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Processing cereal straws by steam explosion in a pilot plant to enhance digestibility in ruminants

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Abstract

Wheat, barley and oat straws were treated by steam explosion (SE) and then washed with 50 g/l NaOH solution. The SE treatment was optimized at batch scale on the basis of carbohydrate recovery. Stocks of fodder (300 kg) were produced at 198 °C for 2.5 min by a continuous reactor and used for *in vivo* digestibility tests carried out on sheep. The flow-sheet and the mass balances were obtained for the entire process. For the three straws, the water consumption has been 7.3 kg/kg of straw. To delignify and improve the digestibility of the straws, 20 g of NaOH/kg straw was used. The yield of fodder, lignin and hemicellulose is dependant on the nature of the starting straw. Delignified fodder (insoluble fraction) can be produced with a yield of 0.64, 0.59, 0.55, respectively, from wheat, barley and oat straw. SE improved the digestibility of the straw by 25%; alkaline washing further increased it by 9%. Balanced rations containing, on a DM basis, 1/4 of treated straw, had digestibility coefficients similar to those of commercial rations based on alfalfa.
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Keywords: Straw; Steam explosion; Digestibility; Fodder

1. Introduction

In the last few years, the interest in the production of safe cattle feed has increased dramatically, primarily due to public concern about the spread of BSE (bovine spongiform encephalopathy). As a result, safer processing technologies have attracted much attention. In this regard, several groups have shown that steam treatment and steam explosion (SE) of lignocellulosic biomass increases the digestibility of the cereal straws, both *in vitro* and *in vivo* (Sciaraffa and Marzetti, 1991; De Castro and Machado, 1990; De Castro et al., 1995; Liu et al., 1999; De Medeiros and Machado, 1993a,b).

Tested substrates have included wood, straws and stalks, demonstrating the flexibility of the SE process and the potential for conversion of agricultural and forestry residues into economically valuable commodities (Montane et al., 1998; Avellar and Glasser, 1998; Glasser and Wright, 1998; Heitz et al., 1991). Similarly, it was also shown that lime treatment increases the digestibility of straws, but high concentrations (100 g/kg straw) of $Ca(OH)_2$ or NaOH are required to achieve significant results (Gandi et al., 1997). A lot of patents have been issued on this subject. Straw is commonly utilized as fodder, but its nutritional value is low because of the low digestibility (0.35–0.55) and high lignin content. Nevertheless, straw is a very abundant and inexpensive agricultural by-product. The FAO reports an annual production of cereals in 2004 of 470 Mt in Europe and 389 Mt in the

Abbreviations: SE, steam explosion; DM, dry matter; BSE, bovine spongiform encephalopathy; HPIC, high performance ionic chromatography; FAO, food agriculture organization; PED, pulsed electrochemical detector; ASTM, american standard testing for materials; TAPPI, technical association of the pulp and paper industry; CPPA, canadian pulp and paper association; GLM, general linear model; ANOVA, analysis of variance.

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USA. It has estimated that, on average, from 1 t of primary crop 0.7 t of straw is obtained (De Castro et al., 1991). In Europe, 149 Mt wheat straw, 64 Mt barley straw and 12 Mt of oat straw are produced from the most common cereal crops.

Lignin cannot be metabolized by animals, but could be exploited if first extracted from the biomass; it can be burnt to provide energy to the process or used as sources of chemicals and bio-degradable composites (Pucciariello et al., 2004). This is an example of the "biorefinery" concept, in which all the biomass components are separated and subsequently used (Ibrahim and Glasser, 1999; Shimizu et al., 1994). To achieve this goal, biomass needs to be treated through processes such as SE. Basically, SE is a hydrothermal process of biomass treatment, involving the application of steam at high pressure, and which can be performed by batch or continuous reactor. The biomass travels through a reactor, where it is exposed to saturated steam (180–230 °C) for 1–10 min; during this time, hemicellulose is hydrolysed and solubilized. Pressure is then suddenly lowered to the atmospheric value. In doing so, the biomass undergoes an explosive decompression which induces disruption of the plant cells, and is pushed out through a blow valve and recovered in a blow tank. The relationships between steam pressure and residence time, and their effect on lignocellulosic biomass, have been shown by Overend and Chornet (1987). It was demonstrated that SE increases the availability of digestible matter by freeing it from lignin and silica and by increasing the hemicellulose solubility (Hart et al., 1981; Horton et al., 1991).

Since most of the experiments on SE for fodder production have been carried out on a small scale, the parameters necessary for an industrial scale-up are still lacking. The aim of this work has been to evaluate the combination of mild steam explosion and dilute alkaline washing to enhance the digestibility and the quality of straw as fodder. Preliminary tests were carried out in batch scale to determine the optimal range of SE treatment and the obtained data was used as rationale for the continuous plant experiment (Zimbardi et al., 1999). Trials were carried out at pilot scale in a continuous plant to obtain process useful data for industrial production, and to characterize the obtained products, also in the perspective of their use as animal feed. Economic evaluations on a SE pilot plant have indicate a treatment cost of 0.077 US$/kg straw (Avellar and Glasser, 1998), but the economics may be improved, if products such as lignin and hemicellulose could be sold as valuable co-products.

2. Experimental

2.1. Materials

In the experiments, common straw of oat (*Avena sativa*), barley (*Hordeum vulgare*) and durum wheat (*Triticum durum*) were used. The cereals were harvested in the Basilicata region (South Italy). The straw was delivered as 20 kg bales and stored in a sheltered area until use.

2.2. Steam explosion of straw by batch reactor

The batch reactor that was used is a STAKETECH apparatus. This apparatus basically consists of a 10 l pressure vessel, which is surrounded by a steam jacket to ensure a stable temperature and minimize the steam condensation. Straw was manually loaded into the reactor, followed by the closing of the pneumatic valve and injection of steam for the designated time. At the end of the treatment, a blow valve was opened, at which time the pressure dropped explosively. The product was then recovered in a connected 150 l expansion tank. The SE severity was quantified as a function of time and temperature, by the parameter Ro (Overend and Chornet, 1987):

$$\mathrm{Ro} = t \cdot \exp\left(\frac{T - 100}{14.75}\right),$$

where T is the temperature in °C and t the time in minutes.

Four severities were tested:

1. $\log \mathrm{Ro} = 3.0$ (200 °C; 1.2 min)
2. $\log \mathrm{Ro} = 3.4$ (200 °C; 3.4 min)
3. $\log \mathrm{Ro} = 3.8$ (210 °C; 4 min)
4. $\log \mathrm{Ro} = 4.2$ (220 °C; 5 min)

At each severity, the products of three runs were carefully mixed to obtain a single batch and dried at 60 °C before analysis.

2.3. Continuous production of fodder

Straws of wheat, barley and oat were treated by a continuous steam explosion and fractionation plant, with a treatment capacity of 150 kg/h (DM, dry matter).

The process consisted of the following steps (Fig. 1):

(a) The bales were opened by a straw-chopper and straw was conveyed on a weighing belt to monitor the feed flow into the digester. Water was added to humidify the biomass to 50% DM.
(b) Straw was introduced into the digester near the saturated steam inlet. For these experiments the residence times were set at 1.5 and 2.5 min, and the steam temperature at 195 and 198 °C. The resulting $\log \mathrm{Ro}$ was 3.0 and 3.3, respectively. These conditions were chosen on the basis of the results from SE batch experiments. After the explosion, the product was separated into solid and volatile streams in a blow bin. The solid stream was conveyed to the extraction section, and the volatile stream was condensed and discarded.
(c) Alkaline washing (extraction) was carried out in a 3 m^3 slurry tank extractor with a 5% NaOH solution at 80 °C. The solid to liquid ratio was 0.2. The slurry was poured onto a continuous, multistage counter-

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