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Analysis of the Heat and Mass Transfer during Convective Drying of a Deformable Porous Medium Composed by Gel-Coated Seeds

Manoel Marcelo do Prado, Douglas Santos Andrade, Dermeval José Mazzini Sartori

***Abstract*—The simultaneous heat and mass transfer between hot air and seeds having an agar gel-based coating was studied during packed bed drying. To describe the process, a two-phase model was employed, in which the effects of bed shrinkage and non-constant physical properties were considered. The model took into account bed contraction by employing moving coordinates. Equations relating shrinkage and structural parameters of the packed bed with moisture content, required in the drying model, were developed from experimental results in thick-layer bed drying. The model verification was based on a comparison between experimental and predicted data on bed-averaged moisture content and temperature along the bed. From the experimental-theoretical analysis, the importance of shrinkage for a more accurate interpretation of heat and mass transfer phenomena in the drying of porous media composed of gel-coated seeds is corroborated.**

***Index Terms*— transport phenomena, shrinkage, drying, coating, gel-seed system.**

I. INTRODUCTION

Research has been devoted to obtain information about polymer range that would make coating technology most effective to aggregate quality and protection to seeds and grains [1] [2]. There is also an increasing interest in agricultural sector on searching for coating systems based on aqueous suspensions containing gelling binders. Encapsulation into agar gel appears as a rather promising method. Prado *et al.* [3] have shown the potential of agar-based coatings for retaining micronutrients in fortified millet as well as for a better crop establishment. Agar coating does not only overcome the problems of barrier to oxygen diffusion during storage, presented by others coating materials, but also its water holding capacity enhances water uptake under germinating conditions, thus improving the crop establishment.

Its gel-forming behavior, by thermal mechanism, which imparts chemical stability to coatings, has motivated investigations on the use of agar as coating system for seeds.

Drying is an essential operation in seed coating, since it ensures moisture removal from the coating, promoting the gel adherence to the seed surface and preventing deterioration due to molds infestation. Although works on drying of seeds [4]–[6] and gels [7]-[9] separately, have been extensively reported in the literature, not much knowledge is available on the drying behavior of the seed-gel system.

Because of the highly deformable polymeric structure of gels, gel-coated seeds tend to be susceptible to shrinkage and to changes in physical properties during drying what alter fluid-particle interaction. Thus, beds composed by these particles offer important challenges for the analysis of simultaneous heat and mass transfer during drying.

Developing a basic understanding on the drying of gel coated seeds is not only a challenge, but also an opportunity and a need. It is necessary to characterize physical changes in the seed-gel system as well as to adequate models of fixed bed dryers [10], [11] to simulate heat and mass transfer in a deformable porous media, so that the particle-fluid interaction can be understood and the drying optimized.

Based on this context and in order to contribute for the integration of researches that deal with the drying of seeds and gels, the objective of this work was to analyze the drying of millet seeds coated with agar gel. The physical-mathematical modeling of simultaneous heat and mass transfer was based on mass and energy balances in fluid (air) and solid (seed-gel system) phases, taking into account the shrinkage phenomenon of the material.

II. MATHEMATICAL MODELING

The physical problem under consideration is illustrated in Fig. 1, in which a packed bed of gel-coated seeds is percolated by a drying fluid flowing upward. The detail of a volume element extracted from the packed bed shows that part of this element is composed of solid particulate material, whereas the remaining void space is occupied by the fluid phase. Interactions between the solid and fluid phases by heat and mass transfer occur simultaneously during drying.

For a complete description of the process, the proposed two-phase model took into account the effects of bed shrinkage and moisture content on the physical properties. Other assumptions adopted included: the airflow is one-dimensional with uniform distributions of velocity, humidity and temperature in the cross section of the bed; heat losses through dryer walls are negligible; the fluid-solid heat transfer in the packed bed is predominantly convective; and heat and mass transport is one-dimensional.

Manoel Marcelo do Prado, Department of Chemical Engineering, Federal University of Sergipe, São Cristóvão, Brazil, +5579991245758.
Douglas Santos Andrade, Department of Chemical Engineering, Federal University of Sergipe, São Cristóvão, Brazil, +5579991280570.
Dermeval José Mazzini Sartori, Department of Chemical Engineering, Federal University of São Carlos, São Carlos, Brazil, +5519999163001

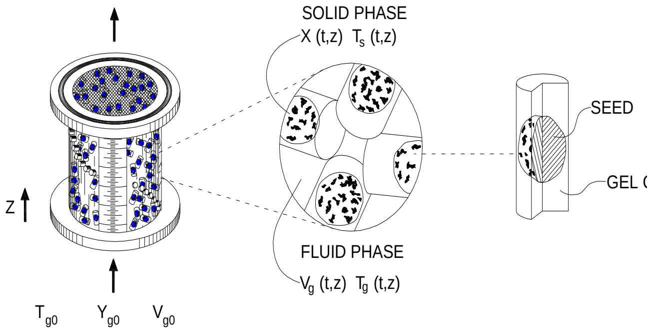

Fig. 1: Details of the control volume of porous medium and coated particle.

The resulting system of coupled differential equations describing the mass and energy conservation balances for the solid phase and the fluid phase are summarized in the Table 1

To incorporate the movement of bed contraction, the model equations were written in Lagrangian formulation. The dimensionless moving coordinate system, ξ, is related to the spatial coordinate by the following equation [12]:

$$dz = \frac{\rho_{b_0}}{\rho_b}\, d\xi = \frac{V_b}{V_{b0}}\, d\xi = S_b\, d\xi \tag{1}$$

The numerical solution of the model equations provides predictions of the following four drying state variables: solid moisture (X), solid temperature (T_s), fluid temperature (T_g) and air humidity (Y_g) as functions of time (t) and bed height (z). The equations were solved numerically using the finite-difference method. From the discretization of spatial differential terms, the initial set of partial differential equations was transformed into a set of ordinary differential equations. The resulting vector of 4 (N+1) temporal derivatives was solved using the DASSL package [13], which is based on the integration method of backwards differential formulation.

The solution of the mathematical model requires knowledge of the thermodynamic equilibrium and interphase transport parameters, which were obtained from specific studies [14]. The development of the equations for predicting the shrinkage parameter (S_b) and structural properties of the packed bed as a function of moisture content, required in the approach employed, was based on experimental results of the present work.

III. EXPERIMENTAL STUDY

In this study, two groups of deep-bed drying experiments were carried out. The objective of the first group was to determine the physical characteristics of porous media composed of coated seeds during drying and to develop equations relating shrinkage and properties of the packed bed with moisture content in order to incorporate them into the mathematical model. The objective of the second group was to evaluate the numerical solution of the two-phase model by comparison with experimental measurements of solid moisture content and temperature.

A. Materials

Millet seeds (*Pennisetum glaucum* L.), were used as core particles in the coating studies owing to its enormous value as food or agricultural commodity. Additional reason for choosing millet is the fact that it is less sensitive to heat, thus warm aqueous emulsions of agar in combination with others coating materials can be used without affecting the product quality.

The used materials for forming coating matrices included agar agar (Acumedia Manufactures, Maryland, USA) as gelling agent, sorbitol (Merck) as plasticizing agent, starch powder (Vetec Química Fina Ltda) as binder. Filler agents of the coating, as cellulose, talc and titanium dioxid, were generously provided by Minérios Ouro Branco Ltda, São Paulo, Brazil.

Table 1: Model equations

Mass balance in the solid:

$$\frac{\partial X}{\partial t} = f \tag{2}$$

Mass balance in the fluid:

$$\rho_g\left(\frac{v_g}{S_b}\cdot\frac{\partial Y_g}{\partial \xi} + \varepsilon\,\frac{\partial Y_g}{\partial t}\right) = -\rho_b\cdot\frac{\partial X}{\partial t} \tag{3}$$

Energy balance in the solid:

$$\rho_b\cdot\left(Cp_S + X\cdot Cp_w\right)\frac{\partial T_S}{\partial t} = ha_v\left(T_g - T_S\right) + \rho_b\cdot\left[L_p + \left(Cp_v - Cp_w\right)\cdot T_s\right]\cdot\frac{\partial X}{\partial t} \tag{4}$$

Energy balance in the fluid:

$$\frac{v_g\cdot\rho_g}{S_b}\cdot\left(Cp_g + Y_g Cp_v\right)\frac{\partial T_g}{\partial \xi} + \rho_g\cdot\varepsilon\cdot\left(Cp_g + Y_g Cp_v\right)\frac{\partial T_g}{\partial t} = \left[ha_v - \rho_b\cdot Cp_v\cdot\frac{\partial X}{\partial t}\right]\cdot\left(T_s - T_g\right) \tag{5}$$

Initial and boundary conditions:

$$\text{t = 0 and }\ z = 0\begin{cases} X = X_0; T_s = T_{s0} \\ Y_g = Y_{g0;} T_g = T_{g0}\end{cases} \text{ for t=0 and }\ z \neq 0\begin{cases} X = X_0; T_s = T_{s0} \\ Y_g = Y_{sat}\left(T_{s0}\right); T_g = T_{s0}\end{cases} \tag{6}$$

$$\text{z = 0 }\ \forall\ \text{ t,}\quad Y_g = Y_{g0}\ \text{ and }\ T_g = T_{g0} \tag{7}$$

B. Coating methodology

Prior to coating, the seeds acquired with moisture of around 12% (dry basis) needed to be cleaned by removing foreign matter and homogenized in a Jhones type quarterer.

The coating mixture was prepared in accordance with the Committee on Food Chemicals Codex [15]. It had the following formulation: 1.5 % agar, 0.5% sorbitol, 1.5 % starch, 3% de cellulose, 1% talco, 0.5% titanium dioxid and 92% water. According to Prado et al. [3], this formulation has a suitable concentration of plasticizing for obtaining a coating matrix sufficiently elastic. On the other hand, the addition of fillers such as starch, titanium dioxid and talc, reduces the shrinkage, contributing to preserve the cylindrical geometry of the particles. The inclusion of cellulose, as structural agent, prevents the rupture of the artificial coating.

Application of the polymeric mixtures in moulds containing the seeds was the adopted technique for entrapping the millet seeds within gel matrices [3]. The beaker containing the gel was immersed in a thermal bath at 50°C to maintain the material in gum phase. Gel transport was carried out using a peristaltic pump. In order to avoid gelation during transport, a heat exchange was also installed. After poured into the moulds the coating mixtures were allowed to gel at room temperature for 2 h to enable high gel strength prior to removing gel-seed system from the moulds. This resulted in the formation of encapsulated seeds, cylindrical in shape 2.6 mm x 5.0 mm (height x diameter).

C. Drying of the seed-gel system

A typical fixed-bed dryer [16] was used to conduct the experiments at inlet air temperatures (T_{g0}) ranging from 30 to 50°C and air velocities (v_g) from 0.5 to 1.5 m/s, defined by a 2^3 factorial design. These operational conditions satisfy the quality standard for seeds as well as the validity range of the equations used in the model.

The shrinkage of the packed bed during drying was determined from measurement of its height at three angular positions. From the weighing and vertical displacement of the packed porous bed with time, the parameter of shrinkage (S_b) was obtained as a function of bed-averaged moisture content. The mass of the packed porous bed was measured using a balance with a 0.001 g accuracy and its dry mass was determined at the end of each experiment by the oven method at (105 $\pm$ 3)°C for 24 hours. From packed bed volume and mass measurements the bulk density was also determined, while seed density was determined from the relationship between the weight and particle volume, which was calculated from the dimensions measured by image analysis. Bed porosity was then calculated from the ratios of the aforementioned densities.

Unprotected thermocouples were inserted along the packed bed to determine the solid temperature distribution and its dynamic behavior during drying. A helical arrangement of the temperature sensors attempted to minimize their interference with the airflow inside the porous bed.

The overall error in temperature measurements was 0.25°C. For airflow, air humidity and solid moisture measurements, the estimated uncertainties were 4%, 4% and 1%, respectively.

IV. RESULTS AND DISCUSSION

The assumptions used in the model formulation were that the shrinkage and changes in physical properties of the packed bed were not negligible. The validity of these assumptions can be proved by the results shown in Fig. 2-4, which illustrate significant variation in bed depth, bulk density and porosity with moisture content. The deviation within the experimental data obtained under different drying conditions was smaller than the measurement uncertainties. This assures that in the experimental range studied the structural properties can be correlated with only the average moisture content.

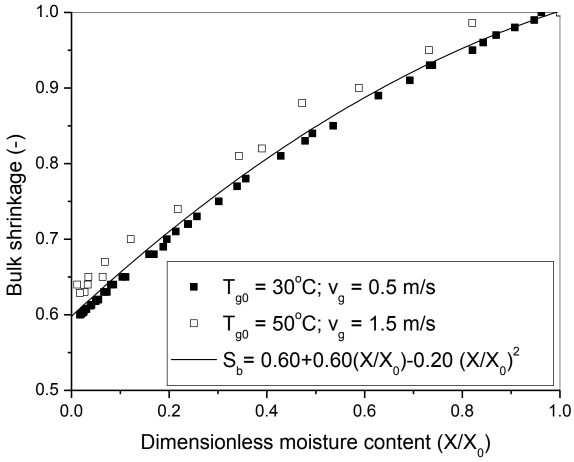

Fig. 2: Bulk shrinkage ratio (S_b) as function of dimensionless bed-averaged moisture content.

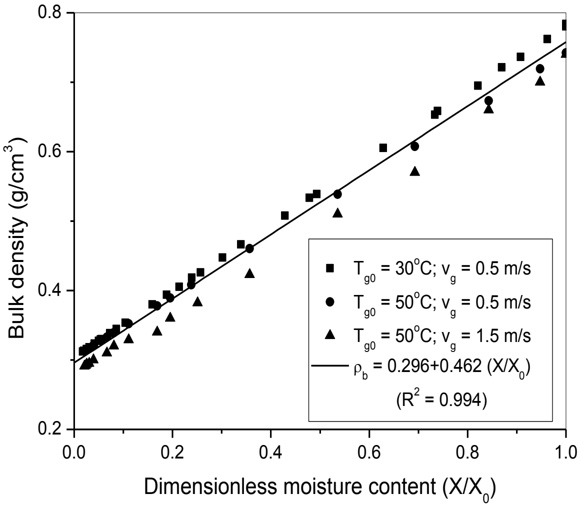

Fig. 3: Bulk density as a function of dimensionless bed-averaged moisture content.

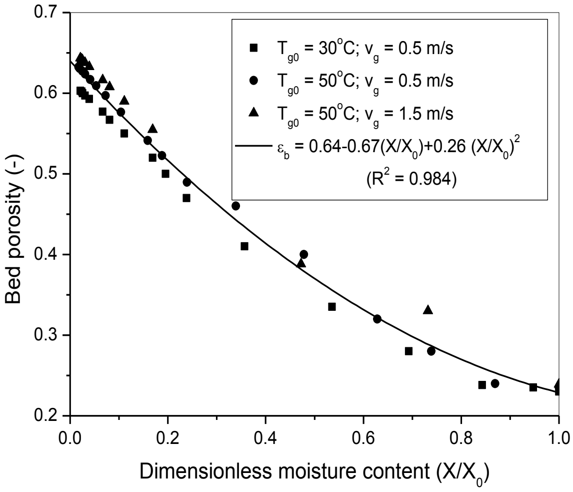

Fig. 4: Bed porosity as a function of dimensionless moisture content.

The relationship between the V_b/V_{b0} ratio and the bed-averaged dimensionless moisture content (X/X_0), was represented by a second-order polynomial (R^2=0.989), expressed as:

$$S_b = \frac{V_b}{V_{b0}} = 0.598 + 0.601\left(\frac{X}{X_0}\right) - 0.196\left(\frac{X}{X_0}\right)^2 \qquad (8)$$

The density of the packed beds (ρ_b), Fig. 3, was found to vary from 784 to 300 kg/m^3, as drying proceeded. The decrease in bulk density evidences that the bed volume contraction is lower than the amount of water evaporated. Thus, voids formerly filled with water are formed within the packed bed, resulting in a significant increase in porosity (ε_b) during deep bed drying, as shown in Figure 4.

The porosity varied between 0.23 for wet porous beds and 0.64 for dried porous beds. The variation of about 177% in porosity was similar to that found in beds composed by mucilaginous seeds, 150% [16]. However, concerning to fixed bed, the final value of porosity appears to be too high.

The volume contraction of porous media composed of gel-coated seeds was then related with the shrinkage of the individual particles. The magnitude of volumetric shrinkage of the packed beds, of about 38%, was not directly proportional to that of individual particles, nearly 73%. This may be due to the rearrangement of particles within the bed, defining a void space between the particles and, consequently, a packing conformation which offers resistance to bed shrinkage. As bed and particle shrinkage behaviors are not equivalent, the space taken by the evaporated water is air-filled.

Other explanation may be the particle agglomeration which occurs due to stickiness of the gel coating. As the amount of aggregates increases, voids are formed between the clusters, contributing for simultaneous air incorporation and thus explaining the low volume contraction as well the high bed porosity at the end of process.

The percentage of particles aggregates after drying was 74 ± 5% (at weight). The agglomerates were composed by multiple and binary groups of particles. Its formation may be the cause of channeling during deep bed drying. However, it should be pointed out that millet seeds coated with a formulation based on agar and fillers constituted a porous media which underwent a minimal disruption during drying in comparison with the beds composed by seeds coated only with agar [14], whose high voids volume did not allow analysis of the process from models based on continuum mechanics. An important advance was, therefore, obtained.

The equations developed to characterize the effects of moisture content on the shrinkage and structural parameters were then implemented in mathematical modeling so as to obtain more realistic results on heat and mass transfer characteristics in the packed bed drying of gel-coated seeds.

Fig. 5 shows typical experimental and simulated results of bed-averaged moisture content as a function of time at different temperatures, air velocities and bed thicknesses.

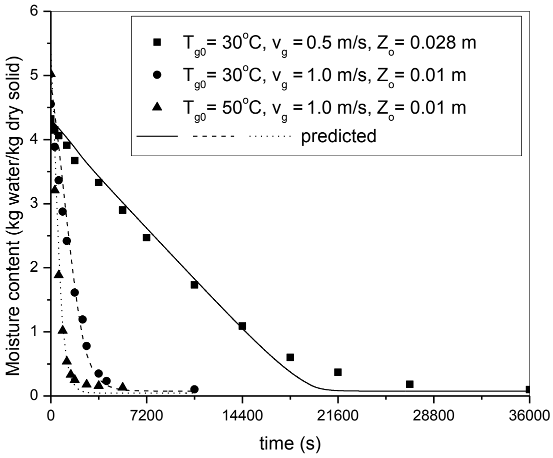

Fig. 5: Predicted and experimental results of bed-averaged moisture content as a function of time.

Agglomeration may explain the disagreement between the values predicted by the model and the experimental data at the final stage of drying. As the aggregates are formed, the area of mass transfer is reduced, thus resulting in a lower efficiency of the drying process. The limitation of macroscopic models based on the continuum mechanics, as the two-phase model, is in the fact that specific phenomena which occur at microscopic scale are not captured at macroscopic scale.

The use of non-invasive techniques for measuring local moisture content during drying could contribute to determine the relationship between the agglomeration of particles and the drying rate along the bed layers. Comparing predicted and experimental values of bed-averaged moisture content at a lower bed thickness, it can be verified a better description of the process. This is probably due to the fact that a reduction in bed thickness, which results at a higher drying rate, minimizes the formation of particles agglomerates and, consequently, its effects on the drying behaviour of the packed bed.

Fig. 6 presents predicted and experimental data of solid temperature as function of drying time at bed depth of 0.03 m. It can be seen that the deep bed drying of seeds with gel coating occurs with respect to heat transfer by three successive phenomena. Initially, it can be noted a rapid decrease of temperature caused by the contact of the hot air with the wet solid, which had an initial temperature higher than the wet bulb temperature. In the second stage, the surface temperature of seeds remains constant and equal to the wet bulb temperature, which characterizes the constant-rate period, in which migration of internal moisture compensates the evaporation rate from the particle surface, maintaining it saturated with a moisture film. As a consequence, all energy is used as latent heat to vaporize the surface moisture and drying occurs under a constant saturation temperature, as evidenced by the temperature plateaus in Fig. 6. In this period, vapor flux in the boundary layer controls the drying process. In the following period, the drying front moves along the bed, so that the temperature at each bed height presents a similar tendency of increase from saturation temperature until an asymptotic temperature below the air temperature at the inlet of the dryer.

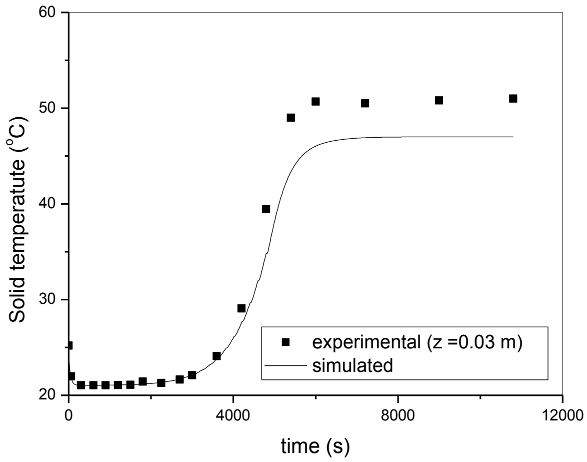

Fig. 6: Dynamic evolution of experimental and simulated solid temperature at a bed height of 0.03 m, for T_{g0} = 50°C and v_g = 0.5 m/s.

The model was capable of predicting the initial phenomena incurred. However, in the decreasing drying rate period, the increase of temperature described by the model did not agree with that experimentally observed, tending to an asymptotic temperature lower than the measured one. The empirical equation used to predict the convective heat transfer coefficient may be affecting the model predictions.

Thus, studies on parametric sensitivity could contribute to selection of an empirical equation adequate for a better reproduction of experimental data. However, considering the uncertainties in experimental measurements as well as the problem of parameter estimation and the fact of model do not predict the formation of particles aggregates, the two-phase model can be considered suitable to describe the drying of millet seeds coated with agar-based polymeric matrix.

Fig. 7 shows how well defined moisture content gradients were developed throughout the packed beds of coated particles. It can also be noted from the simulated profiles the reduction which occurs in the bed depth during moisture removal, indicating that the model was able to reproduce the bed shrinkage.

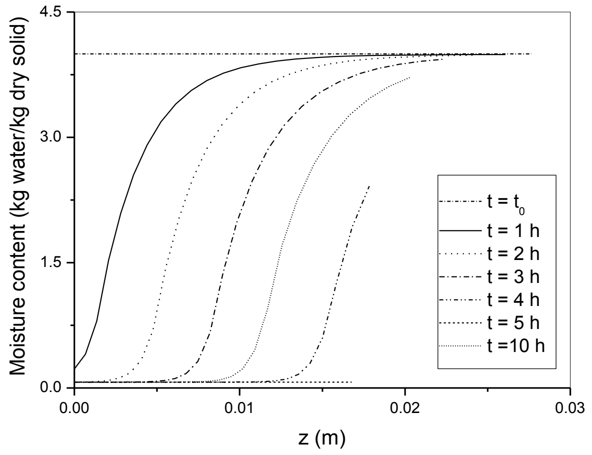

Fig. 7: Simulated moisture content profiles throughout the packed bed during drying at T_{g0}=50°C and v_g = 0.5 m/s.

Uniform distribution of moisture inside the bed is obtained at approximately 10 hours. It should be pointed out that layers below 0.01 m attain the equilibrium moisture content at the half of time. This evidences one of the limitations of the packed bed drying. In order for the upper layers of the bed to reach the desired moisture content, the bottom layers may be overheated leading to losses in product quality.

V. CONCLUSION

The deep bed drying of millet seeds coated with agar gel-based matrix was characterized as a complex process involving many interdependent phenomena, such as heat and mass transfer in a deformable porous media, and agglomeration or surface phenomenon inside the particles bed, whose properties change during the process.

It is concluded from the experimental-theoretical study that, for packed bed drying of gel-coated particles, shrinkage and changes in structural properties can not be ignored from the viewpoint of the process dynamics. Bed contraction and variable properties such as bulk density and porosity must be implemented in modeling in order to obtain more realistic results.

VI. ACKNOWLEDGMENTS

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First Author Graduated in Chemical Engineering at the Federal Rural University of Rio de Janeiro (1997). The doctoral degree in Chemical Engineering was obtained at the Federal University of São Carlos (2004). Currently, an Adjunct Professor III at the Department of Chemical Engineering, Federal University of Sergipe. The main studied areas are separation and mixture operations, acting on the following topics: fluid dynamics, heat and mass transfer in fixed, fluidized and spouted beds dryers, drying of seeds and biomass, and seed coating.

Second Author Graduated in Chemical Engineering at the Federal University of Sergipe (2015). Currently, develops the master's course in Chemical Engineering also at the Federal University of Sergipe, studying the drying and roasting of cocoa beanss. The main research topics are energy and quality aspects in the processing of cocoa beans.

Third Author Graduated in Physics at the São Paulo State University Júlio de Mesquita Filho (1976). The doctoral degree in Chemical Engineering was obtained at the Federal University of Rio de Janeiro (1986). Currently, an Associate Professor IV at the Department of Chemical Engineering, Federal University of São Carlos. The main studied areas are separation and mixture operations, acting on the transport phenomena in particulate systems, drying in fixed and moving beds, and seed coating.