are considered a suitable option to be conducted prior to biological treatment (e.g., aerated lagoons) to reduce the color formation during such biological processes. Various membrane technologies have been applied for treatment of P&P mill wastewater. The combination of membrane technologies and electrochemical ways can be considered an effective treatment way to remove BOD, COD, TSS, and DOC which enhance the removal efficiency and produce smaller quantity of sludge. However, membrane fouling is considered the main limitation of these methods which can be minimized by optimization the operating conditions (e.g., transmembrane pressure as one of the most important parameters). In addition to membrane filtration processes, other physicochemical methods, including adsorption and oxidation, and membrane filtration are capable to degrade biological resistant compounds. Adsorption can remove both soluble and insoluble organic pollutants, especially for high molecular weight fractions. Various oxidation processes have been employed successfully to remove COD, BOD, and color as well as recalcitrant organic pollutants from P&P mill wastewaters. However, such methods are relatively expensive and more efforts are needed to make them more cost effective. Fungi can efficiently remove COD and, to some extent, lignin, and color through production of extracellular enzymes. However, the fungal ability for practical treatment can be restricted under extreme environmental conditions such as high pH and oxygen limitations. Although aerated lagoons have shown acceptable performance for removal of BOD; their ability for removal of color and recalcitrant pollutants is low to moderate. However, some measures such as longer coagulation by, for instance, alum or introducing some species of aquatic weeds to existing stabilization pond can enhance their effectiveness. Activated sludge processes have been the major treatments for P&P mill effluents. Recent studies have shown that adoption of a consortium of different bacteria or combination of activated sludge processes with physicochemical methods can considerably enhance the performance of this method for removal of COD, BOD, color, and TSS. Application of membrane bioreactors can also be considered an effective way to reduce the sludge production and enhance the treatment performance. However, activated sludge treatments are not so efficient in removal of TDS from pulp and paper effluents. Anaerobic digestion processes, such as upflow anaerobic sludge blanket reactor, have been considered attractive treatment ways, because of their merits, especially biogas production, as an energy carrier. It was apparent from this review that the effectiveness of such technologies is directly related to some factors such as BI and C:N ratio of the produced wastewater during the P&P production processes. Investigation of such criteria can be considered the most important step to determine the necessity of the adoption of single or integrated methods to achieve the desired treatment process quality. For instance, a combination of physicochemical and biological treatments can be adopted to improve the BI and/or utilization of co-digestion strategies in the case of C:N

insufficiencies. Moreover, maintaining a suitable pH during anaerobic digestion is considered the main factor to enhance the performance of the methanogenic digestion. However, more studies are needed to improve the removal of the recalcitrant compounds such as AOX and to promote the methane production.

References

- Abbasi, T., Abbasi, S.A., 2010. Enhancement in the efficiency of existing oxidation ponds by using aquatic weeds at little or no extra cost – the macrophyte-upgraded oxidation pond (MUOP). *Bior. J.* 14, 67–80.
- Afroz, Z., Singh, A., 2014. Impact of pulp and paper mill effluent on water quality of river Aami and its effect on aquatic life (fish). *Glob. J. Pharmacol.* 8 (2), 140–149.
- Agridiotis, V., Forster, C.F., Carliell-Marquet, C., 2007. Addition of Al and Fe salts during treatment of paper mill effluents to improve activated sludge settlement characteristics. *Bioresour. Technol.* 98, 2926–2934.
- Akolekar, D.B., Bhargava, S.K., Shirgoankar, I., Prasad, J., 2002. Catalytic wet oxidation: an environmental solution for organic pollutant removal from paper and pulp industrial waste liquor. *Appl. Catal. A Gen.* 236, 255–262.
- Ali, M., Sreekrishnan, T.R., 2001. Aquatic toxicity from pulp and paper mill effluents: a review. *Adv. Environ. Res.* 5, 175–196.
- Alkaya, E., Demirel, G.N., 2011. Anaerobic mesophilic co-digestion of sugar-beet processing wastewater and beet-pulp in batch reactors. *Renew. Energy* 36, 971–975.
- Andrade, M.F., Colodette, J.L., 2014. Dissolving pulp production from sugar cane bagasse. *Ind. Crops Prod.* 52, 58–64.
- Asano, T., Cotruvo, J.A., 2004. Groundwater recharge with reclaimed municipal wastewater: health and regulatory considerations. *Water Res.* 38, 1941–1951.
- Avsar, E., Demirel, G.N., 2008. Cleaner production opportunity assessment study in SEKA Balikesir pulp and paper mill. *J. Clean. Prod.* 16, 422–431.
- Baba, Y., Tada, C., Fukuda, Y., Nakai, Y., 2013. Improvement of methane production from waste paper by pretreatment with rumen fluid. *Bioresour. Technol.* 128, 94–99.
- Babuponnusami, A., Muthukumar, K., 2012a. Advanced oxidation of phenol: a comparison between Fenton, electro-Fenton, sono-electro-Fenton and catalytic ozonation processes. *Chem. Eng. J.* 183, 1–9.
- Babuponnusami, A., Muthukumar, K., 2012b. Removal of phenol by heterogenous photo electro Fenton-like process using nano-zero valent iron. *Sep. Purif. Technol.* 98, 130–135.
- Bajpai, P., 2010. Environmentally Friendly Production of Pulp and Paper. JohnWiley & Sons, Inc, New Jersey (357 p.).
- Bajpai, P., 2012. ECF and TCF bleaching. In: *Environmentally Benign Approaches for Pulp Bleaching*. Elsevier, Waltham, pp. 263–283.
- Balcioglu, I.A., Tarlan, E., Kivildimdan, C., Sacan, M.T., 2007. Merits of ozonation and catalytic ozonation pre-treatment in the algal treatment of pulp and paper mill effluents. *J. Environ. Manage.* 85, 918–926.
- Bayr, S., Kaporaju, P., Rintala, J., 2013. Screening pretreatment methods to enhance thermophilic anaerobic digestion of pulp and paper mill wastewater treatment secondary sludge. *Chem. Eng. J.* 223, 479–486.
- Beneventi, D., Almeida, F., Marlin, N., Curtil, D., Salgueiro, L., Arousseau, M., 2009. Hydrodynamics and recovered papers deinking in an ozone flotation column. *Chem. Eng. Process. Process Intensif.* 48, 1517–1526.
- Bengtsson, S., Werker, A., Christensson, M., Welander, T., 2008. Production of polyhydroxyalkanoates by activated sludge treating a paper mill wastewater. *Bioresour. Technol.* 99, 509–516.
- Betancur, M., Bonelli, P.R., Velásquez, J.A., Cukierman, A.L., 2009. Potentiality of lignin from the Kraft pulping process for removal of trace nickel from wastewater: effect of demineralisation. *Bioresour. Technol.* 100, 1130–1137.
- Bhat, M.K., 2000. Cellulases and related enzymes in biotechnology. *Biotechnol. Adv.* 18, 355–383.
- Borchardt, J.K., Miller, J.D., Azevedo, M.A.D., 1998. Office paper de-inking. *Curr. Opin. Colloid Interface Sci.* 3, 360–367.
- Boroski, M., Rodrigues, A.C., Garcia, J.C., Gerola, A.P., Nozaki, J., Hioka, N., 2008. The effect of operational parameters on electrocoagulation – flotation process followed by photocatalysis applied to the decontamination of water effluents from cellulose and paper factories. *J. Hazard. Mater.* 160, 135–141.
- Boubaker, F., Ridha, B.C., 2008. Modelling of the mesophilic anaerobic co-digestion of olive mill wastewater with olive mill solid waste using anaerobic digestion model no. 1 (ADM1). *Bioresour. Technol.* 99, 6565–6577.
- Buyukkamaci, N., Koken, E., 2010. Economic evaluation of alternative wastewater treatment plant options for pulp and paper industry. *Sci. Total Environ.* 408, 6070–6078.
- Buzzini, A.P., Pires, E.C., 2007. Evaluation of a upflow anaerobic sludge blanket reactor with partial recirculation of effluent used to treat wastewaters from pulp and paper plants. *Bioresour. Technol.* 98, 1838–1848.
- Calvo, L., Gilarranz, M.A., Casas, J.A., Mohedano, A.F., Rodriguez, J.J., 2007. Detoxification of Kraft pulp ECF bleaching effluents by catalytic hydrotreatment. *Water Res.* 41, 915–923.
- Chandra, R., Singh, R., 2012. Decolourisation and detoxification of rayon grade pulp paper mill effluent by mixed bacterial culture isolated from pulp paper mill effluent polluted site. *Biochem. Eng. J.* 61, 49–58.
- Chanworrawoot, K., Hunsom, M., 2012. Treatment of wastewater from pulp and paper mill industry by electrochemical methods in membrane reactor. *J. Environ. Manage.* 113, 399–406.
- Chen, H.-W., Hsu, C.-H., Hong, G., 2012. The case study of energy flow analysis and strategy in pulp and paper industry. *Energy Policy* 43, 448–455.
- Ciputra, S., Antony, A., Phillips, R., Richardson, D., Leslie, G., 2010. Comparison of treatment options for removal of recalcitrant dissolved organic matter from paper mill effluent. *Chemosphere* 81, 86–91.
- Cong, Y., Li, Z., Zhang, Y., Wang, Q., Xu, Q., 2012. Synthesis of α -Fe₂O₃/TiO₂ nanotube arrays for photoelectro-Fenton degradation of phenol. *Chem. Eng. J.* 191, 356–363.
- Costigan, S.L., Werner, J., Ouellet, J.D., Hill, L.G., Law, R.D., 2012. Expression profiling and gene ontology analysis in fathead minnow (*Pimephales promelas*) liver following exposure to pulp and paper mill effluents. *Aquat. Toxicol.* 122–123, 44–55.
- Del Rio, J.C., Gutierrez, A., Gonzalez-vila, F.J., Martin, F., Romero, J., 1998. Characterization of organic deposits produced in the kraft pulping of *Eucalyptus globulus* wood. *J. Chromatogr.* 823, 457–465.
- Deshmukh, N.S., Lapsiya, K.L., Savant, D.V., Chiplonkar, S.A., Yeole, T.Y., Dhakephalkar, P.K., Ranade, D.R., 2009. Upflow anaerobic filter for the degradation of adsorbable organic halides (AOX) from bleach composite wastewater of pulp and paper industry. *Chemosphere* 75, 1179–1185.
- Dilek, F.B., Taplamacioglu, H.M., Tarlan, E., 1999. Colour and AOX removal from pulping effluents by algae. *Appl. Microbiol. Biotechnol.* 52, 585–591.
- Dorathi, P.J., Kandasamy, P., 2012. Dechlorination of chlorophenols by zero valent iron impregnated silica. *J. Environ. Sci.* 24, 765–773.
- Ekstrand, E., Larsson, M., Truong, X., Cardell, L., Borgstrom, Y., Bjorn, A., Ejlertsson, J., Svensson, B.H., Nilsson, F., Karlsson, A., 2013. Methane potentials of the Swedish pulp and paper industry – a screening of wastewater effluents. *Appl. Energy* 112, 507–517.
- El-temsah, Y.S., Joner, E.J., 2012. Ecotoxicological effects on earthworms of fresh and aged nano-sized zero-valent iron (nZVI) in soil. *Chemosphere* 89, 76–82.
- Ericsson, K., Nilsson, L.J., Nilsson, M., 2011. New energy strategies in the Swedish pulp and paper industry – the role of national and EU climate and energy policies. *Energy Policy* 39, 1439–1449.
- Eskelinen, K., Särkkä, H., Kurniawan, T.A., Sillanpää, M.E.T., 2010. Removal of recalcitrant contaminants from bleaching effluents in pulp and paper mills using ultrasonic irradiation and Fenton-like oxidation, electrochemical treatment, and/or chemical precipitation: a comparative study. *Desalination* 255, 179–187.
- European Commission, 2001. Integrated Pollution Prevention and Control (IPPC)-Reference Document on Best Available Techniques in the Pulp and Paper Industry. Retrieved from: (http://eippcb.jrc.ec.europa.eu/reference/BREF/sa_b_ref_0505.pdf).
- FAO, 2012. ForesSTAT database 2012. Retrieved from: (<http://faostat.fao.org/site/626/default.aspx#ancor>).
- Fernandes, L., Lucas, M.S., Maldonado, M.I., Oller, I., Sampaio, A., 2014. Treatment of pulp mill wastewater by *Cryptococcus podzolicus* and solar photo-Fenton: a case study. *Chem. Eng. J.* 245, 158–165.
- Fornell, R., Berntsson, T., Åsblad, A., 2012. Process integration study of a kraft pulp mill converted to an ethanol production plant-part B: techno-economic analysis. *Appl. Therm. Eng.* 42, 179–190.
- Fraser, D.S., O'Halloran, K., van Den Heuvel, M.R., 2009. Toxicity of pulp and paper solid organic waste constituents to soil organisms. *Chemosphere* 74, 660–668.
- Freitas, A.C., Ferreira, F., Costa, A.M., Pereira, R., Antunes, S.C., Gonçalves, F., Rochasantos, T.A.P., Diniz, M.S., Castro, L., Peres, I., Duarte, A.C., 2009. Biological treatment of the effluent from a bleached kraft pulp mill using basidiomycete and zygomycete fungi. *Sci. Total Environ.* 407, 3282–3289.
- Gamelas, J.A.F., Lourenço, A.F., Xavier, M., Ferreira, P.J., Modification of precipitated calcium carbonate with cellulose esters and use as filler in papermaking, *Chem. Eng. Res. Des.* <http://dx.doi.org/10.1016/j.cherd.2014.02.003>, in press.
- Gao, J., Xu, G., Qian, H., Liu, P., Zhao, P., Hu, Y., 2013. Effects of nano-TiO₂ on photosynthetic characteristics of *Ulmus elongata* seedlings. *Environ. Pollut.* 176, 63–70.
- Gao, W.J.J., Lin, H.J., Leung, K.T., Liao, B.Q., 2010. Influence of elevated pH shocks on the performance of a submerged anaerobic membrane bioreactor. *Process Biochem.* 45, 1279–1287.
- Gao, W.J., Lin, H.J., Leung, K.T., Schraft, H., Liao, B.Q., 2011. Structure of cake layer in a submerged anaerobic membrane bioreactor. *J. Membr. Sci.* 374, 110–120.
- Garg, A., 2012. Water pollution from pulp and paper mills. In: Daniels, J.A. (Ed.), *Advances in Environmental Research*, vol. 20. Nova Science Publishers, Inc, Hauppauge NY, pp. 245–252.
- Garg, A., Mishra, I.M., Chand, S., 2007. Catalytic wet oxidation of the pretreated synthetic pulp and paper mill effluent under moderate conditions. *Chemosphere* 66, 1799–1805.
- Ghaly, M.Y., Jamil, T.S., El-seesy, I.E., Souaya, E.R., Nasr, R.A., 2011. Treatment of highly polluted paper mill wastewater by solar photocatalytic oxidation with synthesized nanoTiO₂. *Chem. Eng. J.* 168, 446–454.
- Ghoreishi, S.M., Haghghi, M.R., 2007. Chromophores removal in pulp and paper mill effluent via hydrogenation-biological batch reactors. *Chem. Eng. J.* 127, 59–70.
- Gonder, Z.B., Arayici, S., Barlas, H., 2011. Advanced treatment of pulp and paper mill wastewater by nanofiltration process: effects of operating conditions on membrane fouling. *Sep. Purif. Technol.* 76, 292–302.
- Gonder, Z.B., Arayici, S., Barlas, H., 2012. Treatment of pulp and paper mill wastewater using ultra filtration process: optimization of the fouling and rejections. *Ind. Eng. Chem. Res.* 51, 6184–6195.

- González, L.F., Sarria, V., Sánchez, O.F., 2010. Degradation of chlorophenols by sequential biological-advanced oxidative process using *Trametes pubescens* and TiO_2/UV . *Bioresour. Technol.* 101, 3493–3499.
- Greenlee, L.F., Testa, F., Lawler, D.F., Freeman, B.D., Moulin, P., 2010. Effect of antiscalants on precipitation of an RO concentrate: metals precipitated and particle characteristics for several water compositions. *Water Res.* 44, 2672–2684.
- Grieger, K.D., Fjordbøge, A., Hartmann, N.B., Eriksson, E., Bjerg, P.L., Baun, A., 2010. Environmental benefits and risks of zero-valent iron nanoparticles (nZVI) for in situ remediation: risk mitigation or trade-off? *J. Contam. Hydrol.* 118, 165–183.
- Guedez, A.A., Püttmann, W., 2014. Printing ink and paper recycling sources of TMDD in wastewater and rivers. *Sci. Total Environ.* 468–469, 671–676.
- Hagelqvist, A., 2013. Batchwise mesophilic anaerobic co-digestion of secondary sludge from pulp and paper industry and municipal sewage sludge. *Waste Manage.* 33, 820–824.
- Hazrati, H., Shayegan, J., 2011. Upgrading activated sludge systems and reduction in excess sludge. *Bioresour. Technol.* 102, 10327–10333.
- Hedjazi, S., Kordsachia, O., Patt, R., Jahan, A., Tschirner, U., 2009. Alkaline sulfite-anthraquinone (AS/AQ) pulping of wheat straw and totally chlorine free (TCF) bleaching of pulps. *Ind. Crops Prod.* 29, 27–36.
- Herney-ramirez, J., Silva, A.M.T., Vicente, M.A., Costa, C.A., Madeira, L.M., 2011. Degradation of acid orange 7 using a saponite-based catalyst in wet hydrogen peroxide oxidation: kinetic study with the Fermi's equation. *Appl. Catal. B Environ.* 101, 197–205.
- Hewitt, L.M., Kovacs, T.G., Dube, M.G., Maclatchy, D.L., Martel, P.H., McMaster, M.E., Paice, M.G., Parrott, J.L., Van Den Heuvel, M.R., Van Der Kraak, G.J., 2008. Altered reproduction in fish exposed to pulp and paper mill effluents: roles of individual compounds and mill operating conditions. *Environ. Toxicol. Chem.* 27, 682–697.
- Holik, H. (Ed.), 2006. *Handbook of Paper and Board*. Wiley-VCH, Weinheim.
- Holmberg, K., Siilasto, R., Laitinen, T., Andersson, P., Jäsberg, A., 2013. Global energy consumption due to friction in paper machines. *Tribol. Int.* 62, 58–77.
- Hong, J., Li, X., 2012. Environmental assessment of recycled printing and writing paper: a case study in China. *Waste Manage.* 32, 264–270.
- Hosseinpour, R., Fatehi, P., Jahan, A., Ni, Y., Sepiddehdam, S.J., 2010. Canola straw chemimechanical pulping for pulp and paper production. *Bioresour. Technol.* 101, 4193–4197.
- Hussain, S., Shaikh, S., Farooqui, M., 2013. COD reduction of waste water streams of active pharmaceutical ingredient – atenolol manufacturing unit by advanced oxidation-Fenton process. *J. Saudi Chem. Soc.* 17, 199–202.
- Huuha, T.S., Kurniawan, T.A., Sillanpää, M.E.T.T., 2010. Removal of silicon from pulping whitewater using integrated treatment of chemical precipitation and evaporation. *Chem. Eng. J.* 158, 584–592.
- Jiménez, L., Angulo, V., Rodríguez, A., Sánchez, R., Ferrer, A., 2009. Pulp and paper from vine shoots: neural fuzzy modeling of ethylene glycol pulping. *Bioresour. Technol.* 100, 756–762.
- Jonsson, J., Ruohonen, P., Michel, G., Berntsson, T., 2011. The potential for steam savings and implementation of different biorefinery concepts in Scandinavian integrated TMP and paper mills. *Appl. Therm. Eng.* 31, 2107–2114.
- Kansal, S.K., Singh, M., Sud, D., 2008. Effluent quality at kraft/soda agro-based paper mills and its treatment using a heterogeneous photocatalytic system. *Desalination* 228, 183–190.
- Karikallio, H., Mäki-fränti, P., Suhonen, N., 2011. Competition in the global pulp and paper industries – an evaluation based on three approaches. *J. For. Econ.* 17, 91–104.
- Karrasch, B., Parra, O., Cid, H., Mehrens, M., Pacheco, P., Urrutia, R., Valdovinos, C., Zoror, C., 2006. Effects of pulp and paper mill effluents on the microplankton and microbial self-purification capabilities of the Biobio River, Chile. *Sci. Total Environ.* 359, 194–208.
- Kemeny, T.E., Banerjee, S., 1997. Relationships among effluent constituents in bleached kraft pulp mills. *Water Res.* 31, 1589–1594.
- Khansorhthong, S., Hunsom, M., 2009. Remediation of wastewater from pulp and paper mill industry by the electrochemical technique. *Chem. Eng. J.* 151, 228–234.
- Khristova, P., Bentcheva, S., Karar, I., 1998. SODA – AQ pulp blends from kenaf and sunflower stalks. *Bioresour. Technol.* 66, 99–103.
- Kishimoto, N., Nakagawa, T., Okada, H., Mizutani, H., 2010. Treatment of paper and pulp mill wastewater by ozonation combined with electrolysis. *J. Water Environ. Technol.* 8, 99–109.
- Klugman, S., Karlsson, M., Moshfegh, B., 2009. A Swedish integrated pulp and paper mill – energy optimisation and local heat cooperation. *Energy Policy* 37, 2514–2524.
- Ko, C., Fan, C., 2010. Enhanced chemical oxygen demand removal and flux reduction in pulp and paper wastewater treatment using laccase-polymerized membrane filtration. *J. Hazard. Mater.* 181, 763–770.
- Koistinen, J., Paasivirta, J., Nevalainen, T., Lahtiperä, M., 1994. Chlorinated fluorenes and alkylfluorenes in bleached kraft pulp and pulp mill discharges. *Chemosphere* 28, 2139–2150.
- Kortekaas, S., Wijngaarde, R.R., Klomp, J.-W., Lettinga, G., Field, J.A., 1998. Anaerobic treatment of hemp thermomechanical pulping wastewater. *Water Res.* 32, 3362–3370.
- Krawczyk, H., Oinonen, P., Jonsson, A., 2013. Combined membrane filtration and enzymatic treatment for recovery of high molecular mass hemicelluloses from chemithermomechanical pulp process water. *Chem. Eng. J.* 225, 292–299.
- Le-clech, P., Chen, V., Fane, T.A.G., 2006. Fouling in membrane bioreactors used in wastewater treatment. *J. Membr. Sci.* 284, 17–53.
- Lee, C.K., Ibrahim, D., Omar, I.C., 2013. Enzymatic deinking of various types of waste paper: efficiency and characteristics. *Process Biochem.* 48, 299–305.
- Lei, X., Zhao, Y., Li, K., Pelletier, A., 2012. Improved surface properties of CTMP fibers with enzymatic pretreatment of wood chips prior to refining. *Cellulose* 19, 2205–2215.
- Lewis, R., Nothrop, S., Chow, C.W.K., Everson, A., Leeuwen, J.A. Van., 2013. Color formation from pre and post-coagulation treatment of *Pinus radiata* sulfite pulp mill wastewater using nutrient limited aerated stabilisation basins. *Sep. Purif. Technol.* 114, 1–10.
- Li, S., Zhang, X., 2011. The study of PAFSSB on RO pre-treatment in pulp and paper wastewater. *Proc. Environ. Sci.* 8, 4–10.
- Li, Y., Park, S.Y., Zhu, J., 2011. Solid-state anaerobic digestion for methane production from organic waste. *Renew. Sustain. Energy Rev.* 15, 821–826.
- Lin, H., Liao, B.-Q., Chen, J., Gao, W., Wang, L., Wang, F., Lu, X., 2011. New insights into membrane fouling in a submerged anaerobic membrane bioreactor based on characterization of cake sludge and bulk sludge. *Bioresour. Technol.* 102, 2373–2379.
- Lin, H., Peng, W., Zhang, M., Chen, J., Hong, H., Zhang, Y., 2013. A review on anaerobic membrane bioreactors: applications, membrane fouling and future perspectives. *Desalination* 314, 169–188.
- Lin, Y., Wang, D., Li, Q., Xiao, M., 2011. Mesophilic batch anaerobic co-digestion of pulp and paper sludge and monosodium glutamate waste liquor for methane production in a bench-scale digester. *Bioresour. Technol.* 102, 3673–3678.
- Lin, Y., Wang, D., Wang, T., 2012. Ethanol production from pulp & paper sludge and monosodium glutamate waste liquor by simultaneous saccharification and fermentation in batch condition. *Chem. Eng. J.* 191, 31–37.
- Liu, T., Hu, H., He, Z., Ni, Y., 2011. Treatment of poplar alkaline peroxide mechanical pulping (APMP) effluent with *Aspergillus niger*. *Bioresour. Technol.* 102, 7361–7365.
- Lucas, M.S., Peres, J.A., Amor, C., Prieto-rodríguez, L., Maldonado, M.I., 2012. Tertiary treatment of pulp mill wastewater by solar photo-Fenton. *J. Hazard. Mater.* 225–226, 173–181.
- Machani, M., Nourelfath, M., D'Amours, S., 2014. A mathematically-based framework for evaluating the technical and economic potential of integrating bioenergy production within pulp and paper mills. *Biomass Bioenergy* 63, 126–139.
- Mahmood, T., Elliott, A., 2006. A review of secondary sludge reduction technologies for the pulp and paper industry. *Water Res.* 40, 2093–2112.
- Mahmood-khan, Z., Hall, E.R., 2013. Biological removal of phyto-sterols in pulp mill effluents. *J. Environ. Manage.* 131, 407–414.
- Malaviya, P., Rathore, V.S., 2007. Bioremediation of pulp and paper mill effluent by a novel fungal consortium isolated from polluted soil. *Bioresour. Technol.* 98, 3647–3651.
- Manda, B.M.K., Blok, K., Patel, M.K., 2012. Innovations in papermaking: an LCA of printing and writing paper from conventional and high yield pulp. *Sci. Total Environ.* 439, 307–320.
- Manttari, M., Kuosa, M., Kallas, J., Nystrom, M., 2008. Membrane filtration and ozone treatment of biologically treated effluents from the pulp and paper industry. *J. Membr. Sci.* 309, 112–119.
- Maradur, S.P., Kim, C.H., Kim, S.Y., Kim, B.-H., Kim, W.C., Yang, K.S., 2012. Preparation of carbon fibers from a lignin copolymer with polyacrylonitrile. *Synth. Met.* 162, 453–459.
- Martinez-Inigo, M.J., Gutierrez, A., del Rio, J.C., Martinez, M.J., Martinez, A.T., 2000. Time course of fungal removal of lipophilic extractives from *Eucalyptus globulus* wood. *J. Biotechnol.* 84, 119–126.
- Martin-Sampedro, R., Eugenio, M.E., Villar, J.C., 2011. Biobleaching of *Eucalyptus globulus* kraft pulps: comparison between pulps obtained from exploded and non-exploded chips. *Bioresour. Technol.* 102, 4530–4535.
- Matafonova, G., Shirapova, G., Zimmer, C., Giffhorn, F., Batov, V., Kohring, G., 2006. Degradation of 2, 4-dichlorophenol by *Bacillus* sp. isolated from an aeration pond in the Baikalsk pulp and paper mill (Russia). *Int. Biodeterior. Biodegrad.* 58, 209–212.
- Melegari, S.P., Perreault, F., Costa, R.H.R., Popovic, R., Matias, W.G., 2013. Evaluation of toxicity and oxidative stress induced by copper oxide nanoparticles in the green alga *Chlamydomonas reinhardtii*. *Aquat. Toxicol.* 142–143, 431–440.
- Miranda, R., Blanco, A., Negro, C., 2009. Accumulation of dissolved and colloidal material in papermaking – application to simulation. *Chem. Eng. J.* 148, 385–393.
- Monte, M.C., Fuente, E., Blanco, A., Negro, C., 2009. Waste management from pulp and paper production in the European Union. *Waste Manage.* 29, 293–308.
- Morais, J.L. de, Zamora, P.P., 2005. Use of advanced oxidation processes to improve the biodegradability of mature landfill leachates. *J. Hazard. Mater.* B123, 181–186.
- Muhamad, M.H., Sheikh Abdullah, S.R., Mohamad, A.B., Abdul Rahman, R., Hasan Kadhum, A.A., 2013. Application of response surface methodology (RSM) for optimisation of COD, $\text{NH}_3\text{-N}$ and 2,4-DCP removal from recycled paper wastewater in a pilot-scale granular activated carbon sequencing batch biofilm reactor (GAC-SBBR). *J. Environmental Manage.* 121, 179–190.
- Nasser, M.S., Twaif, F.A., Onaizi, S.A., 2013. Effect of polyelectrolytes on the degree of flocculation of papermaking suspensions. *Sep. Purif. Technol.* 103, 43–52.
- Orrego, R., Guchardi, J., Krause, R., Holdway, D., 2010. Estrogenic and anti-estrogenic effects of wood extractives present in pulp and paper mill effluents on rainbow trout. *Aquat. Toxicol.* 99, 160–167.

- Osman, W.H.W., Abdullah, S.R.S., Mohamad, A.B., Kadhum, A.A.H., Rahman, R.A., 2013. Simultaneous removal of AOX and COD from real recycled paper wastewater using GAC-SBBR. *J. Environ. Manage.* 121, 80–86.
- Pala, H., Mota, M., Gama, F.M., 2004. Enzymatic versus chemical deinking of non-impact ink printed paper. *J. Biotechnol.* 108, 79–89.
- Pan, Y., Xiao, H., Zhao, Y., Wang, Z., 2013. CTMP-based cellulose fibers modified with core-shell latex for reinforcing biocomposites. *Carbohydr. Polym.* 95, 428–433.
- Pellegrin, V., Juretschko, S., Wagner, M., Cotteceau, G., 1999. Morphological and biochemical properties of a *Sphaerotilus* sp. isolated from paper mill slimes. *Appl. Environ. Microbiol.* 65, 156–162.
- Phillips, R.B., Jameel, H., Chang, H.M., 2013. Integration of pulp and paper technology with bioethanol production. *Biotechnol. Biofuels* 6, 13.
- Pokhrel, D., Viraraghavan, T., 2004. Treatment of pulp and paper mill wastewater – a review. *Sci. Total Environ.* 333, 37–58.
- Puro, L., Kallioinen, M., Mänttari, M., Natarajan, G., Cameron, D.C., Nystrom, M., 2010. Performance of RC and PES ultrafiltration membranes in filtration of pulp mill process waters. *Desalination* 264, 249–255.
- Qu, X., Gao, W.J., Han, M.N., Chen, A., Liao, B.Q., 2012. Integrated thermophilic submerged aerobic membrane bioreactor and electrochemical oxidation for pulp and paper effluent treatment – towards system closure. *Bioresour. Technol.* 116, 1–8.
- Rajeshwari, K.V., Balakrishnan, M., Kansal, A., Lata, K., Kishore, V.V.N., 2000. State-of-the-art of anaerobic digestion technology for industrial wastewater treatment. *Renew. Sustain. Energy Rev.* 4, 135–156.
- Ramos, W.D.L.S., Poznyak, T., Chairez, I., I, C.R., 2009. Remediation of lignin and its derivatives from pulp and paper industry wastewater by the combination of chemical precipitation and ozonation. *J. Hazard. Mater.* 169, 428–434.
- Raut, S.P., Sedmake, R., Dhunde, S., Ralegaonkar, R.V., Mandavgane, S.A., 2012. Reuse of recycle paper mill waste in energy absorbing light weight bricks. *Constr. Building Mater.* 27, 247–251.
- Razali, M.A.A., Ahmad, Z., Ahmad, M.S.B., Ariffin, A., 2011. Treatment of pulp and paper mill wastewater with various molecular weight of polyDADMAC induced flocculation. *Chem. Eng. J.* 166, 529–535.
- Renault, F., Sancey, B., Charles, J., Morin-crini, N., Badot, P., Winterton, P., Crini, G., 2009. Chitosan flocculation of cardboard-mill secondary biological wastewater. *Chem. Eng. J.* 155, 775–783.
- Requejo, A., Rodríguez, A., Colodette, J.L., Gomide, J.L., Jiménez, L., 2012. TCF bleaching sequence in Kraft pulping of olive tree pruning residues. *Bioresour. Technol.* 117, 117–123.
- Rodríguez, A., Sánchez, R., Requejo, A., Ferrer, A., 2010. Feasibility of rice straw as a raw material for the production of soda cellulose pulp. *J. Clean. Prod.* 18, 1084–1091.
- Sainlez, M., Heyen, G., 2013. Comparison of supervised learning techniques for atmospheric pollutant monitoring in a Kraft pulp mill. *J. Comput. Appl. Math.* 246, 329–334.
- Sang, Y., Englezos, P., 2012. Flocculation of precipitated calcium carbonate (PCC) by cationic tapioca starch with different charge densities. I: experimental. *Colloids Surf. A Physicochem. Eng. Asp.* 414, 512–519.
- Santos, M.O., Almada-Lobo, B., 2012. Integrated pulp and paper mill planning and scheduling. *Comput. Ind. Eng.* 63, 1–12.
- Schneider, T.E., 2011. Is environmental performance a determinant of bond pricing? Evidence from the U.S. pulp and paper and chemical industries. *Contemp. Account. Res.* 28, 1537–1561.
- Shankar, R., Singh, L., Mondal, P., Chand, S., 2013. Removal of lignin from wastewater through electro-coagulation. *World J. Environ. Eng.* 1, 16–20.
- Shen, J., Song, Z., Qian, X., Liu, W., 2009. Modification of papermaking grade fillers: a brief review. *BioResources* 4, 1190–1209.
- Singh, A., Dutt, R., Kaur, A., Mahajan, R., 2012. An ecofriendly cost effective enzymatic methodology for deinking of school waste paper. *Bioresour. Technol.* 120, 322–327.
- Singhal, A., Thakur, I.S., 2009. Decolourization and detoxification of pulp and paper mill effluent by *Emericella nidulans* var. *nidulans*. *Biochem. Eng. J.* 171, 619–625.
- Soloman, P.A., Basha, C.A., Velan, M., Balasubramanian, N., Marimuthu, P., 2009. Augmentation of biodegradability of pulp and paper industry wastewater by electrochemical pre-treatment and optimization by RSM. *Sep. Purif. Technol.* 69, 109–117.
- Subramanian, R., Fordsmand, H., Paltakari, J., Paulapuro, H., 2008. A new composite fine paper with high filler loading and functional cellulosic microfines. *J. Pulp Pap. Sci.* 34, 146–152.
- Sun, S., Lemley, A.T., 2011. p-Nitrophenol degradation by a heterogeneous Fenton-like reaction on nano-magnetite: process optimization, kinetics, and degradation pathways. *J. Mol. Catal. A Chem.* 349, 71–79.
- Svensson, E., Berntsson, T., 2014. The effect of long lead times for planning of energy efficiency and biorefinery technologies at a pulp mill. *Renew. Energy* 61, 12–16.
- Tarlan, E., Dilek, F.B., Yetis, U., 2002a. Effectiveness of algae in the treatment of a wood-based pulp and paper industry wastewater. *Bioresour. Technol.* 84, 1–5.
- Tarlan, E., Yetis, U., Dilek, F.B., 2002b. Algal treatment of pulp and paper industry wastewaters in SBR systems. *Water Sci. Technol.* 45, 151–158.
- Tenno, R., Paulapuro, H., 1999. Removal of dissolved organic compounds from paper machine whitewater by membrane bioreactors: a comparative analysis. *Control Eng. Pract.* 7, 1085–1099.
- Tewari, P.K., Batra, V.S., Balakrishnan, M., 2009. Efficient water use in industries: cases from the Indian agro-based pulp and paper mills. *J. Environ. Manage.* 90, 265–273.
- Thakur, I.S., 2004. Screening and identification of microbial strains for removal of color and adsorbable organic halogens in pulp and paper mill effluent. *Process Biochem.* 39, 1693–1699.
- Thompson, G., Swain, J., Kay, M., Forster, C.F., 2001. The treatment of pulp and paper mill effluent: a review. *Bioresour. Technol.* 77, 275–286.
- Tiku, D.K., Kumar, A., Chaturvedi, R., Dayal, S., Manoharan, A., Kumar, R., 2010. Holistic bioremediation of pulp mill effluents using autochthonous bacteria. *Int. Biodeterior. Biodegrad.* 64, 173–183.
- Tiku, D.K., Kumar, A., Sawhney, S., Singh, V.P., Kumar, R., 2007. Effectiveness of treatment technologies for wastewater pollution generated by Indian pulp mills. *Environ. Monit. Assess.* 132, 453–466.
- Traversi, D., Villa, S., Lorenzi, E., Degan, R., Gilli, G., 2012. Application of a real-time qPCR method to measure the methanogen concentration during anaerobic digestion as an indicator of biogas production capacity. *J. Environ. Manage.* 111, 173–177.
- Ugurlu, M., Gurses, A., Dogar, C., Yalcin, M., 2008. The removal of lignin and phenol from paper mill effluents by electrocoagulation. *J. Environ. Manage.* 87, 420–428.
- Van Beukering, P.J.H., Bouman, M.N., 2001. Empirical evidence on recycling and trade of paper and lead in developed and developing countries. *World Dev.* 29, 1717–1737.
- Vepsäläinen, M., Kivisaari, H., Pulliainen, M., Oikari, A., Sillanpää, M., 2011. Removal of toxic pollutants from pulp mill effluents by electrocoagulation. *Sep. Purif. Technol.* 81, 141–150.
- Vinita, M., Dorathi, R.P.J., Palanivelu, K., 2010. Degradation of 2,4,6-trichlorophenol by photo-Fenton's like method using nano heterogeneous catalytic ferric ion. *Sol. Energy* 84, 1613–1618.
- Wang, B., Gu, L., Ma, H., 2007. Electrochemical oxidation of pulp and paper making wastewater assisted by transition metal modified kaolin. *J. Hazard. Mater.* 143, 198–205.
- Wang, J., Chen, Y., Wang, Y., Yuan, S., Yu, H., 2011. Optimization of the coagulation-flocculation process for pulp mill wastewater treatment using a combination of uniform design and response surface methodology. *Water Res.* 45, 5633–5640.
- Wanrosli, W.D., Zainuddin, Z., Law, K.N., Asro, R., 2007. Pulp from oil palm fronds by chemical processes. *Ind. Crops Prod.* 25, 89–94.
- Waye, A., Annal, M., Tang, A., Picard, G., Harnois, F., Guerrero-analco, J.A., Saleem, A., Hewitt, L.M., Milestone, C.B., Maclatchy, D.L., Trudeau, V.L., Arnason, J.T., 2014. Canadian boreal pulp and paper feedstocks contain neuroactive substances that interact in vitro with GABA and dopaminergic systems in the brain. *Sci. Total Environ.* 468–469, 315–325.
- Wells, G.F., Park, H., Eggleston, B., Francis, C.A., Criddle, C.S., 2011. Fine-scale bacterial community dynamics and the taxa-time relationship within a full-scale activated sludge bioreactor. *Water Res.* 45, 5476–5488.
- Xilei, D., Tingzhi, L., Weijiang, D., & Huiren, H., 2010. Adsorption and coagulation tertiary treatment of pulp and paper mills wastewater. In: *Proceedings of the 4th International Conference on Bioinformatics and Biomedical Engineering (ICBBE)*.
- Yan, S., Sagoe-Crentsil, K., Shapiro, G., 2011. Reuse of de-inking sludge from wastepaper recycling in cement mortar products. *J. Environ. Manage.* 92, 2085–2090.
- Yan, S., Subramanian, S.B., Tyagi, R.D., Surampalli, R.Y., 2008. Bioplastics from activated sludge treating pulp and paper wastewater. *J. Biotechnol.* 136, S31–S32.
- Yang, Q., Angly, F.E., Wang, Z., Zhang, H., 2011. Wastewater treatment systems harbor specific and diverse yeast communities. *Biochem. Eng. J.* 58–59, 168–176.
- Yang, S., Li, J., Zheng, Z., Meng, Z., 2009. Lignocellulosic structural changes of *Spartina alterniflora* after anaerobic mono- and co-digestion. *Int. Biodeterior. Biodegrad.* 63, 569–575.
- Ye, L., Hou, Q., Liu, W., Hong, Y., Zhang, J., Zhang, R., 2012. Effect of partially substituting MgO for NaOH on bleaching of pine (*Pinus massoniana*) thermo-mechanical pulp. *Carbohydr. Polym.* 88, 1435–1439.
- Yu, Y., Park, B., Hwang, S., 2004. Co-digestion of lignocellulosics with glucose using thermophilic acidogens. *Biochem. Eng. J.* 18, 225–229.
- Yue, Z., Li, W., Yu, H., 2013. Application of rumen microorganisms for anaerobic bioconversion of lignocellulosic biomass. *Bioresour. Technol.* 128, 738–744.
- Zeshan, Karthikeyan, O.P., Visvanathan, C., 2012. Effect of C/N ratio and ammonia-N accumulation in a pilot-scale thermophilic dry anaerobic digester. *Bioresour. Technol.* 113, 294–302.
- Zhang, C., Chen, J., Wen, Z., 2012. Alternative policy assessment for water pollution control in China's pulp and paper industry. *Resour. Conserv. Recycl.* 66, 15–26.
- Zhang, S., Jiang, M., Zhou, Z., Zhao, M., Li, Y., 2012. Selective removal of lignin in steam-exploded rice straw by *Phanerochaete chrysosporium*. *Int. Biodeterior. Biodegrad.* 75, 89–95.
- Zhang, X., Renaud, S., Paice, M., 2008. Cellulase deinking of fresh and aged recycled newsprint/magazines (ONP/OMG). *Enzyme Microb. Technol.* 43, 103–108.
- Zhenying, S., Shijin, D., Xuejun, C., Yan, G., Junfeng, L., Hongyan, W., Zhang, S.X., 2009. Combined de-inking technology applied on laser printed paper. *Chem. Eng. Process. Process Intensif.* 48, 587–591.
- Zhu, X.L., Wang, J., Jiang, Y.L., Cheng, Y.J., Chen, F., Ding, S.B., 2012. Feasibility study on satisfying standard of water pollutants for pulp and paper industry. *Appl. Mech. Mater.* 178–181, 637–640.
- Zwain, H.M., Hassan, S.R., Zaman, N.Q., Aziz, H.A., Dahlan, I., 2013. The start-up performance of modified anaerobic baffled reactor (MABR) for the treatment of recycled paper mill wastewater. *J. Environ. Chem. Eng.* 1, 61–64.