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Particle size and hydration medium effects on hydration properties and sugar release of wheat straw fibers

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ABSTRACT

Wheat straw is gaining importance as a feedstock for the production of biofuels and high value-added bioproducts. Several pretreatments recover the fermentable fraction involving the use of water or aqueous solutions. Therefore, hydration properties of wheat straw fibers play an important role in improving pretreatment performance. In this study, the water retention capacity (WRC) and swelling of wheat straw fibers were studied using water, propylene glycol (PPG) and an effluent from a H_2-producing reactor as the hydration media with three particle sizes (3.35, 2.00 and 0.212 mm). The effects of swelling were analyzed by optical and confocal laser scanning microscopy (CLSM). The highest WRC was reached with the effluent medium (9.84 ± 0.87 g g^{-1} in 4 h), followed by PPG (8.52 ± 0.18 g g^{-1} in 1 h) and water (8.74 ± 0.76 g g^{-1} in 10 h). The effluent hydration treatment had a synergic effect between the enzymes present and the water. The particle size had a significant effect on the WRC ($P < 0.01$), the highest values were reached with 3.35 mm fibers. The CLSM images showed that finer fibers were subjected to a shaving effect due to the grinding affecting its capacity to absorb the hydration medium. The microscopic analysis showed the increase in the width of the epidermal cells after the hydration and a more undulating cell wall likely due to the hydration of the amorphous regions in the cellulose microfibrils. The sugar release was determined, achieving the highest glucose content with the effluent hydration treatment.

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1. Introduction

Wheat is an important cereal grain that is consumed worldwide. According to a recent report during the last year, its consumption was estimated as more than 855 Tg [1]. In Mexico, this grain has a high commercial and cultural value because it has been used in the food chain for a long period. According to the available information, the greatest wheat production in Mexico is located in the states of Sinaloa and Guanajuato, which represent 19% of the country's total production [2]. The primary byproduct obtained from this crop is wheat straw, which can reaches 1.5 times the weight of the initial harvested crop. In Mexico, a recurring agricultural practice is stubble burning, in which the crop remaining on land that has been harvested is burned with the following purposes: to reincorporate the fixed nutrients into the soil, to reduce costs for the following agricultural cycle, to reduce plague propagation and crop diseases. However, in Mexico and other countries, this practice is prohibited since it causes environmental pollution, soil erosion and soil degradation.

Dry wheat straw has 34–40% mass fraction of cellulose and 21–26% mass fraction of hemicellulose which contain sugars such as glucose, xylose, arabinose, galactose and mannose [3–6]. Due to its relatively high sugar content, wheat straw has been widely utilized as cattle feed [7], in composting [8], for manufacture of pulp [9] and in the production of foods such as edible mushrooms [10]. More recently, wheat straw has been utilized as feedstock for the production of second-generation biofuels (ethanol, hydrogen and methane) [4] and high value-added bioproducts.

Production of second-generation biofuels by direct fermentation of wheat straw is a difficult task because the complex lignin-cellulose matrix prevents the degradation by the microorganisms involved. Accordingly, a crucial step for the production of second-generation biofuels is the release of sugars from the matrix. To accomplish that task, the raw material is pretreated to cause the hydrolysis of hemicellulose and to enhance the cellulose accessibility; subsequently, a saccharification of the cellulose is accomplished. Finally, fermentation of the pentose (5C) and hexose (6C) sugars may be carried out, assuming that the microorganisms involved are capable of assimilating both types of sugars. The first step of the pretreatment includes milling and homogenizing the raw material. Then, physicochemical, chemical and biological pretreatments and/or their combinations can be applied. Physicochemical pretreatments include hydrotreatments, in which high pressure ($P > 5$ MPa) and high temperature ($T > 150$ °C) are applied either with liquid hot water or steam. Additionally, chemical pretreatments use aqueous solutions of NaOH (alkali pretreatments), concentrate/diluted H_2SO_4 (acid pretreatments) or ammonia (ammonia fiber explosion or AFEX). Furthermore, oxidizing agents such as hydrogen peroxide and ozone can be employed. Fungal species or their enzymes can be used as a form of biological pretreatment to break up the cellulose and/or lignin [11]. Notably, all pretreatments use a considerable amount of water during their processes. In spite of the pretreatments developed, there is scarce information on the physical properties of wheat straw, particularly its hydration properties.

Relevant hydration properties are the swelling and the water retention capacity. Swelling capacity is defined as the volume occupied by a sample placed in water after equilibrium is reached. Water retention capacity (WRC) is the quantity of water that remains bound to the hydrated fibers following the application of an external force such as compression, centrifugation or gravity [12]. Hydration properties of different cellulosic materials have been extensively studied for applications in paper and textile industries [13,14]. Some factors that strongly impact the hydration properties are pH, ionic forces, inclusion and type of salts, temperature, and fiber conformation, among others [14]. An efficient hydration increases the material volume enhancing its accessibility to the pre-treatment (chemical or enzymatic) and decreases its crystallinity by the reorganization of the structure in which the hydrogen bonds between cellulose and the matrix materials are weakened [13].

Hydration properties of native lignocellulosic materials used for biofuel production have been scarcely explored. A better knowledge of the WRC and swelling of the wheat straw can help to improve the performance of the pretreatments used for sugar recovery and to diminish production costs. The aim of this study was to evaluate the WRC of native wheat straw fibers with different particle sizes and hydration media. Optical and confocal laser scanning microscopy were used to analyze the swelling phenomenon in the leaf epidermises. The hydration media tested in this study were tap water, a nonionic surfactant and the effluent obtained from an anaerobic bioreactor producing H_2 from wheat straw. Additionally, the release of glucose and xylose was investigated during the hydration process.

2. Materials and methods

2.1. Sample preparation and hydration media

Furrow irrigated wheat (*Triticum aestivum* L.; cultivar. Urbina S2007) was grown in Pueblo Nuevo, Guanajuato, Mexico (field location: latitude 20° 31′ North, longitude 101° 22′ West and elevation 1700 m with Phaeozem colluvial sandy clay loam). The crop was planted in late May 2011 and the plants were harvested after 120 days. The winter wheat straw was harvested using conventional hay-harvesting equipment. The collected straw consisting of the uppermost portion of the straw: 1st and 2nd internodes, top and middle nodes and top and middle leaves according to the anatomy described previously [15]. The mass balance showed that the plant components consisted of 65.3% internodes, 10.3% nodes and 24.4% leaves on a dry basis [16]. The water mass fraction was 5 ± 0.4% measured according to ASABE Standard S358.2 for forages [17] by oven drying the samples at 103 ± 2 °C for 24 h in three replicates. The chopped wheat straw samples (50 cm) were ground using a mill with screen opening size of 8 mm in order to narrow the range of particle size and thus obtain homogeneous samples. The samples were stored indoors for four months in an opaque plastic container at the air-conditioned laboratory (28 °C and 55% RH). To separate the different particle sizes, 100 g of uncompressed ground wheat straw sample was passed through a set of Endecotts