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A Study on Meat Drying Process Using a Porous Media Approach. Part 1: Experiments

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This paper presents a basic work that supplies complementary knowledge and open new perspectives to mathematical modeling of salami ripening. An experimental apparatus was realized for controlled meat drying and its procedure set up in order to allow a simple, but significant investigation on the fate of water contained and transported in a minced meat matrix, at various times throughout the drying process.
The experimental results are discussed in terms of weight loss as well as space and time profiles of moisture in the specimen. Then, they are favorably compared to the predictions of a mathematical model of drying, which is based on a porous media description of the minced meat and simply adopts a literature correlation of moisture diffusion. To this end, the Comsol Multiphysics®4.3 software was used, with the “transport in porous media” physics.

1. Introduction

In meat processing, salami products are of great interest from historical, nutritional and economic viewpoints. The various types of dry sausages differ in composition (e.g., type of meat, cut size of lean and fat, ingredients and additives, nature of the casing, microbial starters) or in process and technique for drying and curing (e.g., long-maturing vs short-maturing salamis). The shelf life of fermented sausages belonging to the Italian tradition is determined by lowering free water (i.e., water activity, a_w) below the limit for growth of spoilage microorganisms (Leistener et al., 1987). The acquisition of scientific knowledge about the mechanisms involved in the maturation of the meats is fairly recent (Pirone et al., 2007). Presently, the ability to describe the drying process depends to a greater extent on the knowledge of the phenomena related to water transport inside the product and, to a lesser extent, to evaporation from the outside surface. Obviously, a water concentration gradient establishes between the inner part of the sausage and its external surface. Owing to salami granular structure, water actually moves in a complex way and the main transfer mechanisms (Okos et al., 1992) are usually considered to be: 1) capillary flow of free water; 2) bound water movement; 3) diffusion in liquid phase; 4) condensation-evaporation. These mechanisms are often competitive (Baldini et al., 2001) and the drying kinetics is the consequence of both their interaction and the external conditions applied (Bessadok et al., 2013).
Nowadays, ripening of salami under natural conditions has been replaced by batch production in ventilated industrial chambers. Hence, the same product quality can be obtained regardless of local, environmental (Kottke et al., 1996) and climatic conditions (Kottke et al., 1987). Nevertheless, well-planned and carefully monitored process conditions are necessary to achieve the targeted weight loss and quality of dry fermented sausages. To this end, the availability of reliable mathematical models and manageable software codes for sausage drying, maturation and optimal production are highly welcome.
The water in the whole sausage is obviously present in the lean meat only. Water concentration is a distributed parameter: quite often, the assumption of an effective diffusion coefficient D_e depending on the local water content accounts for water transport inside the sausage (Baldini et al., 2001).
The porous medium approach makes it possible to consider the fat as inert and the lean meat as a porous medium in which the water transport takes place. The model of the lean meat as a porous system considers small pores (≈100 μm), weak evaporation and a capillary pressure formulation (Datta, 2007). However, there

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is clearly a lack and an inadequateness of literature data on moisture diffusivity in such a complex matrix as the minced mixture of lean meat and fat globules, subject to drying and ripening in the salami production process. Therefore, this work is intended to provide a contribution for a better knowledge: a new experimental apparatus, the operating procedure and related results are presented and discussed.

2. Experimental activity

2.1 Apparatus

The new experimental apparatus is a minced meat sample holder equipped with a real-time acquisition system that allows: 1. monitoring the sample weight, 2. measuring the water content in various points of the specimen and 3. measuring temperature and humidity of a controlled atmosphere (Figure 1a).

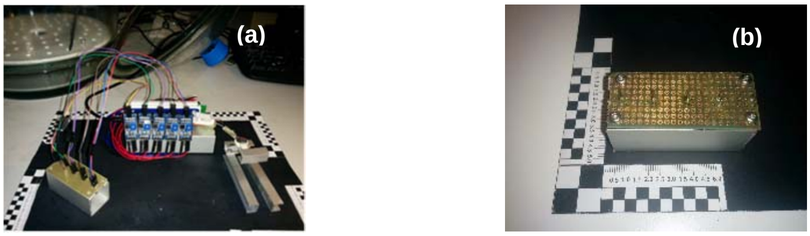

Figure 1: a) Experimental apparatus with the meat sample holder assembled with the sensors; b) meat sample holder picture.

Data are processed by an Arduino Nano MCU. Therefore, the system consists of:

- 1 MCU Arduino Nano, an open-source hardware, for data acquisition and screen-printing in real time, used with the Arduino software.
- 1 Digital-output relative humidity & temperature DHT22 sensor/module for monitoring temperature and humidity of the environmental air. The capacitive-type humidity and temperature module/sensor utilizes an exclusive digital-signal-collecting-technique and humidity sensing technology, assuring its reliability and stability. Its sensing elements are connected to an 8-bit single-chip computer. Measuring range: humidity 0-100% RH; temperature -40~125°C.
- 1 24-bit Analog-to-Digital Converter (ADC) for Weigh Scales, used to continuously acquire the sample weight. The converter, named HX711, is a precision converter designed for weigh scales and industrial control applications to interface directly with a bridge sensor. Measuring range: 0.000~100.000 g @ –40~85°C.
- 5 high sensitivity moisture sensors for measuring the water content in the sample at different points. This moisture sensor uses two probes to pass current through the matrix, originally intended to be a soil, and then it reads that resistance to get the moisture level. Abundant water makes the sample more conductive for electricity (lower resistance), while dry samples are poor conductors (high resistance). Measuring range: 0-100% moisture mass fraction @ 10~30°C.

Each type of probe required a specific programming including zeroing, calibration, sampling time in C++ language. Cascone (2018) reported the code developed for such a purpose.

Each drying test lasted at least 3 days and the sampling time was 1 min (i.e., minimum time indicated in the data sheets of the probes for a stable measurement).

With the PLX-DAQ tool the data are acquired in real-time at each sampling time by a PC and are transferred to Microsoft Excel to plot time series.

Based on the above description, the experimental apparatus was quite cheap, easy to be assembled and flexible in its operation. The geometry of the meat sample holder (Figure 1b) is designed as a parallelepiped with the length much larger than the height, namely L=60 mm>>h=22 mm, in order to minimize water concentration changes in the vertical direction within the sample and, therefore, it is possible to sample the concentration variation in the longitudinal direction. To ensure air circulation, a 5 cm diameter brushless fan at 12 V, designed for computer cooling, was used.

2.2 Procedure

The material studied is minced *longissimus dorsi* meat, as representative of pork lean meat. The experiment is conducted exclusively on such a minced sample of lean meat with an initial water content X_{r0}=75.0 % wt.

The sample is loaded into the specimen holder, humidity sensors are set and the whole apparatus is placed on the load cell to monitor its weight. After this, the whole system is placed in a humidity-controlled atmosphere dryer; a pre-established air humidity is gathered in the dryer thanks to the presence of a lithium chloride supersaturated solution, which allows establishing an air humidity equal to 15% RH at ambient temperature. In any case, a sensor monitors the temperature and relative humidity of such a controlled atmosphere.

Many tests were carried out to set up and tune the procedure, including the calibration of the sensors, until reaching a standardization of the experiment duration, set at 72 h (e.g., by observing the deterioration state of the sample and the time in which further weight losses become not appreciable).

Measuring the sample weight with the analytical scale at the start of the drying test allows calibrating the load cell. This is done by adjusting, within the programming language, the value of a calibration factor used in the Arduino programming so that the load cell produces a weight equal to the measured value on the analytical scale. A separate and independent weight measurement at the end of the drying is done to have a control value. Multiple tests were used to calibrate the humidity sensors on the sample moisture content. The voltage output that is returned by the probe not connected to the sample holder was associated to 0% humidity by assuming a negligible contribution of the sample dry matter to conductivity. The sensor amplifier was tuned in order to have 75% of the maximum voltage output obtained with a fresh sample of lean meat (Cascone et al., 2017). In this way, a calibration line was defined for each of the humidity sensors. This procedure allowed minimizing the difference between readings of the various sensors at the same system humidity.

Two slightly different experimental configurations were used in the test plan. The experiments for the samples named “A” were carried out with a single surface of the sample exchanging humidity with the environmental air. The experiments for the samples named “B” were carried out with two opposite surfaces of the sample exchanging humidity with the environmental air. Each test was performed in triplicate for a duration of 72 h, at ambient temperature (~20°C) and 15% RH set inside the humidity-controlled atmosphere dryer using the lithium chloride supersaturated solution.

Table 1: Sample weight value before and after the test for the two triplicate experiments: “A” using a single sample drying surface and “B” using two sample drying surfaces

(A) Sample	$Weight_{IN}$ [g]	$Weight_{OUT}$ [g]	**(B)** Sample	$Weight_{IN}$ [g]	$Weight_{OUT}$ [g]
A1	25.904	19.327	B1	32.022	23.912
A2	31.734	24.263	B2	31.389	24.096
A3	31.854	26.473	B3	32.579	24.16

2.3 Results

Gross results for weight losses in the experiments are reported in Table 1.

Details of weight losses at different times (every 24 h) are reported in Table 2 for both experimental configurations “A” and “B”. More frequent drying data, taken every hour, are reported by Cascone (2018). The experiments setting are 72 h, T_{amb}, 15% RH.

Table 2: Weight losses recorded for the two experiments “A”(1 drying surface) and “B” (2 drying surfaces) repeated in triplicate

Time [h]	Weight loss A1 [%]	Weight loss A2 [%]	Weight loss A3 [%]	Average [%]	Std deviation [%] **(A)**
0	0	0	0	0	0
24	7.249	5.331	5.951	6.177	0.799
48	10.12	9.351	10.217	9.896	0.387
72	12.202	12.524	13.383	12.703	0.498

Time [h]	Weight loss B1 [%]	Weight loss B2 [%]	Weight loss B3 [%]	Average [%]	Std deviation [%] **(B)**
0	0	0	0	0	0
24	9.568	12.422	11.16	11.05	1.168
48	15.754	19.277	17.446	17.492	1.439
72	20.704	25.018	22.598	22.774	1.765

The five probes for the sample humidity allowed determining a moisture ratio C/C_0 in 5 points of the longitudinal direction of the sample holder. It was decided to take into consideration a new concentration profile in the longitudinal direction just every 24 h, in order to observe appreciable changes in the experimental data. The results of these measurements are summarized in Table 3a for sample A1 and Table 3b for sample B1. Extended data, including A2, A3, Average A, Std Deviation A, B2, B3, Average B, Std Deviation B for the experiments repeated in triplicate are reported by Cascone (2018).

Table 3: Values of C/C_0 for the two experiments "A"(1 drying surface) and "B" (2 drying surfaces)

Sample A1				**(a)**
Longitudinal abscissa [mm]	0 h	24 h	48 h	72 h
5	1	1.014	1.014	1.014
15	1	0.946	1.014	0.973
30	1	1.014	1	1.014
45	0.986	0.973	0.973	0.959
55	0.986	0.946	0.932	0.905

Sample B1				**(b)**
Longitudinal abscissa [mm]	0 h	24 h	48 h	72 h
5	0.971	0.9	0.878	0.865
15	0.993	0.918	0.949	0.956
30	1	0.967	0.952	0.913
45	0.993	0.951	0.918	0.887
55	0.993	0.905	0.809	0.795

3. Mathematical modeling

The porous media approach is adopted in this work with reference to a system with small pores (≈100 µm), weak evaporation and a capillary pressure formulation (Datta, 2007). Since the samples are made by lean meat, a homogeneous approach is possible. The resulting mathematical model is the classical water transport partial differential equation:

$$\frac{\partial c_w}{\partial t} - \nabla(D_w \nabla c_w) = 0 \qquad (1)$$

$$I.C.: @t = 0, c_w = c_0$$

$$B.C.: \begin{cases} @\ x \in \Gamma_{NO\ flux}, N_w = 0, & \forall t > 0 \\ @\ x \in \Gamma_{flux}, N_w = N_R, & \forall t > 0 \end{cases}$$

where:

c_w= water concentration in the capillary system (kg/m^3), c_w=*f*(X);
c_w= initial water concentration in the capillary system (kg/m^3);
Γ_{flux}= boundary where the mass transfer takes place;
$\Gamma_{NO\ flux}$= boundary where the mass transfer does not take place;
N_w= water interface flux (kg/m^2 s);
N_R= interface flux (Cascone, 2018);
D_w= capillary diffusivity (m^2/s);
t= time.

Due to a lack of literature data for the expression of diffusivity in the meat matrix, for the sake of simplicity, an easy-to-handle equation is adopted, which was used in the past to describe the moisture diffusion in swordfish tissue (Zogzas et al., 2013):

$$D_w = 9 \cdot 10^{-11} + 1.6 \cdot 10^{-10} X \qquad (2)$$

where:
D_w= capillary diffusivity (m^2/s); X=*f*(c_w) moisture content on dry basis.
In fact, this equation has the advantage of linearly correlate diffusivity with the sample water content.

4. Simulation

The COMSOL Multiphysics® 4.3b software was chosen for modeling, simulation and graphical representations.
The "Transport in porous media" physics, adapted to Datta (2007) model, was adopted to develop a code. The governing equations, i.e., the water mass balance, expressed in terms of Partial Differential Equations (PDEs) with their boundary and initial conditions in Eq(1), were solved by COMSOL Multiphysics® by means of the Finite Element Methods (FEM). The simple sample holder geometry was easily implemented. Due to configuration chosen for the meat sample holder (Figure 1b), the variation of the water concentration along the longitudinal direction is by far prevailing on those along the other directions within the sample; therefore, only the derivative component along x of the gradient in Eq(1) is actually significant.
Energy balances were neglected because the drying experiment was carried out at ambient temperature under isothermal conditions. The mesh used for the simulation is of the type Free Tetrahedral with maximum element size: 0.6 mm, maximum element growth rate: 1.1 and resolution of narrow region: 1 (i.e., "extremely fine" calibrated dimension for General physics). Properties of the materials built-in in the software were not used, but all the characteristics of the lean meat were implemented in Parameters in Global definitions (if parameters) or in Variables in Definitions (if variables depending on the moisture content). Running the code requires as input data the initial properties of the fresh minced lean meat (commercial l*ongissimus dorsi* pork meat) and the drying air conditions. So, as input to the model, the data related to experimental drying test were used:

Table 4: Code data input with porous media model for the experimental drying conditions

Name	Value	Description	Name	Value	Description
T_0=T_{air}=T	303 K	Air and meat temperature	k_{oswin}	10.8e-2	K Oswin constant
Xr_0	0.75	Initial meat moisture fraction	n_{oswin}	0.43	n Oswin constant
m_t	31.997 g	Initial meat weight	u	0.2 m/s	Air velocity
L_{sample}	60 mm	Specimen length	Duration	3 days	Drying time
B_{sample}	22 mm	Specimen height	Step	0.1 day	Time calculation step
RH	0.15	Air relative humidity			

For other conventional parameters, literature correlations with dependencies from temperature and water concentration are used from Perry's Chemical Engineer Handbook (Perry et al., 1998).

The mathematical model implementation requires to choose 1 or 2 boundary surface Γ_{flux},, according to the two types of experimental configurations: "A" with one moisture exchanging surface, "B" with two moisture exchanging surfaces.

5. Comparison between predicted and experimental results

The comparison between predicted and experimental results is reported in Figure 2 for weight losses and in Figure 3 for humidity profiles at different drying times. In these figures, error bars on experimental data are standard deviations. The predicted weight loss slightly underestimates the experimental weight loss at the end of the experiment in Figure 2A, while slightly overestimating the experimental weight loss at the beginning of the experiment in Figure 2B. The predicted water content profiles in Figure 3 are very close to the experimental values sampled at various times. The observed agreement is good for weight losses and humidity profiles in spite of the simple linear equation (Eq(2)) used to describe the dependency of diffusivity from the local sample humidity.

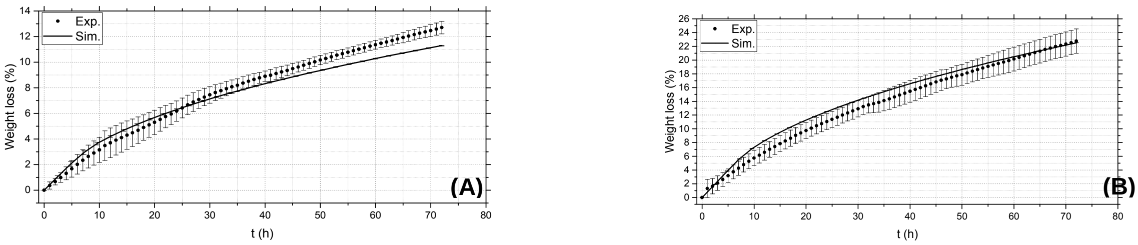

Figure 2: Comparison between experimental and predicted weight losses for the two experiments: "A" (1 drying surface) and "B" (2 drying surfaces)

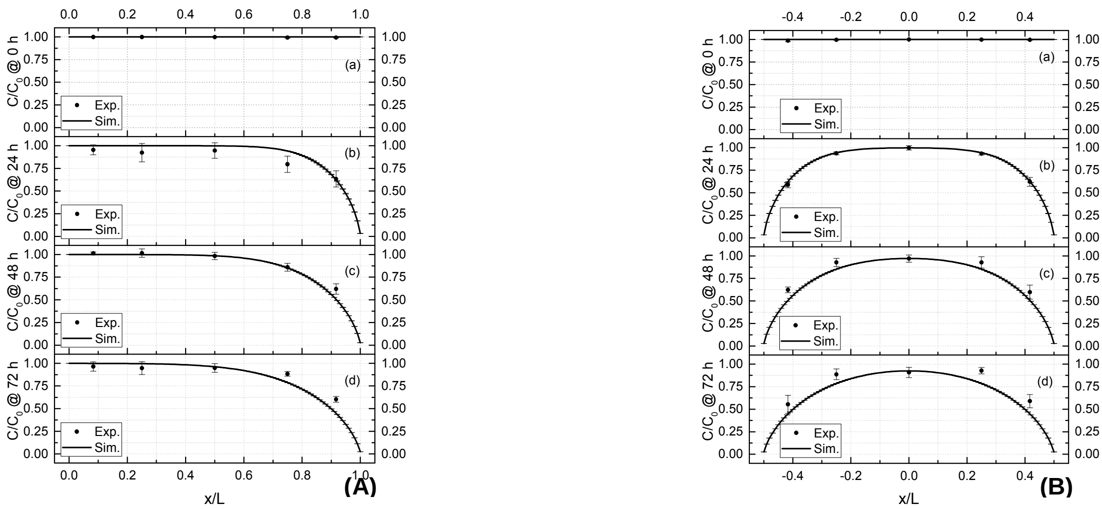

Figure 3: Comparison between experimental and predicted moisture concentration profile: "A" (1 drying surface) and "B" (2 drying surfaces)

6. Conclusion

During the study, a simple, cheap, and flexible experimental apparatus was built; correspondingly, an an easy-to-handle experimental procedure was set up and successfully proven to investigate the water transport as a function of time and space variables in a minced meat matrix under drying. The experimental apparatus allowed real-time monitoring of the weight and water concentration profiles that establish in the material under investigation.

The novelty of the presented work is in the adopted approach, i.e., the description of the minced meat as a porous medium, considered as a very wet porous matrix, i.e., a material under conditions for which the capillary diffusivity can be well approximated by an effective diffusion coefficient, with a dependence from the local water content.

A distributed-parameter mathematical confirmed the experimental results in terms of weight losses and longitudinal profiles of the non-dimensional water content of the meat sample the during the drying process.

All in all, the present study opens the door to evaluate the dependence of the water diffusivity from the local water content in such a complex system as a porous minced meat matrix.

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