INTRODUCTION

Fruit cultivation is one of the most diversified and important agroindustrial activities in Brazil. Due to the country’s size (nearly half of South America) and different types of climate, a wide variety of fruits, ranging from tropical fruits to those considered cold climate fruits, such as apples, pears and peaches, are produced. Out of the total annual production, it is estimated that 14% (about 5 million tons) constitutes little-exploited tropical fruits, such as umbu (Spondias tuberosa), hog plum (Spondia lutea), red mombin (Spondia purpurea), hog plum mango (Spondias dulcis), sour sop (Annona muricata), sapodilla (Manilkara achatias), and mangaba (Hancornia speciosa), among others. Tropical fruits are tasty and aromatic and, in addition to being hydrating, provide energy and are rich in vitamins and mineral salts, mainly calcium, iron, and phosphorous. Despite a significant consumption of fruit in Brazil, both in their natural form and as juices (the best form to maximize their nutrients) or prepared as sweets, jams, compotes, ice creams, etc., and the surge in agribusiness and exports, there is still a high level of fruit wastage, mainly in cyclically produced seasonal fruits.

On the other hand, dry fruit consumption has increased significantly in recent years, mainly in health foods, such as granola, enriched cereals, and whole wheat breads. However, most drying techniques used require long exposure to heat, with losses in heat-sensitive nutrients and irreversible changes in physical and chemical characteristics. As a consequence, the rehydration process does not regenerate the natural characteristics of dried fruits.\[1,2\]

Aiming at increasing the useful life of fruit without altering its nutritive and sensory characteristics, new technologies for fruit processing have been developed and introduced in the agribusiness sector. With these technologies, wastage can be minimized and fruit consumption can be increased during the out-of-season period and fruits exploited as raw material in the manufacture of industrialized products, such as sweets, ice creams, baby foods, etc.

Some fruits cultivated mainly in the northeast of Brazil, such as hog plum, umbu, red mombin, and Surinam cherry (Eugenia uniflora), among others, are very acidic and juicy with a low pulp/pit ratio, which renders them unsuitable for dry fruit production. These fruits, whose consumption is mainly in the form of juice and ice cream, are depulped and commercialized frozen, requiring large storage and transportation space. Conservation by freezing results in high energy costs and adds no value to the product.

The development of fruit powder through post-harvest processing ensures a product with low water content, greater stability, and prolonged storage under ambient conditions. Among the techniques used in fruit powder production are lyophilization, encapsulation of juices by co-crystallization with sucrose, and spray drying as well as fluidized bed and spouted bed (SB) drying with inert particles.

Lyophilization is complicated and costly. Though already studied as an alternative for obtaining dried fruit,\[3,4\] this technique is more commonly used in the

Results of drying of tropical fruit pulps in spouted beds (SBs) are presented, focusing on the effects of fruit pulp composition on the SB fluid dynamics and process performance and the development of new products formulated from mixtures of pulps with varied composition. It was verified that high starch and lipid contents favored stable fluid dynamics and high powder production efficiency, while high reducing sugar concentrations resulted in bad dynamic regime and very low powder production. Powder production efficiency was statistically correlated with the pulp composition. Also, drying of mixtures of fruit pulps with addition of starch and lipids was investigated. Results of fluid dynamics, drying performance, and sensory tests of yogurts enriched with the powders revealed promising potential of the SB for obtaining high-quality fruit powders.

**Keywords** Drying of fruit mixtures; Drying performance; Spouted bed drying of pastes; Spouted bed with inert particles

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drying of heat-sensitive products of high commercial value, such as medicines, dry extracts, etc.

Spray drying is considered a viable alternative in fruit powder production. It is known to produce large amounts of solids, and the nutritional characteristics of the product are maintained owing to the short contact time of the raw material with the heating gases inside the dryer. However, as in co-crystallization,[5] additives and/or adjuvant are added to the fruit juice formulation as emulsifiers, thickeners, and wall materials. Generally, wall material is used in the formulation to retain volatile ingredients by micro-encapsulation and also to avoid degradation of the vitamins and browning. Despite the importance of adjuvant in the above-mentioned processes, their presence causes changes in the characteristic fruit flavor, significantly modifying the original fruit composition.

Fruit powder production with the minimum addition of adjuvant, using simpler low-cost drying techniques, has been the subject of study in Brazil and in other countries.[6–9] Drying of tropical fruit pulps in SBs with inert particles has been extensively studied in Brazil on account of the excellent quality of the powdered products obtained, simplicity and ease of operation of the equipment as well as low building, set-up, and maintenance costs.[9–12] Also, advances in the SB technology to dry pastes and suspensions with inert particles as well as new equipment design have been recently published showing importance and advantages of the technique.[13–18]

In this work, a summary of results of SB drying of tropical fruit pulps is presented, with emphasis on three aspects: (i) the effects of fruit pulp composition on SB fluid dynamic behavior and process performance; (ii) optimization of powder production as a function of composition of the processed pulp; (iii) development of new products formulated from mixtures of fruit pulps with adjusted composition.

**EFFECTS OF PULP COMPOSITION ON SPOUTED BED DRYING OPERATION**

The conventional SB paste dryer, shown in Figure 1, has a drying chamber consisting of a cylindrical column with a conical base. A gas, usually air, is injected into the column at the inlet orifice. When gas velocities over the minimum spout velocity are used, the inert particles start a cyclic movement, ascending in the central region and falling along the annulus of the bed. Particles in the spout move in an upward direction, and after reaching the top of the bed in decelerated motion, form a fountain just above the annulus. The particle path in the annulus is directed towards the base, returning to the central channel or spout. This cyclic movement of particles creates three distinct regions: the spout – a dilute phase with high porosity; the annulus – a low porosity moving bed; and the fountain – a region above the bed where particles change the direction of their vertical motion from upwards to downwards. This gas-particle contact configuration induces high rates of heat and mass transfer between gas and particles, allowing efficient drying of pastes and suspensions.[19]

The suspension feed is sprayed, dropped, or injected into the bed of inert particles, usually at the top or bottom of the column. Feeding can be continuous, batch-wise, or intermittent. The liquid spreads over the surface of the particles and, after drying, forms a thin film covering them. The inter-particle attrition and slippage cause the breakage of the film, resulting in a fine powder that is entrained by air and collected in the cyclone.

The effects of the paste-like material feeding on SB fluid dynamic parameters and drying performance have been studied since the 1980s.[6,20–29]

Traditional work on this subject[20] verified that, upon adding water and glycerol to the bed of inert particles, there was a reduction of about 10% in the minimum spouting flow rate, \(Q_{ms}\), which was attributed to the decrease in the number of particles entering the spout region in beds of wet particles. Other work[6] analyzed the influence of umbu pulp feeding on \(Q_{ms}\), maximum and stable spouting pressure drop, \(\Delta P_{max}\) and \(\Delta P_{ssp}\). The findings showed that an increase in the mass of umbu pulp fed resulted in a significant increase in \(\Delta P_{max}\), no significant variation in \(\Delta P_{ssp}\), and a significant decrease in \(Q_{ms}\). However, other authors[25] observed an increase in \(Q_{ms}\) when pure water or an aqueous alumina suspension was added to a bed of inert particles. This effect was more pronounced for the alumina suspension. By analyzing the fluid dynamic behavior of an SB with the addition of acerola pulp, similar tendencies were reported.[20,26]
The complex fluid dynamic behavior of the SB with paste-like materials, which seemed to result in discrepant observations by different authors, is a function of paste feeding mode (continuous or intermittent), its physico-chemical properties, bed geometry, and paste-inert wettability characteristics.

A critical analysis made in\textsuperscript{[28]} led to the following conclusions: (i) a critical feed flow rate exists, above which the inter-particle cohesion forces caused by the formation of liquid bridges are significant; (ii) the cohesion forces depend on the paste and inert properties, and are higher for particles of smaller sizes and lower sphericity; (iii) when these forces are significant, $Q_{ms}$ increases with the paste feeding flow rate until the bed collapses; (iv) $Q_{ms}$ decreases when cohesion forces are negligible due to the formation of a thin layer of paste on the inert surface, causing particle slippage.

Studies on drying of different pastes in SBs, such as foods of vegetable and animal origin, organic and inorganic chemical products, bioproducts, and medicines, emphasized material characteristics as one of the factors that significantly influences the process.\textsuperscript{[7,21]} Analyses of the drying behavior of different vegetable products have related particle adherence and spout regime collapse to the sticky characteristics of fruit pulps and vegetable juices due to their high sugar contents (glucose, fructose, and sucrose). However, none of the works available in the literature could quantify and properly explain these interactions.

Medeiros and co-workers\textsuperscript{[29]} focused on the influence of the chemical composition of fruit pulps on the fluid dynamics and drying operation in SBs. Since the chemical composition of the pulp directly affects the properties of the paste, it is expected to influence both drying performance and product quality. To quantify these effects, an experimental methodology was developed.

### Experimental Methodology

Different tropical fruit pulps (umbu, hog plum, hog plum mango, sweetsop, red mombin, acerola, and mango), without any chemicals or water added, were analyzed to identify and quantify their main constituents. They were characterized by the following contents: reducing and non-reducing sugars, fibers, starch, pectin, total solids, soluble solids, lipids, and water. pH and citric acid percentage were also determined. All these analyses followed standard, well-established methods from the literature.\textsuperscript{[30]} Starch and pectin were identified as significant components, apart from reducing sugars, lipids, and fibers.

According to preliminary drying experiments five significant constituents (reducing sugars, lipids, fibers, starch, and pectin) were defined as independent variables for analyzing the drying process. Natural mango pulp was adopted as a standard pulp and its composition could be modified, when needed, by adding known amounts of reducing sugars, starch, pectin, lipids, and fibers. A $2^5\times1$ fractional factorial experimental design with three replicates at the central point was adopted to study the effect of the variables, as shown in the six first columns of Table 1.

<table>
<thead>
<tr>
<th>Pulp</th>
<th>$C_{sugar}^w$ (%)</th>
<th>$C_{lipids}^w$ (%)</th>
<th>$C_{fibers}^w$ (%)</th>
<th>$C_{starch}^w$ (%)</th>
<th>$C_{pectin}^w$ (%)</th>
<th>$\eta_{pd}$ (%)</th>
<th>$\chi_{pd}$ (%)</th>
<th>Loss (%)</th>
<th>$\theta_{pdry}$ (degree)</th>
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<td>11.05</td>
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</table>
Because efficiency was defined in relation to the total solids in the pulp fed, the water content was no longer an independent variable. For that reason, the pulp compositions were parameterized in relation to the water content \( C^w = C_w / C_{so} \) in order to normalize, to get easier comparisons between the factor influences, and to obtain more generalized results. The maximum levels of concentration for each component were those found in tropical fruit pulps, whereas the minimum levels corresponded to those of the mango pulp. Materials used to modify and control the pulp composition were glucose and fructose (as reducing sugars), soluble starch, citric pectin, olive oil (as lipids), fibers (extracted from the natural mango pulp), and distilled water.

Six different responses were chosen to evaluate process performance. The first three, namely, \( Q_{ms}, \Delta P_{spx}, \) and \( \theta_{p-dr} \), the drained angle of repose for the pulp-wetted inert particles, are related to bed fluid dynamic behavior and instability. The other three variables, mainly used to optimize the pulp composition, were the drained angle of repose of the inert particles after drying, \( \theta_{p-dry} \), the powder production efficiency, \( \eta_{pd} \), and the retention of powder on the inert particle surface (adhered or adsorbed onto the particle surface), \( \zeta_{pd} \).

The values of \( \eta_{pd} \) and \( \zeta_{pd} \) are defined as follows:

\[
\eta_{pd} = \frac{M_{pd}(1 - m_{pd})}{M_{pp}(1 - m_{pp})} \times 100
\]

\[
\zeta_{pd} = \frac{M_{pd-ret}}{M_{pp}(1 - m_{pp})} \times 100
\]

Besides the responses to the factorial experimental design (\( Q_{ms}, \Delta P_{spx}, \theta_{p-dr}, \theta_{p-dry}, \eta_{pd}, \) and \( \zeta_{pd} \)), the bed dynamics were observed every minute during the first 10 minutes from the pulp feeding to the bed.

To perform the tests, a cone-cylindrical SB dryer made of stainless steel and having acrylic windows was used, following the scheme presented in Figure 1. The conical base had included angle of 60°, height of 13 cm and inlet orifice of 3 cm, and the cylindrical part of the bed had 18 cm of diameter and height of 72 cm. More details on the equipment and methodology can be found in.[31]

High-density polyethylene particles (\( d_p = 3.9 \text{ mm}, \rho_{ap} = 950 \text{ kg/m}^3, \) and sphericity = 0.76) were chosen as inert. The static bed porosity of these particles is 0.29 and their drained angle of repose is 19.5°. From the \( \Delta P \) vs. \( Q \) curve obtained for characterizing the SB of inert particles (without pulp), the minimum spouting conditions were determined as \( Q_{ms0} = 17.04 \times 10^{-3} \text{ m}^3/\text{s} \) (0.67 m/s) and \( \Delta P_{ms0} = 670 \text{ Pa} \) at \( T_{g-in} = 70^\circ \text{C} \) and \( M_{inert} = 2.5 \text{ kg} \).

Influence of the Chemical Composition of the Pulp on Spouted Bed Fluid Dynamics

Based on preliminary tests, the following operating conditions were selected for carrying out the experiments: \( M_{inert} = (2.500 \pm 0.005) \text{ kg}, M_{pp} = (50 \pm 1) \text{ g}, \) \( t_{top} = 40 \text{ min}, \) \( T_{g-in} = (70 \pm 1)^\circ \text{C}, \) and \( Q / Q_{ms} = 1.25 \pm 0.05 \). The \( \Delta P \) vs. \( Q \) curves were obtained for the SB of inert with pulp according to the following procedure: (i) spouting the bed of inert particles by air at \( Q / Q_{ms0} = 1.25 \) and \( T_{g-in} = 70^\circ \text{C} \) until reaching the steady stable regime (i.e., \( \Delta P_{ms0} = \Delta P_{spx} = \text{constant and } T_{g-in} = \text{constant} \)); (ii) feeding the pulp over the fountain region using a syringe during about 1 min; (iii) monitoring \( \Delta P, Q, T_{g-out} \) and annulus and fountain heights during and after feeding the pulp until steady state was re-established; (iv) decreasing \( Q \) slowly and recording its value and the corresponding pressure drop as well as any other parameters that were changing; and (v) registering as \( Q_{ms} \), the lowest \( Q \) value for which the fountain was still observed. For comparison, distilled water was also used as a standard liquid fed into the SB of inert particles.

Changes in the fluid dynamics became evident within a few minutes after injection of pulp into the bed of inert. For almost all experiments, the SB flow regime stabilized about 10 minutes after injection of the pulp, by which time most of the pulp moisture had evaporated. Such behavior was not observed for pulp 2, in which case the SB was characterized by a diluted and lower height fountain and serious trends to collapse the spout. The very poor quality of the fluid dynamic exhibited when injecting pulp 2 is due to agglomerates formation caused by the high concentration of sugar in this pulp, which resulted in channelling and reduced pressure drop.

Pulps 1, 2, 3, 5, and 9 (see Table 1) were chosen to analyze the effect of the chemical composition on the SB stability and hydrodynamics, since these pulps have the maximum concentration of each individual main component: pectin, reducing sugars, lipids, fibers, and starch.

The presence of water resulted in a sharp decrease in \( \Delta P \). An expansion of the annulus and an increase in the fountain height were also observed in this case. However, as drying proceeded, initial values of \( \Delta P \) were gradually restored. Similar behavior was also obtained with the addition of mango pulp. Immediately after feeding the mango pulp, \( \Delta P \) sharply decreased. As drying continued, \( \Delta P \) increased. However, the SB steady condition was attained at a \( \Delta P \) smaller than \( \Delta P_0 \). These observations confirm that, apart from the first instantaneous effects of water and mango pulp feeding, the influence of the mango pulp on the bed fluid dynamics was still present when practically all of the water had already evaporated, which may be attributed to powder retention on the surface of the inert particles.
All other pulps also caused a sharp decrease in $\Delta P$ immediately after being added to the bed of particles. According to Spitzner Neto and Freire,\textsuperscript{[27]} this decrease is explained by the agglomeration, which together with the pulp viscosity, jeopardizes particle circulation in the bed, increasing the air flow rate in the spout region. With a greater resistance in the annulus region, the air flow rate and the voidage in the spout region increase, leading to a decrease in the pressure drop across the bed. The higher the fluid dynamic instability brought about by the pulp, the larger is this reduction in $\Delta P$.

It was verified that water resulted in a decrease in pressure drop of about 12\% in relation to the dry bed, while for the fruit pulps, the reduction ranges from 24\% (for pulp 3 with the highest content of lipids) to 80\% (for pulp 2 with the highest content of reducing sugars). This corroborates that the reducing sugar content in pulps contributes more to instabilities in SB dynamics than the lipid content.\textsuperscript{[31]}

Similar behavior of increasing fountain height just after the addition of liquid was observed for all pulps, except for pulp 2. After feeding pulp 2, the fountain height decreased and oscillated (around 85\% of the initial value) as drying proceeded. With regard to the annulus, its expansion, measured by the increase in height, was observed after feeding each one of the 19 pulps. The greatest expansion was recorded for pulp 2. This annular bed expansion is explained by a decrease in the circulation rate, which caused a redistribution of particles inside the bed, with higher solids concentration in the annulus, resulting in its expansion.

Values of minimum spouting flow rate, $Q_{ms}$, ranged from $13.0 \times 10^{-3}$ m$^3$/s to $19.6 \times 10^{-3}$ m$^3$/s (corresponding to minimum spouting velocities in the range of 0.51 m/s to 0.77 m/s) and $\theta_{p-d}$ varied between 1.21 and 2.01° for all the pulps. It was verified that, although these parameters varied within a narrow range for all the pulps, the highest $Q_{ms}$ corresponded to pulp 2, whereas the lowest value of $\theta_{p-d}$ was obtained for pulp 1. The results suggest that high starch and lipid content favor bed flowability, as expected due to their lubricant characteristic. Nevertheless, a more detailed statistical analysis was made to confirm the observed trends.

**Drying Performance**

The last four columns in Table 1 show the results obtained for the drying parameters that are related to process performance. The loss refers to the percentage of powder mass retained in the equipment, i.e., adhering to the walls, dispersed at the column outlet, and eventually lost in the cyclone.

In the work by Medeiros et al.\textsuperscript{[9]} and Medeiros,\textsuperscript{[29]} the results of the statistical analysis of the fractional factorial design for confidence level of 95\% were presented, which showed that all the pulp components, except fibers, exert significant effect on $\eta_{pd}$. Reducing sugars cause a decrease in $\eta_{pd}$ and this effect is the most significant one. Starch, pectin, and lipids favor $\eta_{pd}$, with starch concentration being the most influential. This result is in accordance with the dynamic results for reducing sugar, starch, and lipid concentrations.

As regards $\eta_{pd}$, the same components show significant effects, and as expected, such effects are opposite to those on $\eta_{pd}$.

Pulps having high concentrations of reducing sugars form highly adherent films on the surface of inert particles, and interparticle attrition and impacts, are not sufficient to break these films as drying proceeds. In addition, due to the sticky characteristics of reducing sugars, particle agglomeration occurs, compromising the regime stability and even leading to SB collapse. Lipid concentration, followed by starch, exerts the most important effects on $\eta_{pd}$. The important negative effect of lipids on $\eta_{pd}$ is related to their lubricant characteristic, which interferes with the bed dynamics, enhancing particle circulation and thus facilitating breakage of the adherent film.

For $\theta_{p-dry}$, only the lipid concentration was significant\textsuperscript{[9,29]}. According to the results of the fractional factorial design, fiber concentration does not significantly affect drying performance. Therefore, this variable was excluded from the statistical analysis, and the experimental design could then be rearranged into a complete $2^4$ factorial design with three replicates at the central point.

Based on this $2^4$ complete factorial design, a predictive model was obtained for $\eta_{pd}$ at a confidence level in 95\%. As shown by Medeiros and co-workers,\textsuperscript{[9]} the percentage of explained variation of $\eta_{pd}$ predicted by the model is 93.73\%. The three last lines in Table 1 show results of the replicates at the central condition of the experimental design. Regression and residue analyses showed that reproducibility of the data was satisfactory for all responses analyzed.\textsuperscript{[29]} More details about the regression and residue analyses can be found in.\textsuperscript{[29]}

In the following equations, $C_w = C_i/C_w$ is expressed in wt\% and $\eta_{pd}$ in mass percentage of powder produced in relation to the solids content in the pulp feed. The model is represented by the following equation:

\[
\eta_{pd} = 15.68 - 9.71 \left( \frac{C_{sugar} - 13.81}{6.14} \right) \\
+ 4.31 \left( \frac{C_{lipids} - 3.81}{3.03} \right) + 5.89 \cdot \left( \frac{C_{starch} - 2.59}{2.07} \right) \\
- 2.36 \cdot \left( \frac{C_{sugar} - 13.81}{6.14} \right) \cdot \left( \frac{C_{lipids} - 3.81}{3.03} \right) \\
+ 2.55 \cdot \left( \frac{C_{starch} - 2.59}{2.07} \right) \cdot \left( \frac{C_{pectin} - 1.24}{0.57} \right)
\]  

\text{(3)}
resulting in

\[
\eta_{pd} = 17.40 - 11.10C_w^{\text{sugar}} + 3.17C_w^{\text{lipids}} + 0.17C_w^{\text{starch}} + 0.52C_w^{\text{pectin}} - 0.13C_w^{\text{sugar}}C_w^{\text{lipids}} + C_w^{\text{starch}}C_w^{\text{pectin}}
\]

(4)

The correlation represented by Equation (4) was assessed using experimental data related to the drying of different natural tropical fruit pulps, as shown in Figure 2. Drying of red mombin pulp resulted in the only significant deviation from the \( \eta_{pd} \) prediction given by Equation (4). This deviation can be explained by the different drying conditions used in processing this pulp (lower \( Q \) and \( T_{g,in} \) with \( Q/Q_{ms} = 1.05 \) and \( T_{g,in} = 50^\circ C \)) and by agglomeration problems during this test.

In Equation (4) it can be seen that interactions between the components of the pulp resulted in changes to the pulp properties in a way that could enhance or jeopardize drying performance. Analyses of these properties’ changes on a fundamental point of view were not possible yet in this work. Preliminary tests were made trying to relate drying behavior to the pulp viscosity and surface properties of the pulp-inert in the spouted bed. However, changes of these properties during drying and difficulties to correlate data of the properties for different fruits led to the application of the methods adopted in this work. Use of statistical analysis helped in determining the influences of interactions of the components of the pulps on the process performance, which was later verified for several kinds of natural fruit pulps, as shown in Figure 2. From a practical point of view, the development of this work was important to subsidize decisions on adding starch and lipids to act as adjuvant and enhance process performance, making it feasible to treat tropical fruit pulps in SBs.

The promising results obtained from the statistical modelling of \( \eta_{pd} \) led to the proposition of an optimized pulp composition, which maximizes the efficiency in an amplified range of concentrations of reducing sugars, lipids, starch, and pectin, now covering the range encountered in many tropical fruit pulps. As the mango pulp was the basis for the modified pulp compositions, concentrations of the components below the ones encountered in the standard mango pulp could not be tested with the experimental design. According to Equation (4), the highest efficiency should occur for lowest sugar content and highest lipid, starch, and pectin contents.

After application of an optimization routine, the optimum pulp composition was determined by means of conventional optimization methods available in literature and commercial software[9]. The objective function was the optimized pulp, which would then have the following composition: \( C_w^{\text{sugar}} = 5.52\% \), \( C_w^{\text{lipids}} = 14.69\% \), \( C_w^{\text{starch}} = 4.93\% \), and \( C_w^{\text{pectin}} = 2.78\% \), resulting in a maximum \( \eta_{pd} \) of 81\%.

A pulp having the optimized composition was prepared and a drying experiment was carried out at \( Q/Q_{ms} = 1.22 \) and \( T_{g,in} = 70^\circ C \), with five intermittent pulp feedings into the bed of inert particles. The experimental results obtained for \( \eta_{pd} \) are shown in Figure 3. Excellent drying performance with uniform powder production was achieved in this experiment. Although the efficiency was lower than that predicted by the optimization procedure (81\%), \( \eta_{pd} \) of about 70\% was considered an excellent result, reproducing the drying behavior obtained with natural tropical fruit pulps, but showing a significantly higher powder production rate and efficiency.

This result for the optimized pulp composition motivated the development of the next step of the research utilizing mixtures of fruits, taking advantage of the different natural pulp compositions to generate the optimized composition with the help of some oil and starch additives. It is
worth mentioning that powder mixtures of fruits have shown very good market acceptance.

**DRIYING OF MIXTURES OF TROPICAL FRUIT PULPS IN A SPOUTED BED**

The choice of a mixture of tropical fruit pulps is explained by the functionality of the mixture produced by the synergy of the individual compositions. This powder mixture, with natural flavor, aroma, and functional components, may result in products of sensory and nutritional quality that will make their way onto the market.

The optimum composition obtained in the previous work was the basis for preparing mixtures of pulps. The mixture formulations included pulps of mango, which has high fiber and carotenoid contents with aroma preservation; umbu, which has high lipid, vitamin C, and complex B contents; and red mombin, which has a high starch content. Additives such as commercial cornstarch, pectin (citric pectin from Merck®), and lipids were added to the mixture of pulps aiming at reaching the optimum composition that makes the spouted bed drying feasible. It is worth highlighting that, although the concentration of lipids identified as optimal for fruit pulp drying is high, the mixtures were formulated to contain around 2% of lipids due to their adverse health effects.

**EXPERIMENTAL METHODS**

Mango, red mombin, and umbu pulps without any additives, even water, were acquired at the local market. The pulps were packed in 100 ml plastic bags and stored in cold chambers at -18°C. The physicochemical characteristics of the pulps (reducing and total reducing sugars, proteins, total solids, moisture content, lipids, pH, and acidity expressed as the percentage of citric acid) were determined by standard methods. Data on fruit composition were considered in the mass balances.

Different products were tested as a lipids source: olive and Brazil nut oils, coconut milk, heavy milk, palm fat powder, and palm olein.

Heavy milk is an emulsion of fat in milk, having a large amount of milk fat.

Coconut milk is extracted from mature coconut pulp. It is rich in protein, lipids, calories, carbohydrates, vitamins A, B1, B2, B5 and C, and mineral salts, mainly potassium and magnesium.

Olive oil is well recognized for its benefits to health and for having large amounts of monounsaturated fat, which reduces the risk of coronary diseases.

Brazil nuts are rich in Ω-6 and vitamin E, and ideal for consumption in salads and on fish. Their main advantages are their high protein content, good fiber content, high content of fatty acids of vegetable origin (Ω), and ideal concentration of essential minerals such as selenium.

Palm fat is a vegetable fat that substitutes hydrogenated and animal fat in preparing diverse products in the food industry. It is totally free of trans fat, making the final products more healthy. Also, it is commercialized encapsulated in carbohydrate, which enhances dissolution and product flavor. Finally, the palm olein is one of the richest sources of vitamin E, helping in the reduction of the circulating cholesterol, among other benefits to health.

All formulas contained around 30% mango, umbu, and red mombin pulps; 1.3 to 1.5% pectin; 1.3 to 1.5% corn starch; 6% water; and the contents of different types of lipids as shown in Table 2.

Drying experiments were conducted to define adequate formulations of the pulp mixture in terms of lipid source. The mixture formulations were submitted to drying under fixed operating conditions. These fixed conditions were defined based on the results obtained in the previous work on the drying of modified tropical fruit pulps: an inert load of 2.50 ± 0.01 kg, $T_{\text{min}}$ of 70 ± 2°C. Feeding of the mixtures into the bed was intermittent, with a volume of 100 ml added during 20 minutes, followed by an interval of 15 minutes before the next feeding. The same air flow rate (20% above the minimum spouting for the bed of inert at 70°C) was maintained in the drying experiments of the different mixtures. The results were analyzed in terms of drying performance and sensory tests.

Drying performance was evaluated by process efficiency and the fraction of solids retained in the bed (Equations (1) and (2), respectively).

The same methodology as that used to formulate industrialized yogurts with the addition of fruit pulps was applied to prepare samples of yogurts incorporating the powders obtained from the drying of the mixtures shown in Table 2. Proportions of 93.4% yogurt (natural, skimmed, without sugar, and with a thick consistency), 1.8% powder, and 4.8% sugar were maintained in the samples. Samples were tasted by 20 tasters at the Food Engineering and Nutrition Schools of UFRN (Federal University of Rio Grande do Norte in Brazil).

After establishing the appropriate types of lipids, new drying runs were done with the mixtures containing the

<table>
<thead>
<tr>
<th>Formula name</th>
<th>Lipid composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOLIVE</td>
<td>Olive oil (1.3%)</td>
</tr>
<tr>
<td>FHMILK</td>
<td>Heavy milk (5.5%)</td>
</tr>
<tr>
<td>FCOCOM</td>
<td>Coconut milk (5.5%)</td>
</tr>
<tr>
<td>FBRNUT</td>
<td>Brazil nut oil (1.3%)</td>
</tr>
<tr>
<td>FPALMF</td>
<td>Palm fat (powder) (2.0%)</td>
</tr>
<tr>
<td>FPALMO</td>
<td>Palm olein (2.0%)</td>
</tr>
</tbody>
</table>

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chosen lipid sources, aiming at having a sufficient amount for their characterization.

Physical and physicochemical characteristics were determined for the dry powders obtained from these mixture formulations. Solubility and reconstitution time as well as the properties of the product after reconstitution were also evaluated.

Physicochemical Characterization of the Mixtures of Pulps and Products (Dry Powders)

All characterization analyses as described below were done in triplicate.

The moisture content was determined by the oven method until reaching constant weight using an oven with air circulation at 70°C.[30]

Determinations of pH, lipid content, titratable acidity, total soluble solids, residue by incineration, protein content, and vitamin C content (mg AA/100 ml of sample) were made according to standard methods in the literature.[30] Reducing sugars were determined by the method described in[32] and water activity was obtained directly in an analyzer that applies the dew point principle.

Percentage of vitamin C loss was obtained relating the AA (ascorbic acid) contents found for the powder and the pulp mixtures in natura, expressed on a dry basis.

\[
VC_{\text{loss}} = 100 - \left(100 \times \frac{VC_{\text{pd}}}{VC_{\text{pp}}}ight) \quad (5)
\]

Physical Characterization of the Mixtures

Measurements of surface tension of the pulp mixtures were taken with a Krüss tensiometer by the well-known ring method, and density was obtained by pycnometry.

A digital rheometer (RheoStress – from Haake, model RS-150, sensor geometry of co-axial cylinders, model DG-41, with a thermostatic bath, also from Haake, model K20) was utilized to analyze the rheological behavior of the mixtures and the reconstituted powder. An interval of 15 to 150 s⁻¹ of rate of shear strain was covered in the tests, due to equipment limitations (instabilities occurred for lower values of shear stress). Data on shear stress as a function of rate of shear strain were adjusted to the Power Law model, which represents the rheological behavior of fruit pulps.[33]

Powder Characterization

Dry powder was characterized by its solubility, reconstitution of the pulp mixture, angle of repose, and Hausner factor.

Powder solubility was determined by the method described in[34] and the procedure specified in[22] was applied to evaluate the time of reconstitution of the powder to the pulp mixture.

Powder mixture flowability was analyzed by the static angle of repose and Hausner factor. The latter was determined as the ratio of the experimentally observed tapped and free apparent densities.

RESULTS AND DISCUSSION

Physicochemical Characterization of the Pulp Mixture Formulations

The results of characterization of the pulp mixtures with the addition of corn starch, pectin, and the different types of lipids are shown in Table 3.

Total soluble solids expressed as °Brix are lower than the values found in other work[35] for pasteurized and sterilized purée of various fruits (27.0°Brix). Also, the formulations in this work had lower solids contents, and higher moisture contents, than the pulps modified and analyzed by Medeiros.[29] The difference can be explained by the low solids content and very high moisture content of the umbu pulp used in this work. This result points to the good performance of the drying process using the mixture formulations proposed here, as reducing sugars (which correspond to almost the total solids content in fruit pulps) interfere in a negative way in the spouted bed drying of fruit pulps.

The pH of the different mixtures shown in Table 3 is compatible with the pH range of the modified pulps (from 2.9 to 4.2) studied in.[29] It is known that the pulps’ properties are influenced by their compositions and pH. For example, some properties of fruit pulps having a high reducing sugar content (mainly glucose) are altered when pH is reduced to values lower than 3. This effect may not show up in the mixtures analyzed in this work due to the low sugar content and pH > 3. Also, the pH of a food is an important factor as it can indicate the growth, survival, or destruction of microorganisms present. According to the pH range (3.2 to 3.9), the mixtures are classified in the group of very acidic foods, in which microbial development is restricted to yeast and mold, with possibly some lactic and acetic bacteria.

With respect to surface tension, one can observe that there was no significant variation between the different mixtures analyzed in this work due to the low sugar content.

<table>
<thead>
<tr>
<th>TSS (°Brix)</th>
<th>TTA (%)</th>
<th>pH</th>
<th>σ (dyn/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F_Olive</td>
<td>11.3</td>
<td>1.1</td>
<td>3.3</td>
</tr>
<tr>
<td>F_HmilK</td>
<td>10.0</td>
<td>0.8</td>
<td>3.2</td>
</tr>
<tr>
<td>F_Cocom</td>
<td>10.7</td>
<td>0.8</td>
<td>3.3</td>
</tr>
<tr>
<td>F_Brunut</td>
<td>11.4</td>
<td>0.9</td>
<td>3.2</td>
</tr>
<tr>
<td>F_Palmf</td>
<td>13.1</td>
<td>0.9</td>
<td>3.3</td>
</tr>
<tr>
<td>F_Palmo</td>
<td>13.1</td>
<td>0.9</td>
<td>3.9</td>
</tr>
</tbody>
</table>
formulations; the measurements are close to the umbu pulp surface tension (62.1 dyn/cm).

Water activity was similar for all mixtures analyzed and very high, as expected (mean value: 0.986 ± 0.003).

The results also showed that the different types of lipids in the mixtures did not affect their densities (1.061 ± 0.003 g/ml). The densities obtained in this work are slightly lower than those of the natural fruit pulps that compose the mixtures; they are compatible with the ones determined for the modified pulps used by Medeiros.[29]

**Drying**

Figure 4 contains plots of the mass of powder (accumulated) collected during the pulp mixture drying. The graphic shows that for most of the experiments the mass of powder increased linearly with time, indicating that the production rate was practically constant.

The effect of different types of lipids on powder production is more evident for the palm fat powder and the heavy milk. The largest and smallest collections of powder were obtained with the formulas including F_PALMF and F_HMILK, respectively. The production rate estimated from the linear model corresponds to 0.355 g/min (21.3 g/h) and 0.257 g/min (14.4 g/h), respectively. The straight lines almost overlap for the other lipid sources with an average powder production of 0.3 g/min (18 g/h).

The results obtained for the moisture contents of the pulp mixtures in natura (m_pp) and of the powder (m_pd) as well as the process efficiency (η_pd) and the material retention in the bed (v_pd) are shown in Table 4. It was verified by experimental observations that the drying of some mixtures resulted in high levels of material retention inside the bed (mainly for the formulation using heavy milk) or material adhering to the dryer walls (as for the mixture having coconut milk).

No significant variation is observed for the pulp moisture content, which corresponds almost completely to the average of the moisture contents of the fruit pulps which the formulations are composed.

Powder moisture contents were in the range of 4.11 to 8.05%. These values are compatible with the ones found by Medeiros and co-workers.[9]

As shown in Table 4, drying efficiencies were in the range of 35.6 to 52.3%, which is higher than the drying efficiencies obtained for drying of umbu, mango, and red mombin pulps using the same equipment and inert.[9]

In the drying of F_HMILK there was higher retention of material in the bed than the drying yield, which agrees with experimental findings. Heavy milk is the only animal fat source used in the mixture compositions proposed in this work. Interactions between this type of fat and the other components of the pulps may be the reason for the adhesion of the film of this mixture to the inert particles.

Drying of F_COCOM resulted in low material retention; however, the drying efficiency was also low due to the loss of powder attached to the bed walls in accordance with the experimental reported data.

For the drying of F_PALMF and F_PALMO, the efficiencies were higher and, specifically for the F_PALMO, the material retention was very low (13.8%). Stable fluid dynamics were observed during the drying experiments. Bed pressure drop and heights of the fountain and of the annulus remained stable during the drying runs, showing only alterations inherent to those in the intermittent feeding of the pulp mixtures.

Apart from process performance, results of sensory testing of the yogurts prepared with the addition of the dried mixtures were also used as a criterion to select the appropriate mixture formulations. Yogurts containing dried F_HMILK, F_COCOM, F_PALMF, and F_PALMO were approved in the sensory test. For the other yogurts, characteristic odor of the lipid source utilized negatively influenced the tasters.

Despite their sensory acceptance, the mixtures with addition of heavy milk and coconut milk were also

![FIG. 4. Powder production during drying of the pulp mixture formulations (color figure available online).](color-figure-available-online)
For evaluation on a dry basis, the loss of vitamin C was 37% (average), which is of the same order of magnitude and slightly lower than the vitamin C loss recorded in other work.[11]

Powder moisture contents were compatible with the results for dried Surinam cherry pulp without additives (8.12%) and with the addition of 15% maltodextrin (7.64%).[36]

The acidities (expressed as citric acid content) found for FPALMF (5.42%) and FPALMO (4.65%) were lower than the ones obtained for green acerola powder dried in an oven and lyophilized (7.68 and 8.50%, respectively),[37] and higher than the value reported for powder from pineapple bagasse (2.58%).[38]

Powders obtained from the two mixture formulations showed good solubility, of the same order of magnitude. Averages of the static angle of repose were 49° for the two mixture formulations. Angles of repose lower than 45° are characteristic of free-flowing powders, while angles of repose above 50° suggest cohesiveness. The value obtained in this work is at the limit between free flowability and cohesiveness.

Mean free apparent densities obtained for FPALMF and FPALMO powders were 0.29 g/ml and 0.21 g/ml, respectively. These values are of the same order of magnitude as those for other powders from fruit pulps with and without additives obtained in a spray dryer and in a SB.[36,39]

Tapped densities were evaluated for the powders from the two mixtures, showing values of 0.40 g/ml and 0.33 g/ml for FPALMF and FPALMO, respectively. The Hausner factor was calculated as the ratio of the tapped to the free apparent densities, resulting in 1.46 and 1.58 for FPALMF and FPALMO. The Hausner factor is related to the cohesive forces of a particulate material; if the factor is lower than 1.25, the material can be classified as free-flowing. Hausner factors higher than 1.4 are typical of cohesive materials.[40]

Analysis of the powder characterization reveals similarity between the products of the two mixture formulations, FPALMF and FPALMO. The powders had low moisture contents; ascorbic acid contents were not high in the mixtures and important losses of vitamin C were reported. Acidity analysis classifies the powders as acids, consequently making microbiological contamination difficult. The Hausner factor indicates that the powders of both formulations are cohesive.

Experiments on pulp reconstitution resulted in an average time of 315 s for complete reconstitution. A similar result was found for the reconstitution of tomato powder obtained in SB.[22] It is important to note that drying temperature influences reconstitution time, as verified in other work.[22,41] Reconstitution times were higher for higher drying temperatures. The bridges formed between the particles during drying could be more rigid at high
temperatures, altering the reconstitution and solubility of the final product.

A summary of the properties of the reconstituted and in natura pulp mixtures (F_{PALMF} and F_{PALMO}) is presented in Table 7.

No significant alterations can be seen between the reconstituted and in natura pulp mixtures. The small variations observed can be explained by the higher moisture content of the reconstituted pulp and probably by the drying process with volatile losses.

Results of the rheological characterization (fit to the power law model) of the mixture formulations, in natura and reconstituted, are shown in Table 8.

Similar results for each mixture, in natura and reconstituted, confirm the potential of SB drying for tropical fruit pulp mixtures.

**CONCLUSIONS**

For most of the pulps, a sharp decrease of the bed pressure drop was obtained just after the addition of pulp into the bed. As drying continued, the pressure drop increased until a steady condition, which was attained at a smaller pressure drop than the initial one. Observations confirmed that, apart from the first instantaneous effects of pulp fed, an influence of the pulp on the bed dynamics was still present when almost all water was evaporated, which was attributed to powder retention on the surface of the inert particles.

Pulps with high lipid and/or high starch contents resulted in stable spouting regime.

The higher the fluid dynamic instability brought about by the pulp, the larger was the reduction in the bed pressure drop, as verified for the pulps having high reducing sugar contents.

Analysis of the fluid dynamics suggested that high starch and lipid contents favored bed flowability and reducing sugars resulted in bad dynamic regime.

Repetitions at the central condition of the experimental design resulted in appropriate reproducibility of powder production efficiency.

For some conditions of the experimental design there was no powder produced, as in the runs with pulps containing high reducing sugar and low starch concentrations. The highest efficiency was obtained for the pulp with low reducing sugar and fiber contents, and high pectin, lipid, and starch contents.

Statistical analysis of the fractional factorial design for 95% of confidence level revealed that all the components, except fibers, exerted significant effect on efficiency of powder production. Reducing sugars caused a decrease in the efficiency and this effect was the most significant. Starch, pectin, and lipids favored powder production, the starch concentration being the most influential.

A predictive statistical correlation was obtained for efficiency of powder production as a function of the pulp composition. Regression and residue analyses as well as comparisons of predicted and experimental values of efficiency of powder production for all the modified pulps, for natural mango pulp, and for different tropical fruit pulps dried in the same SB dryer attested a good fit of the proposed correlation to the experimental data.

An optimized pulp composition was determined, which would result in a maximum efficiency of powder production of 81%.

In the drying of mixtures of mango, red mombin, and umbu pulps with addition of starch and different lipid sources, formulas with palm fat powder and palm oil resulted in higher efficiencies and, specifically for the palm oil, material retention in the bed was very low. Stable fluid dynamics were observed during the drying experiments. Bed pressure drop and heights of the fountain and annulus stayed stable during the drying runs.

Powders from the mixtures of pulps with adjusted composition (using palm fat powder and palm oil as lipid sources) had good solubility in water, intermediate cohesiveness, and moisture contents, citric acid percentages and reconstitution times compatible with the results found in the literature for other pulps. Also, yogurts

<table>
<thead>
<tr>
<th>Parameters</th>
<th>F_{PALMF}</th>
<th>F_{PALMO}</th>
</tr>
</thead>
<tbody>
<tr>
<td>m_{pp} (%)</td>
<td>82.3</td>
<td>86.1</td>
</tr>
<tr>
<td>TSS (°Brix)</td>
<td>13.1</td>
<td>12.8</td>
</tr>
<tr>
<td>TTA (%)</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>pH</td>
<td>3.3</td>
<td>3.4</td>
</tr>
<tr>
<td>ρ_{pp} (kg/m³)</td>
<td>1062</td>
<td>1057</td>
</tr>
<tr>
<td>σ (dyn/cm)</td>
<td>62.6</td>
<td>45.8</td>
</tr>
</tbody>
</table>
containing these powders obtained good scores in sensory analyses.

SB drying of the pulp mixtures (with palm fat powder and palm oil) resulted in a high-quality product for use by industry in the preparation of enriched foods. Considering that palm oil is a Brazilian product of moderate price that has been replacing the powder of palm fat in the Brazilian industries, the mixture including palm oil was chosen to continue this research. The next step will be to analyze process performance for this fixed formulation of the pulp mixture, aiming to optimize process efficiency through modifications of the operating conditions and the dimensions of the SB drier.

**NOMENCLATURE**

- $C'_w = C_i/C_w$: Conc. component i/conc. comp. w (%)
- d: diameter (m)
- K: parameter (power law model) (N·m$^{-2}$·s$^{-1}$)
- M: mass (kg)
- m: moisture content, wb (%)
- n: parameter (power law model) (–)
- P: pressure (N·m$^{-2}$)
- Q: flow rate (m$^3$·s$^{-1}$)
- RS: Reducing sugars (%)
- $R^2$: Correlation coefficient (–)
- T: temperature (°C)
- t: time, (s)
- TRS: Total reducing sugars (%)
- TSS: Total soluble solids (°Brix)
- TTA: Total titratable acidity (%)
- VC: vitamin C content (mg AA/100 ml of sample)

**Greek Letters**

- $\Delta$: variation (–)
- $\theta$: angle of repose (°)
- $\eta$: efficiency (%)
- $\iota$: retention (%)
- $\rho$: density (kg·m$^{-3}$)

**Subscripts**

- $0$: initial
- ap: apparent
- g: gas
- in: inlet
- loss: loss
- max: maximum
- ms: minimum spouting
- out: outlet
- p: particle
- pd-ret: powder retained
- p-dry: dry particles
- p-fl: wetted particles
- pp: pulp
- ssp: stable spouting

**REFERENCES**


