The potential of anaerobic-constructed wetland system for wastewater treatment of rice straw pulping

Y Setiawan* and H Hardiani
Centre for Pulp and Paper-Ministry of Industry, Jl. Raya Dayeuh Kolot No. 132
Bandung-40258, Indonesia
Email: yusupsetiawan1960@gmail.com

Abstract. Wastewater of cooking rice straw in the manufacture of pulp contains high levels of pollutants that must be treated first before being discharged into the environment. The purpose of this research is to study the potential of anaerobic and constructed wetland systems in treating pulp-making wastewater from rice straws. Anaerobic reactor with a volume of 30 L was filled with 5 L domestic sludge as sludge seed. Wastewater with COD of 762 – 17,900 mg/L, BOD$_5$ of 354 – 8,000 mg/L, and TSS of 123 – 350 mg/L was fed into the anaerobic reactor. The organic loading rate was varied from 0.15 to 2.13 kg COD/m$^3$·day, during the residence of wastewater for 5–8 days. Anaerobic reactor effluent was further processed in a constructed wetland reactor that varies in height from a mixture of sandy soil of 10–30 cm. The hydraulic residence time of wastewater in the constructed wetland reactor was 6.7 - 11.6 days. Influent and effluent of anaerobic and constructed wetland reactors were analysed for COD, BOD$_5$, TSS, and pH parameters. The result indicated that wastewater treatment with anaerobic system could reduce COD of 63–72% and BOD$_5$ of 65–75%, and the constructed wetland system could reduce COD and BOD$_5$ of 96.5% and 96.1%, respectively.

1. Introduction
Rice straw is an agricultural waste which is available in quite a lot in Indonesia. Rice straw can be used as a raw material for making pulp which is a raw material for making special paper which has a high export value. Pulp making with rice straw raw materials is carried out by small scale industries which are generally located in villages close to the source of raw materials. The small-scale pulp and paper industry generally have old machines, consume a lot of water and energy so that it produces a lot of waste water. A serious environmental problem faced by the agro-based industry is the release of black liquor containing chemicals which are highly polluting the environment in the form of lignin and cooking chemicals that cannot be recovered through chemical recovery unit before being discharged into receiving water bodies. The small-scale pulp and paper industry generally have no chemical recovery plant that functions to recover cooking chemicals that are still contained in black liquor because it is not economical [1,2].

Wastewater containing lignin and cooking chemicals contain a high concentration of pollutants which is difficult to treat in wastewater treatment plants because lignin is not easily decomposed [1,3]. When this wastewater is discharged directly into the environment, it will pollute the receiving water. Therefore, it needs to be treated before being discharged into the environment. Since the pollutants contained in this wastewater are quite high, the treatment of wastewater requires several stages of treatment [4]. Wastewater treatment systems, which are used in the pulp and paper industry, are biological treatment processes such as activated sludge systems, oxidation ponds, activated sludge combined systems and oxidation ponds, and combined systems of anaerobic ponds and oxidation...
ponds [2]. One alternative wastewater treatment that is able to treat wastewater with high pollutants is an anaerobic biological treatment system. A wastewater treatment with anaerobic system is basically a system where wastewater flows into a reactor containing anaerobic sludge. During the wastewater flow in the reactor, pollutants are degraded by anaerobic microorganisms into simpler compounds.

The mechanism of the decomposition process of organic substances by anaerobic microorganisms through the stages of the process of hydrolysis, acidogenesis, acetogenesis, and methanogenesis producing the final result of CH₄ (50-70%) and CO₂ [4]. Wastewater treatment with conventional anaerobic systems is usually in the form of open ponds with organic loads ranging from 0.04-0.30 kg COD/m³.day and the hydraulic residence time of wastewater in ponds ranges from 30-50 days [5]. The disadvantage of this anaerobic ponds is the problem of odour and loss of methane gas as energy into the atmosphere [6,7].

Wastewater treatment with activated sludge aerobic and anaerobic systems using plastic media such as polypropylene (PP), polystyrene (PS), and polyethylene (PE) as the media for attaching microorganisms has been applied to industrial wastewater treatment [8]. The organic loading rate of this system could reach 3-4 times of the organic loading rate of activated sludge conventional system, 0.2-0.6 kg BOD/kg MLVSS. day with producing similar effluent quality [9]. This wastewater treatment requires quite high construction and operational costs. In addition, the effluent from the initial stage of wastewater treatment has mostly not met the quality standard due to the high pollutant concentration requiring polishing treatment [4].

The constructed wetland has a high level of biological activity that can convert pollutants contained in wastewater into non-toxic compounds. Constructed wetland is used for secondary and tertiary treatment in some cases [10,11]. Constructed wetlands can use local materials and local labour, which is a major advantage in developing countries such as Indonesia [12,13]. The mechanism of reducing pollutant levels that occur in constructed wetlands involves physical treatment such as sedimentation and filtration, chemical treatment such as adsorption and precipitation, and biological treatment such as bacterial metabolism, plant metabolism and plant adsorption. For this reason, it is necessary to investigate the feasibility of applying the constructed wetland subsurface as a viable technology for industrial wastewater treatment. Some studies show that vegetation used in constructed wetland bulrush species is not only able to remove organic and inorganic substances in wastewater but also is able to eliminate the heavy metal content [13–15]. In constructed wetland vegetation has a role in providing oxygen in the root zone, being the attachment of bacteria, and absorbing pollutants in wastewater [12,16].

This paper presents the results of research on wastewater treatment systems for making pulp from rice straw with anaerobic and constructed wetland systems. The purpose of this paper is to look at the potential application of anaerobic and constructed wetland treatment systems as an appropriate wastewater treatment technology for rice straw-based pulp and paper industries.

2. Materials and methods

2.1 Materials

Wastewater used in the experiment was mixed wastewater from cooking rice straw with soda process and pulp washing. The raw material for rice straw was taken from a pulp and paper industry located in West Java. Anaerobic reactor was made of plastic material that has a volume of 30 L. Anaerobic reactor was equipped with a feed channel, biogas channel, and treated wastewater channel. Recycled polypropylene (PP) plastic flakes of mineral water glass with a length of 2 cm and a width of 2 cm with a volume of about 9 L was filled into anaerobic reactors.

Seed sludge from anaerobic ponds treating domestic wastewater in the amount of 5 L with a total solid concentration of 1.8% was used as anaerobic reactor seed sludge. Three wetland reactors were made of plastic materials, each of which has an effective volume of 96.8 L, 124 L and 154 L. At the bottom of each the wetland reactor a pile of gravel about 2-5 cm in diameter was installed as high as about 10 cm. The surface of the gravel was covered by palm fibers about 1 cm high and the palm fiber surface was covered with sandy soil with varying height of about 10 cm (WL1), 20 cm (WL2) and 30 cm (WL3). Water plants used were bulrush (Scirpus longii) and water hyacinth.
2.2 Methods
Wastewater was fed continuously into an anaerobic reactor that already contains seed sludge and recycled polypropylene (PP) plastic flakes with wastewater flow rate adjusted to the hydraulic residence time of wastewater in the anaerobic reactor of 5-8 days. Flowing of wastewater was carried out in 2 stages, namely drainage of dilute wastewater as an adaptation of anaerobic seed sludge and drainage of concentrated wastewater. During the experiment, the pH of the wastewater entering the anaerobic reactor was maintained at a pH of 6.5-7.5. In the initial stage of the experiment or an adaptation stage of anaerobic seed sludge, dilute wastewater with a COD concentration of 762-1,800 mg/L was flowed into the anaerobic reactor for 54 days with the flow rate of 4.2 L/day so that the hydraulic retention time (HRT) of 5 days. Starting from the 62nd day to the 99th day, wastewater containing COD of 8,000-17,900 mg/L was flowed into the anaerobic reactor with the flow rate of 2.6 L/d so that the wastewater was adjusted to the hydraulic residence time of the wastewater in the anaerobic reactor of 8 days.

The anaerobic reactor effluent was collected in the storage tank which was further treated in the wetland. Each wetland reactor that has been planted with bulrush (Scirpus longii) and water hyacinth was first cleaned from the impurities using tap water until clean, before feeding an anaerobic reactor effluent. Then the wetland reactor was fed by an effluent anaerobic reactor containing COD of around 5,000 mg/L and BOD₅ of around 2,200 mg/L in the flow rate of 14.4 L/day. After 12 days the number of aquatic plants is calculated to see the rate of plant growth. The dimensions and operating conditions of the experimental constructed wetland reactor are as shown in table 1. Schematic diagram of wastewater treatment of rice straw pulping with anaerobic reactors-constructed wetlands system is shown in figure 1.

Table 1. The dimensions and operating conditions of the experimental constructed wetland reactor.

| Dimensions:    | WL1  | WL2  | WL3  |
|----------------|------|------|------|
| - Length (m)   | 1.10 | 1.10 | 1.10 |
| - Width (m)    | 0.40 | 0.40 | 0.40 |
| - Height (m)   | 0.26 | 0.36 | 0.46 |
| - Total volume (m³) | 0.094 | 0.124 | 0.154 |
| - Water depth (m) | 0.10 | 0.10 | 0.10 |
| - Substrate depth (m) | 0.16 | 0.26 | 0.36 |
| - Plants name  | bulrush (Scirpus longii) | and water hyacinth |
| - No. of rhizome/m² | 22   |      |      |

Operation conditions:
- OLR (g BOD₅/m².day) | 13.9 | 8.9 | 8.9 |
- HRT (day)            | 6.72 | 8.67| 10.61 |

Figure 1. Schematic diagram of wastewater treatment of rice straw pulping with anaerobic reactors-constructed wetlands system.
Influent and effluent of anaerobic reactors and constructed wetlands which include COD, BOD, TSS, and pH parameters were analyzed using standard methods for the examination of water and wastewater [17].

3. Results and discussions
3.1. Characteristic of wastewater
Characteristics of pulp-making wastewater from rice straw has a neutral pH, with a relatively low total suspended solid (TSS) content. However, it contains high level of organic compounds as indicated by the parameters of COD and BOD$_5$ as shown in table 2. This wastewater contains lignin which is not easily decomposed by anaerobic microorganism and the effluent from an anaerobic biological treatment system has mostly not met the quality standard due to the high pollutant concentration requiring polishing treatment [1,3,4].

| No. | Parameter | Unit | Concentration  |
|-----|-----------|------|---------------|
| 1.  | pH        | -    | 7.0-7.1       |
| 2.  | TSS       | mg/L | 123-350       |
| 3.  | COD       | mg/L | 762-17,900    |
| 4.  | BOD$_5$   | mg/L | 354-8,005     |

3.2. Performance of anaerobic reactor
At the beginning of the experiment (1$^{st}$ to 54$^{th}$ day), dilute wastewater was flowed into the anaerobic reactor aims to provide an opportunity for the anaerobic seed sludge to adapt to wastewater. This diluted wastewater run for about 2 months. Dilute wastewater with a concentration of COD around 762-1800 mg / L and BOD$_5$ around 354-845 mg / L are flowed into the anaerobic reactor at a rate of 4.2 L / day so that the hydraulic residence time (HRT) of wastewater in the anaerobic reactor is about 5 days. The organic loading rate during the adaptation process was between 0.1510-0.3566 kg COD/m$^3$.day as shown in figure 2. Under these conditions, the anaerobic seed sludge used was of good quality and the amount is optimum enough so that they can quickly adapt to this wastewater. This is indicated by the removal of pollutant parameters, especially COD and BOD$_5$ whose removal values tend to increase with the length of time of the experiment. As shown in figure 3, removal of COD and BOD$_5$ which on the 11$^{th}$ day showed a high removal value of 66% for COD and 68% for BOD$_5$. After that until the 54$^{th}$ day, COD and BOD$_5$ removal increased to 80-85% and 83-86%, respectively. This shows that the anaerobic reactor is in steady state.

On the 55$^{th}$ day until the end of the 99$^{th}$ day of the experiment, the anaerobic reactor was flowed with concentrated wastewater at a flow rate of 2.6 L / day with a COD concentration of 8,000-17,900 mg/L and a BOD$_5$ of 3,680-8,005 mg/L. In this condition the organic loading rate is around 0.9811-2.1953 kg COD/m$^3$.day and hydraulic residence time (HRT) of 8 days as shown in figure 2 and figure 3. This higher organic loading rate causes anaerobic sludge in the anaerobic reactor to a slight shock. This can be seen from the removal of COD and BOD$_5$ decreasing to 52.5% and 59.1% respectively. Even though the hydraulic residence time (HRT) has been extended to 8 days. But after that the anaerobic sludge in the anaerobic reactor can adapt again to the organic loading rate received which is indicated by the increasing return of COD and BOD$_5$ removal reaching 72.1% and 74.7%, respectively. At the end of the experiment, concentrations of COD and BOD$_5$ of 5,000 mg/L and BOD$_5$ of 2,200 mg/L could be achieved. Such concentrations of COD and BOD$_5$ are still above the quality standard requirements and require polishing treatment [1,3,4,16].
When compared with conventional anaerobic treatment systems, open ponds, which have organic loading rates ranging from 0.04–0.30 kg COD/m³.day and the hydraulic residence time (HRT) of 30–50 days [5], anaerobic reactors equipped with recycled polypropylene (PP) plastic flakes of mineral water glass in the amount of 30% of the reactor volume can increase organic loading rate and can reduce HRT by around 4 times. This can be caused by the number of microorganisms attached on the surface of recycled polypropylene (PP) plastic flakes. However, the number and types of microorganisms attached to recycled polypropylene (PP) plastic flakes need further study.
Table 3. The plants growth of bulrush (*Scirpus longii*).

| Wetland Reactor | Number of Plant Stems and Growth Rate | 1st Day | 12th Day | Growth Rate (Stems/day) |
|-----------------|---------------------------------------|---------|----------|-------------------------|
| WL1             | 10                                    | 42      |          | 2.67                    |
| WL2             | 10                                    | 37      |          | 2.25                    |
| WL3             | 10                                    | 36      |          | 2.17                    |

Figure 4. Influent, effluent and removal of constructed wetland.

3.3. Performance of constructed wetland reactor

From observations, bulrush (*Scirpus longii*) can grow in wetlands flowed by wastewater. Number of plant stems and growth rate is shown in table 3. The growth rate of bulrush (*Scirpus longii*) is 2.17-2.67 stems/day and increases with the length of planting time.

In the experimental conditions as shown in table 1 and the growth rate of bulrush (*Scirpus longii*) as shown in table 3, each constructed wetland produced effluent quality with the highest pollutant removals values as shown in figure 4. The highest removal of COD and BOD5 were obtained by WL3 with COD and BOD5 removal of 97.6% and 96.1%, respectively. The COD and BOD5 concentrations were 173.5 mg/L and 84.9 mg/L, respectively. The performance of WL3 is slightly better compared to WL1 and WL2, which is likely to be caused by higher substrate in the form of higher sandy soil in WL3. The height of this substrate affects the number of microorganisms that grow both in the substrate itself and in the roots of aquatic plants [15,18]. In addition, WL3 has a longer HRT (10.61 days) and OLR (8.9 g BOD/m².day) which is lower than that of WL1 and WL2. The amount of OLR (8.9 g BOD/m².day) from WL3 is slightly larger than Vymazal (2010) recommendation of 6 g BOD/m².day for the treatment of various types of wastewater [10].

Overall, wastewater treatment with anaerobic-constructed wetland system can remove COD of 99% and BOD5 of 96.1% with the effluent containing COD and BOD5 of 173.5 mg/L and 84.9 mg/L, respectively. The ability to reduce the high concentration of wastewater pollutants, anaerobic-
constructed wetland system has the potential to be applied as an appropriate wastewater treatment technology in the rice straw-based pulp and paper industry.

4. Conclusions
Anaerobic-constructed wetland treatment system could remove organic pollutants of rice straw pulping wastewater up to 99% for COD and 96.1% for BOD\textsubscript{5}. This high ability in reducing of organic pollutants of rice straw pulping wastewater indicates that anaerobic-constructed wetland system has the potential to be applied as an appropriate wastewater treatment technology in the rice straw-based pulp and paper industry.

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