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Research Paper

Rolling deformation characteristics of Chinese eaglewood leaf during drying and rehydration

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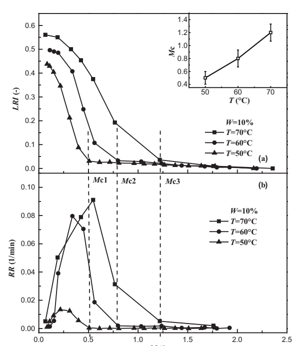
HIGHLIGHTS

- The leaf rolling shows the low and fast rolling stages, divided by critical moisture content M_c.
- M_c increases with increasing drying temperature.
- M_c is hardly influenced by ambient air humidity, leaf size, and forced initial *LRI*.
- The dried leaf cannot completely return to its initial state before drying by rehydration.
- Increasing rehydration temperature decreases difference between rolling and unrolling.

GRAPHICAL ABSTRACT

LRI (a) and *RR* (b) during the drying process under constant ambient air humidity (10%). The rolling process is divided into two periods: the slow rolling stage that lasts until the critical moisture content (M_c) is reached and the fast rolling stage. In the latter, *RR* initially increases and then decreases until *LRI* reaches a stable drying equilibrium *LRI* (LRI_e). When drying temperature is high, the values of M_c, *LRI* during the drying process, and LRI_e will also be high.



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ABSTRACT

This study involves the rolling and unrolling phenomena of Chinese eaglewood leaves during drying and rehydration processes. In the early period of drying, eaglewood leaf rolls slightly and has a low leaf rolling index (*LRI*), i.e., <0.05, with decreasing leaf moisture content. Once moisture content declines to a critical value (M_c), the drying process enters into a fast rolling stage until *LRI* eventually reaches a drying equilibrium (LRI_e). The leaf will then unroll upon rehydration; however, *LRI* cannot return to its initial value before drying and it will remain at a rehydrating equilibrium ($RLRI_e$). M_c increases with increasing drying temperature and is hardly influenced by ambient air humidity, leaf size, and forced initial *LRI*. LRI_e increases with increasing drying temperature, leaf size, forced *LRI*, and decreasing ambient air humidity. Meanwhile, $RLRI_e$ decreases as rehydration water temperature increases.

1. Introduction

Chinese eaglewood (Chen Xiang) [1,2], as one of the traditional Chinese medicines, exhibits a wide array of pharmacological properties, such as sedative [3], laxative [4], neuroprotective [5],

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anti-inflammatory [6], and anti-bacterial [7] activities. The harmful effects of nicotine to the human body can be reduced by adding a certain amount of dry eaglewood leaves to cigarettes [8]. During the manufacture of cut tobacco, eaglewood leaves undergo a series of steps, which include drying, rehydration, and shredding. The fresh leaves should be dried until the moisture content below 14% to ensure a long shelf-life during transportation. However, the dried leaves are fragile, which will hinder the shredding process. Furthermore, rolling phenomenon of eaglewood leaves occurs during drying, which would produce irregular shred, and affect the quality of cut tobacco. Therefore the rehydration is necessary, during which the leaves will recover flexible and unrolling.

Many experiments have been performed to study the volume shrinkage phenomenon during the drying process of food products, such as apples [9], potatoes [10], dehydrated fruits [11], Japanese eggplant [12], fig fruit [13], and 'Kent' mango slices [14]. The experiments of Khraisheh [10] under both microwave and air-drying conditions indicated that the shrinkage of potatoes exhibited a linear behavior in relation to different moisture content levels. Llave [12] observed an approximately equal reduction rate in moisture content losses and volume shrinkage. Senadeera [15] and Panyawong [16] proposed that moisture gradients within products could induce microstructural stresses, which would lead to product shrinkage and deformation. The rehydration of dried products could increase their moisture content. Medenim [17] compared the rehydration capacities of several kiwifruit samples that were dried using different methods. The experiments of Drouzas [18] indicated that rehydrating banana slices would lead to excellent quality as indicated in taste, aroma, smell, and rehydration tests.

To date, only few studies have been conducted on the rolling deformation of plant leaves during drying. The current research selects the leaf rolling process of Chinese eaglewood leaf as the research object and comprehensively examines the rolling and unrolling deformation characteristics of this leaf during drying and rehydration.

2. Experimental materials and methods

2.1. Experimental materials and device

All the eaglewood leaves used in the experiments were collected from Hainan, China (fresh, no moth-eaten parts, no damage). The shape of the leaves is nearly ellipse. One side is the sunken side of the bright green vein, whereas the other is the convex light green vein. We selected leaves with similar characteristics for the experiment (length of major axis: 150 ± 2 mm, length of minor axis: 50 ± 1 mm, area: 3000–4000 mm^2), with an initial moisture content of 69.53 ± 1.17%. The drying device used was the Constant Environment Testing Machine (CETM, KBF115, BINDER, Germany).

2.2. Definition of experimental parameters

The moisture content of the leaf samples was measured according to the national criterion GB/T 5009.3-2010 [14]. The moisture content of the drying base (M) and the dimensionless moisture ratio (MR) were adopted to describe the drying process of leaves. M_t and MR are respectively presented as Expressions (1) and (2):

$$M = (m_t - m)/m, \tag{1}$$

$$MR = M/M_0, \tag{2}$$

where m_t denotes leaf mass after t minutes of drying, m indicates leaf mass after complete drying, and M_0 represents the initial moisture content of the drying base of a leaf sample.

The rolling level of the leaf is quantitatively described using the leaf rolling index (LRI). Different methods have been used to estimate LRI in the literature [19]. We adopted Expression (3) in the current study. The rolling rate (RR), which is similar to the drying rate, is also defined as Expression (4) to depict rolling speed.

$$LRI = (s_t - s)/s_t, \tag{3}$$

$$RR = (LRI_{t+\Delta t} - LRI_t)/\Delta t, \tag{4}$$

where s_t is the initial leaf margin spatial area before drying; s is the area of leaf margin after t minutes of drying. Leaf is lain horizontally on measured platform. The measurement of leaf area size is taking photographs of leaves in various time, processing the images with Image-pro plus (as Fig. 1), and the actual area size can be obtained after proportion exchange. Δt is the time interval; LRI_t and $LRI_{t+\Delta t}$ are the $LRIs$ after t and $t + \Delta t$ minutes of drying, respectively; and s and s_t are measured according to the leaf edge, as shown in Fig. 1. The leaf was flat before drying, and the edge spatial area was similar to the actual area of the leaf. After drying, the edge spatial area decreased as the leaf rolled.

2.3. Experimental methods

2.3.1. Experimental drying methods

Leaves were placed in the CETM one at a time to perform the drying process. The leaves exhibited different drying processes and rolling characteristics when the temperature (T) and humidity (W) of the CETM were varied. The leaves were immediately taken out from the device after a given interval time for mass measuring and photographing.

In industrial drying processes, leaves are piled and pressed with each other. To clarify the effect of external pressure on leaf rolling, we restrained a leaf with a stiffness ribbon during drying; that is, the leaf had a forced initial LRI ($FLRI$).

The drying process was terminated when the moisture content of the leaf remained constant. The detailed experimental conditions are provided in Table 1. Each condition was tested thrice to ensure accuracy, and the average value was presented as follows.

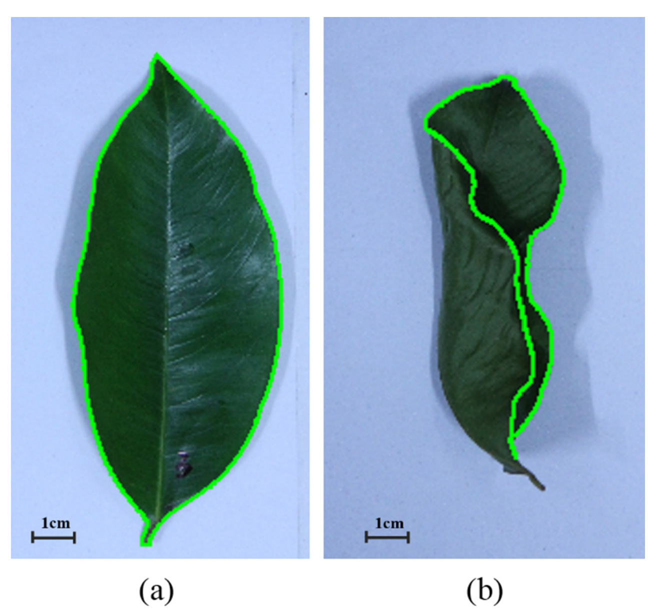

Fig. 1. Measurement of leaf size. Before drying (a) and after drying (b).