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Water transport in parchment and endosperm of coffee bean

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ABSTRACT

This paper aims at contributing to identify the eventual regions where fungus *Aspergillus ochraceus* could grow and produce ochratoxin A (OTA) during drying of coffee beans. Internal structure of coffee bean was analyzed by optical microscopy for endosperm and parchment. From the expression of the dissipation in the grain due to the water transport, we show that a relationship formally analogous to an equation of diffusion governs the water transport. Three structures with mass transfer resistance potential are studied: parchment, silver skin and endosperm. An experimental technique to study the water transfer into the parchment was proposed. In the endosperm, for moisture contents above 65%, a constant transport coefficient controls the drying kinetics of the whole bean. Below this moisture content, water transport coefficient (with and without silver skin) were significantly lesser than those for the whole bean. This is firstly due to the reduction of the pore space occupied by water and second to the increasing bonding energy between solid structure and water as moisture content decreases. The contribution of parchment to the protection of the endosperm is highlighted.

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1. Introduction

Coffee is the second most valuable legal commodity in the world (Pendergrast, 1999; Kouadio et al., 2007). According to FAO (2008), coffee is sold in 78 countries around the world and 20 to 25 million families depend on its trade. Coffee cherries are subjected to two different post-harvest treatments where the main objectives are to remove the various layers surrounding coffee beans and to dry them in order to prevent the growth of microorganisms (Paulino De Moraes and Luchese, 2003; Suárez-Quiroz et al., 2004). The most usual treatment is called "wet". In this method, coffee cherries are put in a tank filled with water in order to separate the defective beans and to remove the pulp and mucilage. Then, "washed" coffee beans are dried. An alternative is to use the "dry" method in which coffee cherries are directly dried to get grayish beans known as "coffee coke" or "natural coffee". After drying, the parchment and the other layers covering the beans are removed mechanically to get the "green" coffee.

Regardless the post-harvest method, drying can be carried out naturally (using sun) and/or artificially (using dryers). Drying has been identified as a step where fungal contamination can develop (Frank, 2000; Paulino de Moraes and Luchese, 2003; Taniwaki et al., 2003; Kouadio et al., 2007). Particularly, *Aspergillus ochraceus*, a common host fungus, produces a toxin (Ochratoxin A, OTA) which have teratogenic, immunotoxic and possibly neurotoxic and carcinogenic properties. Moreover, this toxin has a high thermal stability up to 250 °C (FAO, 2008). Considering the risk for human health, fungus development should be avoided to prevent OTA production. Among the factors that govern the fungal development, water activity (a_w) has been underlined to be the most important (Suárez-Quiroz et al., 2004; Kouadio et al., 2007). Actually, temperature influences the production rate while not being a limiting factor (Suárez-Quiroz et al., 2004). The optimal conditions for the growing of *A. ochraceus* are given by a water activity of 0.95 and a temperature of 35 °C while its development is inhibited with a water activity lower than 0.80 and a temperature less than 10 °C (Suárez-Quiroz et al., 2004). From this research, it results that 0.8 is a critical value for the prevention of OTA production. However, it represents an average value over the whole coffee bean that does not account for the water distribution resulting from moisture diffusion during the drying process. Moreover, *A. ochraceus* develops at the coffee bean surface while fungal spores penetrate about a few micrometers inside. Then, the development of *A. ochraceus* in coffee bean may be seen as a competition between its capacity of water supply and a decrease on the water

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Nomenclature

a	Thermodynamic activity
C	Volumetric concentration (kg m^{-3})
D	Dissipation (J m^{-3} s^{-1})
h	Parchment thickness (m)
k_c	Mass transfer coefficient (m s^{-1})
K_{eq}	Average water distribution constant between phases
$K(X)$	Water transport coefficient in a structure (kg s m^{-3})
l	Characteristic length for diffusion (m)
m	Mass (kg)
M	Molecular mass (kg kgmol^{-1})
N	Mass flux (kg m^{-2} s^{-1})
r	Mass transfer resistance (kg m^{-2} s^{-1})
R	Gas constant (8314.0) (J kgmol^{-1} K^{-1})
S	Entropy (J K^{-1})
t	time (s)
T	Temperature (K or °C)
U	Internal energy (J)
v	apparent velocity (m s^{-1})
V	Volume (m^3)
X	Moisture content (kg (kg dm)$^{-1}$)

Greek symbols

μ	Chemical potential (J kg^{-1})
ρ	Density (kg m^{-3})
Δ_w	Water transport coefficient (m^2 s^{-1})

Subscripts

0	At initial or in one side
1	At the other side
a	For air
av	Averaged
e	At equilibrium
en	In endosperm
pa	In parchment
s	For dry matter
w	For water
α	In a heterogeneous structure

activity in the internal parts of the grain consecutive to drying. When coffee bean has not been damaged (cracks, separation of the parchment) this competition takes place on the surface of the grain, and it is the combination between the water activity and the water transport properties in the parchment and the surface layer of the endosperm. As consequence, it seems essential to analyze precisely the water distribution rather than its average content (Frank, 2000).

During the drying process, water transport coefficient is one of the most important parameters because it governs water distribution in the grain (Geankoplis, 1998). Usually, water transport is evaluated from the fitting of an adequate Fick's law equation to experimental drying kinetic (Mulet, 1994; Maroulis et al., 1995; Wang and Brennan, 1995; Bialobrzewski and Markowski, 2004; Efremov and Kudra, 2004; Hernández-Díaz et al., 2008). Sfredo et al. (2005) and Correa et al. (2006) have determined the water transport coefficient in coffee cherries. Both rely on a Crank's solution of Fick's law valid for sphere (Crank, 1975) since it is a fair approximation of the coffee cherry geometry. The water diffusivity values measured obtained by Sfredo et al. (2005) lie in the range $[0.1 - 1 \times 10^{-10}]$ m^2 s^{-1} at 45 °C and $[0.3 - 3 \times 10^{-10}]$ m^2 s^{-1} at 60 °C, while those found by Correa are 2.91×10^{-10}; 3.57×10^{-10} and 4.96×10^{-10} m2 s^{-1} at 40, 50 and 60 °C respectively. To improve the geometrical description of coffee cherries, Hernández-Díaz et al. (2008) developed a Fick's law solution considering a non-conventional geometry: prolate spheroid geometry.

In many products with a complex micro-structure such as wood and pasta (Mrani and Bénet, 2005), Agar gel (Mrani et al., 1995) and latex (Auria et al., 1991), water transfer is controlled by physico-chemical and mechanical interactions occurring at the interfaces between phases: capillarity, osmotic effects, surface adsorption, liquid–gas phase change (Bénet et al., 2009), water transfer between cells and walls. Therefore, transfer coefficients represent a superposition of different phenomena and depend on moisture content. In particular water transfer coefficients cancel as the moisture content tends towards zero. In this case, the use of diffusion and of Crank's solutions to describe mass transfer may be questionable for media presenting a complex microstructure.

Finally, the objective of this study is to contribute, through microscopic analysis and local mass transfer measurements, the potential regions where fungus could develop and produce OTA during drying processes. Therefore, this paper deals with the four following aspects: (1) Analysis by a thermodynamic approach of the law for water transport in a complex media (2) Microscopic observation of coffee bean in order to identify the different structures of coffee beans and their heterogeneity; (3) Characterization of the relationship between water activity and moisture content and (4) Study of the dependence of transport properties on moisture content.

These physical characteristics will be useful to improve the numerical modeling of the drying process. By simulating various drying scenarios, it should lead to propose different strategies to avoid the development of fungus.

2. Thermodynamic approach to water transport in complex media

Complex media such as food, gel and biological tissues are characterized as having several structures (α at Eq. (1)) which can be solid, liquid or gas phases, superficial layers, film layers, membranes, cells, and cell walls. In such complex media the use *a priori* of a law similar to Fick's law seems not appropriate. However many experimental results of media as complex as coffee endosperm (wood, gels, food) seem to show that this law is sufficient to describe water transfer at the macroscopic level as it will be demonstrated in the following discussion.

The thermodynamic state of water in a structure α is characterized by the mass chemical potential, given by (Callen, 1985):

$$\mu_{w\alpha} = \left(\frac{\partial U_\alpha}{\partial m_{w\alpha}}\right)_{S_\alpha, V_\alpha, m_{\alpha j} j \neq w} \tag{1}$$

where $\mu_{w\alpha}$ is the water chemical potential at structure α and is defined as the partial derivative of the internal energy contained in a Representative Elementary Volume (REV), with respect to water mass, taking entropy, volume of α in the REV and the mass of the other constituents as constants. The chemical potential characterizes the action of the other media constituents upon the water from the structure α, regardless of the form of the water: liquid, gas, adsorbed by the liquid phases, in films or in superficial layers.

Water transport phenomena in the structure obey the second principle of thermodynamics. Assuming uniform and constant temperature, in the absence of chemical reactions and neglecting the effect of gravity, the dissipation in structure α due to water

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