**Scientific Note**

# Fuzzy system in a ferrous sulfate pre-treatment of elephant grass[1]

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## ABSTRACT

Renewable energies have been occupying more and more space in energy matrices worldwide, and lignocellulosic biomasses are promising for these energy sources. This study aimed to develop a fuzzy model to optimize the ferrous sulfate concentration and temperature in the pre-treatment of elephant grass. Five concentrations (10, 15, 20, 25 and 30 mM) and three temperatures (25, 40 and 55 ºC) were used as input. The application of the fuzzy model evidenced that the best results for cellulose exposure (53.1 %) were achieved by using a ferrous sulfate concentration between 20 and 22.5 mM and temperature between 39.5 and 42.5 ºC.

KEYWORDS: *Pennisetum purpureum* Schum., cellulose, mathematical modeling.

## RESUMO

Sistema *fuzzy* em pré-tratamento de capim-elefante com sulfato ferroso

As energias renováveis vêm ocupando cada vez mais espaço nas matrizes energéticas mundiais, e as biomassas lignocelulósicas são promissoras para essas fontes de energia. Objetivou-se desenvolver um modelo *fuzzy* para otimizar a concentração de sulfato ferroso e temperatura no pré-tratamento de capim-elefante. Foram utilizadas como entrada cinco concentrações (10; 15; 20; 25; e 30 mM) e três temperaturas (25; 40; e 55 ºC). A aplicação do modelo *fuzzy* evidenciou que os melhores resultados para a exposição à celulose (53,1 %) foram alcançados utilizando-se concentração de sulfato ferroso entre 20 e 22,5 mM e temperatura entre 39,5 e 42,5 ºC.

PALAVRAS-CHAVE: *Pennisetum purpureum* Schum., celulose, modelagem matemática.

In 2018, the United Nations presented to the world 17 goals of sustainable development, focusing on energy efficiency and energy production from renewable sources (Godinho & Caneppele 2021).

A primary source that is drawing attention worldwide, especially in Brazil, is biomass (Godinho et al. 2021a). This source may come from different sectors, such as agriculture with corn straw, soybean stalks and elephant grass, among others (Godinho & Caneppele 2021). For the livestock sector, it comes from animal waste, and, in agribusiness, mainly from material that is not used in the primary process, such as cassava waste, in addition to urban waste and construction materials (Godinho 2018).

Like any plant, biomass has a complex structure called lignocellulosic system, consisting of cellulose, hemicellulose and lignin (Godinho et al. 2021b). Biomass has several benefits for the production of renewable energy, such as biogas, biochar, bio-oil, bioethanol and electricity from thermoelectric plants (Caneppele et al. 2020). However, for this biomass to be used as a raw material, it needs to go through some processes such as pre-treatment (Xu et al. 2016). According to Godinho et al. (2019), pre-treatment is an industrial process that aims to break down lignin and increase cellulose exposure to enzymes and microorganisms, thus making the process economically viable.

A pre-treatment is effective when it avoids the size reduction of biomass particles, limiting the formation of degrading products that can inhibit the growth of fermentative microorganisms, ultimately minimizing energy demand (He et al. 2015). However, for the pre-treatment process to be effective, it is essential that the production chain is supported by optimization and the development of more favorable conditions for the production of a given material, thus reducing costs, time, analysis,

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etc. A model that meets this optimization is the fuzzy logic (Góes et al. 2020).

Fuzzy logic is a tool used for efficient and effective decision-making, resulting in more precise actions that may contribute to the advancement of a process or academic research (Putti et al. 2017). Godoy et al. (2020) state that the fuzzy logic works with linguistic data, transforming real values into uncertainty data such as "if it rains, the temperature can fall quickly".

Given the versatility presented by this computational mathematical tool, the present study aimed to develop a fuzzy model to optimize the best ferrous sulfate concentration and temperature for the pre-treatment of elephant grass, in order to reach a greater cellulose exposure in the plant cell.

The fuzzy model was elaborated based on real laboratory experimental data, in which the BRS Capiaçu elephant grass cultivar was used. The grass was planted in July, with harvest occurring in December of the same year (2019). There was no need to apply fertilizer in the area because the soil analysis proved that the conditions were satisfactory for the crop: $K = 1.06$ cmol$_c$ dm$^{-3}$; $Ca = 10.81$ cmol$_c$ dm$^{-3}$; $Mg = 2.10$ cmol$_c$ dm$^{-3}$; $P = 49.40$ mg dm$^{-3}$ (Mehlich-1 extractor); $Al = 0.2$ cmol$_c$ dm$^{-3}$; $H + Al = 3.71$ cmol$_c$ dm$^{-3}$; pH ($H_2O$) = 5.54; and base saturation = 76.06 %. The planting took place in the Brizantha farm (24º53'33.0"S, 54º01'52.0"W and 392 m of altitude), located in Marechal Cândido Rondon, Paraná state, Brazil. There was no application of any type of pesticide from planting to harvesting.

Figure 1 shows the rainfall and temperature data in the period from planting to harvesting of the elephant grass.

After six months, the elephant grass was harvested manually with a sickle and taken to the laboratory. The biomass was pre-treated with ferrous sulfate ($FeSO_4.7H_2O$) at 5 concentrations (10, 15, 20, 25 and 30 mM) and 3 temperatures (25, 40 and 55 ºC). A factorial experimental design was used in triplicate to quantify the percentage of cellulose and lignin in the biomass (Godinho 2018).

The modeling sought to analyze the effects on the cellulose variable, using the same data from the aforementioned field experiment. In this way, a fuzzy set was formed for each variable, being called membership function. Thus, the input variables were defined as concentration (mM) and temperature (ºC). Table 1 lists the ranges allowed for these variables, represented by triangular membership curves (Figures 2 and 3).

The membership curves of the output variable were developed based on real laboratory research by Godinho et al. (2019). Thereby, a fuzzy membership function set was developed to obtain a greater exposure of cellulose in the biomass cell, in percentage. Cellulose was classified according to the following ranges: 47.5-51.25 %; 49.38-53.12 %; and 51.25-55.00 % (Table 2 and Figure 4).

The intervals adopted for the input [temperature (ºC) and contraction (mM)] and output [cellulose (%)] variables were characterized by triangular membership curves (Figures 2, 3 and 4), which,
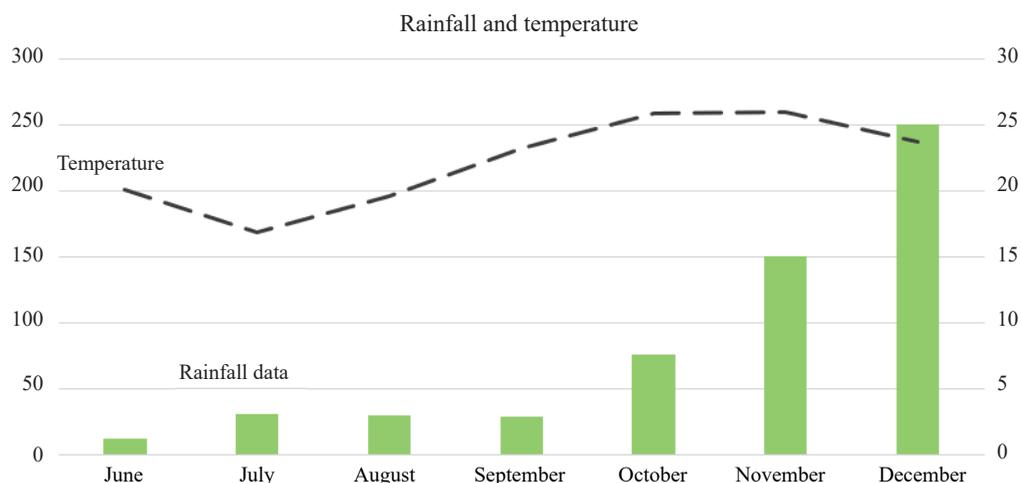


Figure 1. Rainfall (mm) and temperature (ºC) data from planting to harvesting of the elephant grass (Marechal Cândido Rondon, Paraná state, Brazil, 2019).

Table 1. Fuzzy sets for the input variables.

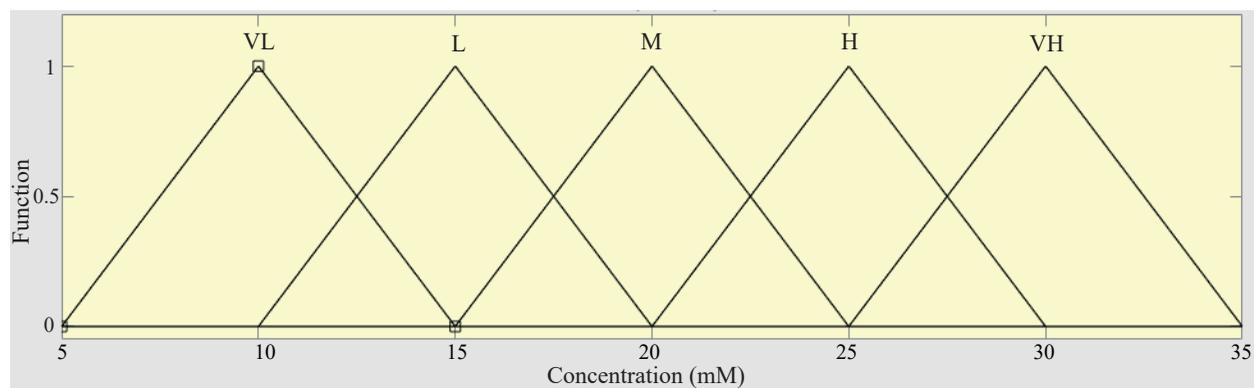| Concentration (mM) | | | | | Temperature (ºC) | | |
|---|---|---|---|---|---|---|---|
| 10 | 15 | 20 | 25 | 30 | 20 | 40 | 55 |
| [5 10 15] | [10 15 20] | [15 20 25] | [20 25 30] | [25 30 35] | [25 32.5 40] | [32.5 40 47.5] | [40 47.5 55] |



Figure 2. Membership curves of the fuzzy logic input variable Concentration. VL: very low; L: low; M: medium; H: high; VH: very high.
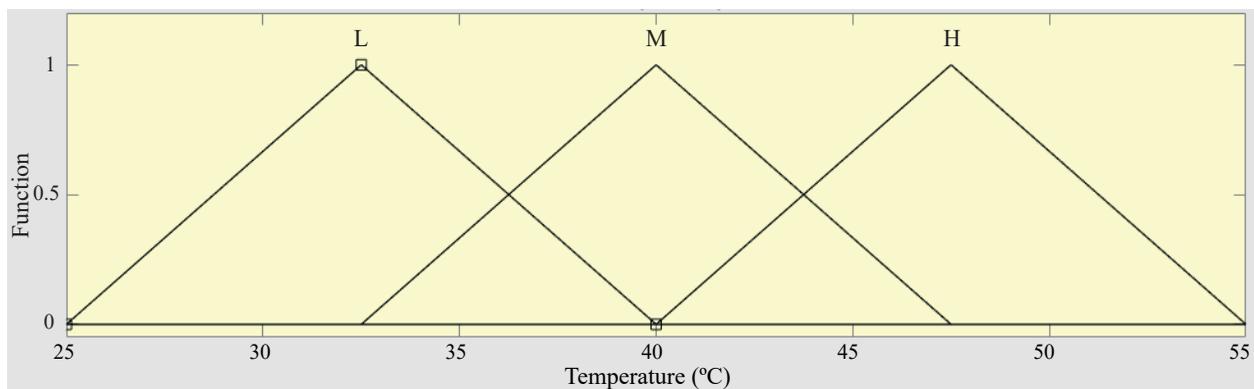


Figure 3. Membership curves of the fuzzy logic input variable Temperature. L: low; M: medium; H: high.
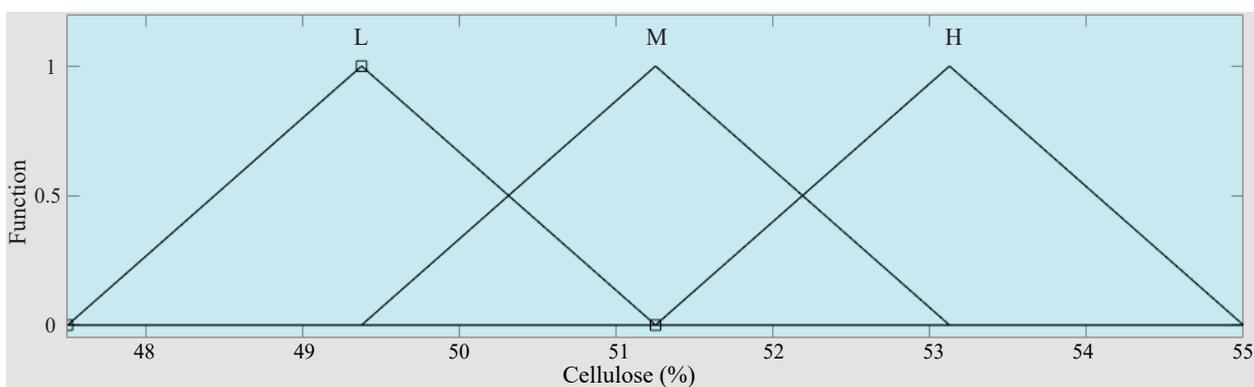


Figure 4. Membership curves of the fuzzy logic output variable Cellulose. L: low; M: medium; H: high.

Table 2. Fuzzy sets for the output variable.

| Cellulose (%) | | |
|---|---|---|
| 49.4 | 51.25 | 53.1 |
| [47.5 49.38 51.25] | [49.38 51.25 53.12] | [51.25 53.12 55.00] |

Table 3. Fuzzy inference rule system for the highest cellulose exposure (%).

| | Rule base |
|---|---|
| 1 | If C is 10 and T is 20, then Cel is 49.40 |
| 2 | If C is 10 and T is 40, then Cel is 51.25 |
| 3 | If C is 10 and T is 55, then Cel is 51.25 |
| 4 | If C is 15 and T is 20, then Cel is 49.40 |
| 5 | If C is 15 and T is 40, then Cel is 49.40 |
| 6 | If C is 15 and T is 55, then Cel is 51.25 |
| 7 | If C is 20 and T is 20, then Cel is 49.40 |
| 8 | If C is 20 and T is 40, then Cel is 53.10 |
| 9 | If C is 20 and T is 55, then Cel is 53.10 |
| 10 | If C is 25 and T is 20, then Cel is 49.40 |
| 11 | If C is 25 and T is 40, then Cel is 51.25 |
| 12 | If C is 25 and T is 55, then Cel is 51.25 |
| 13 | If C is 30 and T is 20, then Cel is 49.40 |
| 14 | If C is 30 and T is 40, then Cel is 49.40 |
| 15 | If C is 30 and T is 55, then Cel is 49.40 |

C: concentration (mM); T: temperature (ºC); Cel: cellulose (%).

according to Vias Neto et al. (2019), represent better the data set.

The Mamdani inference method, which proposes a binary fuzzy relation $M$ between $x$ and $u$ to mathematically model the rule base, was used. This method is based on a combination of input values by means of the minimum operator and then by the superposition rules by the maximum operator.

Table 3 presents the rule base, showing the combinations of fuzzy propositions presented in the if-and-then form. These combinations have been elaborated from information in Tables 1 and 2 and the use of real laboratory data. The base was composed by 15 direct rules.

The development of the fuzzy model made it possible to obtain a response surface showing the best ranges of concentration and temperature, resulting in a greater exposure of cellulose when using the ferrous sulfate pre-treatment of the elephant grass. The diffuse response surface model (Figure 5) was thus developed.

The developed model evidenced a correlation between the ferrous sulfate concentration and the temperature for a greater exposure of cellulose in biomass, with concentration of 20-22.5 mM and temperature of 39.5-42.5 ºC.

Godinho (2018) corroborates these results in a ferrous sulfate pre-treatment of elephant grass. By using a factorial $2^5$ experimental design, the author managed to improve the cellulose exposure by 20 %, in relation to its original chemical structure. In that study, the experiment resulted in 47 % of exposure in the plant cell at the central point (concentration of 23.5 mM and temperature of 40.5 ºC).
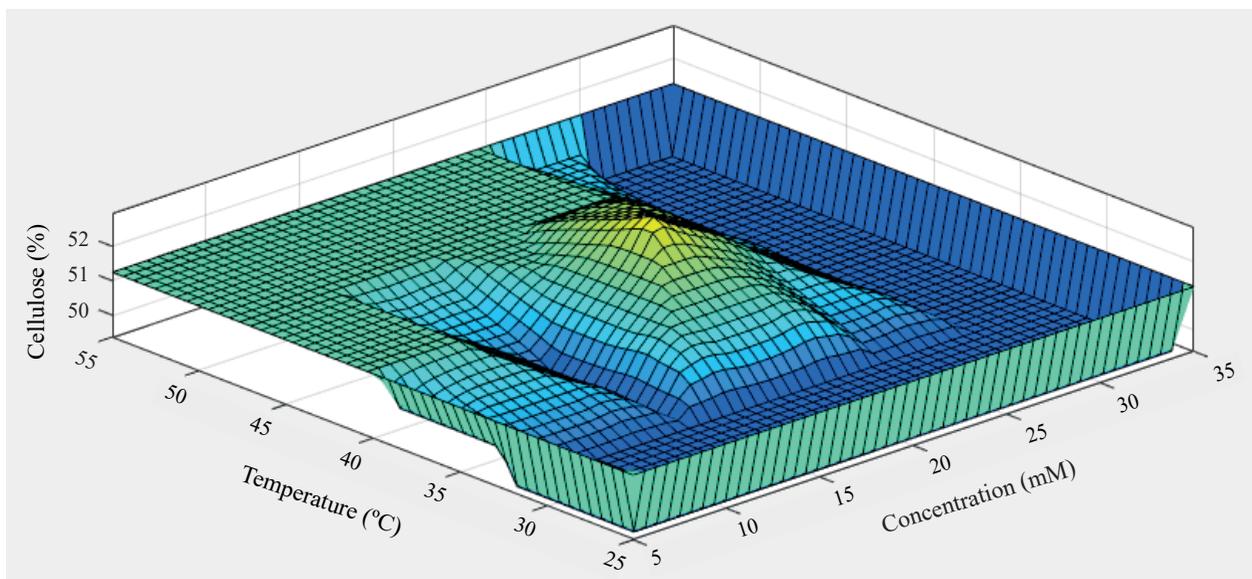


Figure 5. Three-dimensional surface model of cellulose response to the pre-treatment of the elephant grass.

Michalska et al. (2012) obtained a better average yield for the biomass of sorghum treated with ferrous sulfate (20.0 mM at 40 ºC), in relation to an untreated one, with an increase of 30 % in the cellulose exposure. This corroborates the results of the present experiment using the fuzzy logic.

Figure 6 shows the contour map produced after applying the rule bases developed by the fuzzy logic. The region B represents an unfavorable condition for a greater exposure of cellulose in biomass when applying the ferrous sulfate pre-treatment. On the other hand, region A consists of an area that presents a high response to the exposure of cellulose in the biomass for concentration and temperature close to the midpoints.

This point is within an intermediate condition, which is also considered for determining cellulose, yielding 53.1 %. The analysis of the degrees of association between input and output evidences that the point has a greater degree of relevance within the diffuse set (Figure 7).
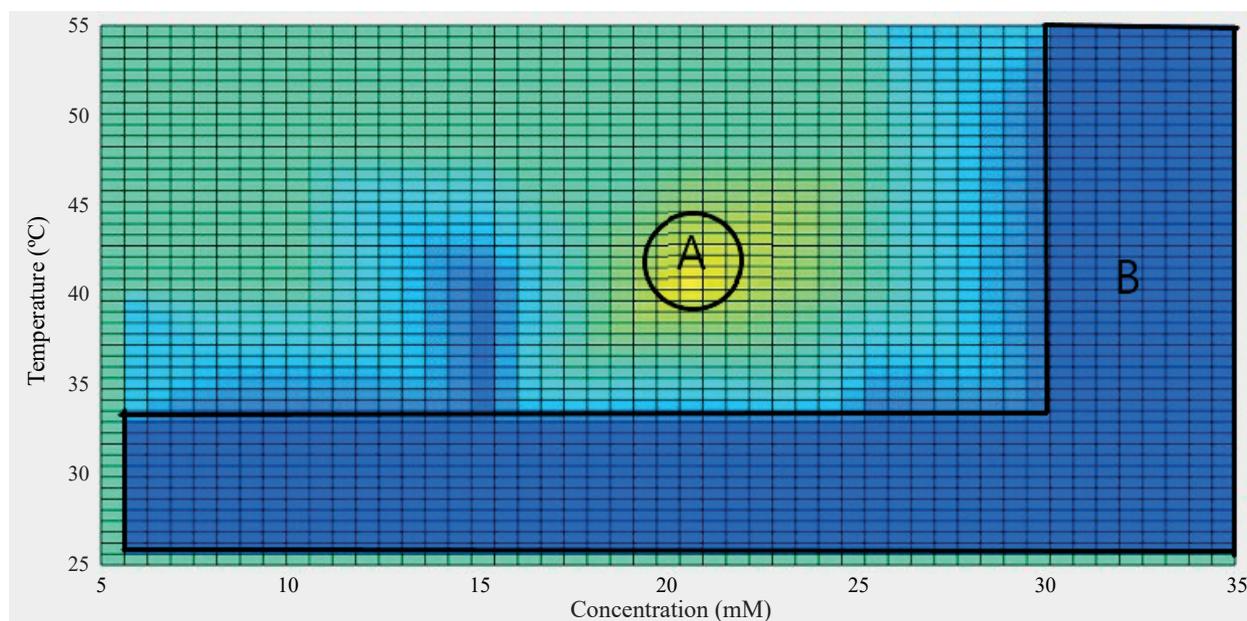


Figure 6. Response surface model of the percentage of the highest cellulose exposure, in a ferrous sulfate pre-treatment of elephant grass at different concentrations and temperatures. A: best result; B: unsatisfactory result.
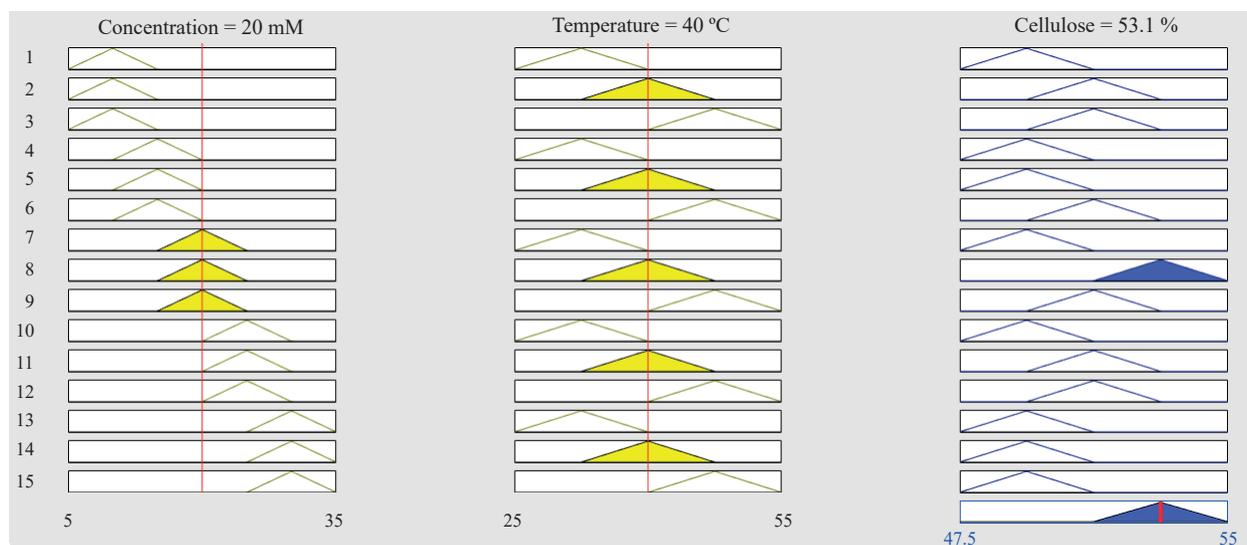


Figure 7. Mandani inference method for the use of the fuzzy logic in a ferrous sulfate pre-treatment of elephant grass.

Figure 7 shows the response of the Mandani inference method with the main points used for the concentration between 20 and 22.5 mM, with a greater accuracy at 20 mM, and temperature of 39.5-42.5 ºC, with a greater accuracy at 40 ºC, for a 53.1 % cellulose response.

These data corroborate that the specific concentration of 20 mM and temperature of 40 ºC in the Mandani inference method are considered ideal points for a greater efficacy in the exposure of cellulose in biomass (elephant grass).

The application of the fuzzy model evidenced that the best results for cellulose exposure (53.1 %) were achieved by using a ferrous sulfate concentration between 20 and 22.5 mM and temperature between 39.5 and 42.5 ºC.

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