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Mathematical modeling and simulation of soluble protein extraction during leaching process in surimi elaboration

M.A. Reinheimer [a,b,*], J.R. Medina [c], N.J. Scenna [a,b], S.F. Mussati [a,d], M. Freyre [e], G.A. Pérez [c]

[a] CAIMI – Centro de Aplicaciones Informáticas y Modelado en Ingeniería-UTN, FRRo – Universidad Tecnológica Nacional, Facultad Regional Rosario, Zeballos 1346, S2000BQA Rosario, Argentina
[b] CONICET – Consejo Nacional de Investigaciones Científicas y Técnicas, Av. Rivadavia 1917, C1033AAJ Buenos Aires, Argentina
[c] Facultad de Ingeniería Química, Universidad Nacional del Litoral, Santiago del Estero 2829, S3000 AOM Santa Fe, Argentina
[d] INGAR-CONICET, Instituto de Desarrollo y Diseño, Avellaneda 3657, S3002GJC Santa Fe, Argentina
[e] Instituto de Tecnología de Alimentos, Facultad de Ingeniería Química, Universidad Nacional del Litoral, Santiago del Estero 2829, S3000 AOM Santa Fe, Argentina

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ABSTRACT

This work presents a mathematical model to simulate the extraction process of soluble protein from *sábalo* (*Prochilodus platensis*) during the surimi elaboration. The mathematical model consists of both partial differential and algebraic equations. Central finite difference method and the explicit scheme were applied to discretize the partial differential equation. The resulting model was implemented into the optimization environment General Algebraic Modeling System (GAMS). Experimental data obtained from laboratory scale using *sábalo* as raw material, was used to verify the output results of the proposed model. A good agreement between experimental and simulated extraction yields was obtained ($R^2 = 0.9552$). Once validated, the model was used to investigate the influence of several parameters such as, particle's diameter, volume fraction of the solvent, residence time and agitation velocity on the extraction efficiency. The results are presented and discussed through different case studies.

1. Introduction

The possibility of using Argentinian freshwater species of fishes as raw materials in the elaboration of surimi has been previously addressed (Medina, 2000; Medina and Garrote, 2002; Medina et al., 2010). More precisely, *surubí* (*Pseudoplatystoma coruscans*) and *sábalo* (*Prochilodus platensis*) fish species have been studied.

Specifically, *sábalo* is the most abundant fishery resource in the Argentine lower Río de la Plata basin. Surimi technology presents advisable advantages for the marketing and operation of food products based on proteins from *sábalo*, which is a fish resource only exploited for freshly consume.

Most advances related to surimi technology deal with marine or low fat content fish species of lesser commercial value (Suzuki, 1981; Mireles De Witt and Morrisey, 2002; Karthikeyan et al., 2004; Ohkuma et al., 2008; Sánchez-González et al., 2008). Hence, processing fatty fish species for surimi manufacture faces many challenges, for example: high oil content, intense odor, darker flesh and faster deterioration rate. Anyway, researchers as (Tokunaga and Nishioka, 1988; Nishioka and Tokunaga, 1990) have achieved important improvements in processing technology of fatty species, attaining surimi with excellent functional properties, which is a good prospect for this research area.

Myofibrillar proteins have functional properties, such as emulsifying properties, gel-forming ability and water holding capacity (Ohkuma et al., 2008). Generally, fish myofibrillar protein is thermally and chemically less stable than chicken or mammal proteins (Lanier, 1986). The gelling process involves the association of myofibrillar protein chains which produces a continuous three-dimensional network in which water and other components are ensnared (Sánchez-González et al., 2008). Sarcoplasmic proteins have an adverse effect on the gel formation by interference in myosin cross-linking during gel matrix formation (Suzuki, 1981). Hence, the washing process is a fundamental step to remove sarcoplasmic protein fractions which have the characteristic of being soluble in water or soluble in low ionic strength solutions (Wahyuni et al., 1998). Also, this stage is more critical when fatty fish species are processed, either marine or freshwater, which entails a thorough wash treatment.

The surimi process starts from holding fish, sorting by size and cleaning. After that, process stages for meat separating are achieved, which are heading and gutting by mechanical fish meat separators, a preliminary washing to remove the blood and adherent particles and then, deboning and mincing.

The cyclic washing and rinsing processes of the minced fish, which is also called leaching process are the central stage. The objective of this process stage is to remove soluble compounds

* Corresponding author at: CAIMI – UTN, FRRo – Universidad Tecnológica Nacional, Facultad Regional Rosario, Zeballos 1346, S2000BQA Rosario, Argentina. Tel.: +54 341 4480102.
E-mail address: mareinheimer@santafe-conicet.gov.ar (M.A. Reinheimer).

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Nomenclature

a	specific surface for mass transfer (m^2/m^3)
c	protein concentration (mg/ml)
C_D	friction coefficient
D_p	particle's diameter (m)
$D_{\beta\gamma}$	mass diffusivity (m^2/s)
i	spatial node index
j	temporal node index
J_D	Chilton and Colburn factor
k_c	global mass transfer coefficient (m/s)
K	distribution constant
M_w	molecular weight (kDa)
M	number of radial discretization points
N	number of temporal discretization points
R	sample radius (m)
r	variable radius (m)
T	temperature (°C)
t	time (s)
Δt	temporal grid with (s)
v	agitation velocity (m/s)
V_γ	volume of the solvent phase (m^3)
V_β	volume of the minced fish (m^3)
Y	percentage of extraction (%)

Dimensionless groups

Re	Reynolds's number
Sc	Schmidt's number

Greek symbols

ε	volume fraction of solvent
δ	spatial grid with (m)
ρ	density (kg/m^3)
μ	viscosity ($N\,s/m^2$)
θ	residence time (s)

Subscripts

0	at initial
c	cycle
i	at interface
β	minced fish
γ	solvent phase
EP	from the removable proteins
f	at final time
p	particle
T	from total proteins

resulting in concentrated myofibrillar proteins, which mainly contribute to gel formation (Suzuki, 1981; Benjakul et al., 2003).

The leaching process is achieved in three stages. Each stage is formed by a leaching tank, *LTK*, and rotary sieve, *RS*, at the industrial scale (Fig. 1). In this work, the same leaching tank is sequentially used at the laboratory scale to validate the model. In the first two of these cycles distilled water is used as washing stream, and in the last cycle NaCl solution at 0.2% is used.

In this work, a mathematical model is proposed in order to investigate the influence of several operating variables on the washing efficiency, during the elaboration of surimi made from *sábalo*. The following are the main operating variables to be studied: water: mince ratio, temperature, time, number of cycles, and agitation velocity. Also, based on experimental data obtained from laboratory scale, mass transfer coefficients and the distribution constant will be studied.

2. Process modeling

In this section the study of the washing stage in three leaching cycles, which is sketched in Fig. 1, will be presented.

In the proposed mathematical model, the contents of soluble and crude protein in the minced fish and the washing solutions in each cycle, respectively, are defined as parameters in order to follow the evolution of the unit operation. The mass transfer process will be studied at micro (minced particles) and macro (washing equipment) levels to determine protein concentration profiles and mass transfer coefficients of the leaching process.

Each cycle, c, in the washing stage is modeled as solid–liquid extraction of sarcoplasmic proteins within fish meat spheres of known diameter, D_p, coming from the mincing process stage. Soluble proteins are transferred from the solid matrix of each sphere to the bulk phase of the washing solution.

The phenomenon involved by the extraction process is quite complex and several possible mechanisms of mass transfer for food materials have been proposed in the literature in order to model the extraction process (Aguilera and Stanley, 1999). Basically, the following phenomenological steps are considered:

- Entrance of the solvent into the solid matrix.
- Solvent penetration and diffusion inside the solid matrix.
- Solubilization of the soluble compound.
- Transport of the solute to the exterior of the solid matrix by diffusion.
- Migration of the extracted solute from the external surface of the solid into the bulk solution.

The following assumptions are used to derive the mathematical model:

- Soluble proteins diffuse to the surface of each sphere according to Fick's second law
- Model 1-D. Temporal variations of the concentration in the radial direction are contemplated.
- Spherical particles do not change of size and shape during the leaching process.
- The external surface of each sphere is supposed to be surrounded by the extracting solvent.
- Perfect mixture.
- Only the soluble proteins diffuse from the minced fish to the surface. Then, sarcoplasmic proteins are transferred by convection in the interface spheres-solvent.
- Soluble proteins' concentration is homogeneous at the solvent phase.

Based on the above assumptions, the following mathematical model is developed:

$$\frac{(1-\varepsilon_c)}{D_{\beta\gamma}}\frac{\partial c_{\beta,c}(r,t)}{\partial t} = (1-\varepsilon_c)\cdot\frac{\partial^2 c_{\beta,c}(r,t)}{\partial r^2} + \frac{2\cdot(1-\varepsilon_c)}{r}\frac{\partial c_{\beta,c}(r,t)}{\partial r}, \quad 0 < r < R \tag{1}$$

$$c_{\beta,c}(r,t) = \langle c_{\beta 0}\rangle_c, \quad t = 0, \quad \forall\, 0 \leqslant r \leqslant R \tag{2}$$

$$\frac{\partial c_{\beta,c}(r,t)}{\partial r} = 0 \quad r = 0, \quad \forall t > 0 \tag{3}$$