DYNA
ISSN: 0012-7553
ISSN: 2346-2183
Universidad Nacional de Colombia

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DYNA, vol. 86, no. 209, 2019, April-June, pp. 188-197
Universidad Nacional de Colombia

DOI: https://doi.org/10.15446/dyna.v86n209.73585

Available in: https://www.redalyc.org/articulo.oa?id=49662418022

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Selection of a sustainable alternative for the reduction of chromium pollution in leather tanning wastewater

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Received: July 18th, 2018. Received in revised form: January 28th, 2019. Accepted: April 10th, 2019.

Abstract
Various solutions that have been proposed to address the contamination problem of leather tanning wastewater at El Cerrito (Valle del Cauca, Colombia) have generated conflicts between stakeholders. Therefore, with the purpose of selecting a sustainable alternative for the reduction in chromium present in liquid effluents of the local tanning sector, the Social Multi-Criteria Evaluation (SMCE) method was used to analyze three proposed treatment options. These consisted of a physicochemical treatment based on MgO precipitation and acid redissolution, a biotechnological treatment with native yeasts coupled to cleaner production (CP) and a nontreatment option. During the evaluation, the social, economic, environmental and technical criteria considered allowed the selection of the biotechnology alternative as the treatment option with the highest sustainability. The physicochemical alternative demonstrated low acceptance, while the nontreatment option proved unfeasible by affecting the natural environment and social component and was favored only by the economic criterion.

Keywords: bioremediation; *Candida fluviatilis*; cleaner production; social multicriteria evaluation; tanneries; *Yarrowia lipolytica.*

Selección de una alternativa sostenible para la reducción de la contaminación por cromo en aguas residuales de curtiembres

Resumen
Varias soluciones propuestas para abordar el problema de contaminación de las aguas residuales del curtido de pieles en El Cerrito (Valle del Cauca, Colombia) han generado conflictos de intereses entre las partes interesadas. Por lo tanto, con el objetivo de seleccionar una alternativa sostenible para la reducción del cromo presente en los efluentes líquidos del sector curtidor, se utilizó el método de Evaluación Multicriterio Social (EMCS) para analizar tres opciones de tratamiento. Estas consistieron en un tratamiento fisicoquímico basado en precipitación con MgO y redisolución ácida, un tratamiento biotecnologico con levaduras nativas acopladas a Producción Más Limpia (CP) y una opción sin tratamiento. Los criterios sociales, económicos, ambientales y técnicos, permitieron seleccionar la alternativa biotecnológica, como la opción con mayor sostenibilidad. La alternativa fisicoquímica demostró una baja aceptación, mientras que la opción sin-tratamiento resultó inviable, al afectar el entorno natural y el componente social, favorecida por el criterio económico.

Palabras clave: biorremediación; *Candida fluviatilis*; producción más limpia; Análisis multicriterio social; curtiembres; *Yarrowia lipolytica*.

1. Introduction

Tanneries are characterized as producing liquid effluents with high pollutant loads, which contain mainly organic matter, chromium, sulfur, solid wastes and volatile compounds [1]. Given that more than 80% of the pollution generated by tanneries comes from wet processes, the main objective in the majority of pollution control and prevention measures is reducing this load [2]. Although clean technologies for the tanning production process can be implemented, these will always generate effluents that need to be treated, either by recycling, reuse, or final disposal [3].

Within cleaner production practices, the recycling of tanning effluents containing high chromium loads is being promoted

How to cite: Benítez-Campo, N. and Peña-Salamanca, E.J.,Selection of a sustainable alternative for the reduction of chromium pollution in leather tanning wastewater. DYNA, 86(209), pp. 188-197, April - June, 2019.

through the method of precipitation with magnesium oxide (MgO) and posterior redissolution with sulfuric acid. The obtained residual baths are reused in the tanning of byproducts such as flesh splits [4]. Although this physicochemical option has the advantage of allowing recycling and the minimization of chromium loads in effluents, it has been shown to produce neutral salts and other contaminants [5]. In addition to the 4-5 days required for achieving complete treatment [6], the main limitation of this technology is the high cost of energy and chemical reagent consumption.

The high costs of physicochemical technologies are added to the low availability of economic resources of tanneries in developing countries, with Colombia among them. In this country, the tanning sector is represented by small and medium-sized enterprises [7] that, in most cases, discharge their liquid effluents into the sewage system or natural water sources without prior treatment [8]. Given this situation, the environmental agencies responsible for pollution control, such as the Autonomous Regional Corporation of Valle del Cauca (CVC) covering tanneries in El Cerrito, have demanded the implementation of wastewater treatment plants.

However, this has led to a conflict of interest between the social actors of tanneries in the El Cerrito municipality because of differences in the reactions towards the solutions proposed to address the contamination problem generated by this productive system. Tannery business owners do not consider physicochemical treatment feasible due to the costs of this technology, which has led them to apply no treatment and to end up dumping their effluents into the sewerage systems, where these leather tanning wastewaters are mixed with domestic wastewater [6].

In conflict of interest situations, the social multicriteria evaluation (SMCE) method may be useful for evaluating the different alternatives proposed. This is a versatile technique that has been used for decision-making when conflicts have arisen between competing values and interests and between the different groups and communities that represent them [9].

Gamboa and Munda [9] illustrated the use of this method to solve the problem of localizing a wind farm. Despite the good environmental image these alternative energy systems have, they generate opposition because of the land use they require, their possible effects on tourism, the visual impact or the extreme noise they generate, as well as the fact that few people will allow their proximity to their homes. Others are usually in favor of these farms because they perceive them as a possibility of development or simply as a source of income. In these situations, decision-making requires an ample dialog process between multiple social actors capable of ensuring the equitable participation of all of those involved.

The SMCE method has equally been used in studies about environmental sustainability where similar conflicts of interest to those studied in this research have existed. Sánchez *et al*. [10] reported the use of this methodology for identifying water resource management priority areas in the Sarapiqui River basin in Costa Rica. This method has also been used to analyze the expansion of potato and cattle productive systems in the paramo areas in Cundinamarca, Colombia, deeming both productive systems as unsustainable [11].

Based on the experiences described, the SMCE method was used in this study to simulate possible solution scenarios for the reduction of chromium present in leather tanning wastewater and, therefore, to select a sustainable alternative for the El Cerrito municipality tanneries, in Colombia.

2. Materials and methods

2.1. Study area

This study was conducted in the village of El Cerrito located in the Valle del Cauca department, Colombia, at a height of 987 masl, with an average temperature of 24°C and a population of approximately 57,463 inhabitants. The tannery sector is considered the third most important economic municipality, following the cultivation of sugar cane and livestock breeding [12,13].

2.2. Social Multicriteria Evaluation

2.2.1. Phase I: Institutional Analysis

The SMCE methodology consists of two phases, illustrated in Fig. 1. The first phase corresponds to institutional analysis, which is based on the historical, regulatory and social perception aspects related to the tanning environmental problem. For this, bibliographic revisions were carried out, and the social groups involved were identified and interviewed. These stakeholders were represented by employers, tannery workers and public officials whose work positions were at institutions related to the tanning sector such as the Municipal Health Secretariat, Municipal Planning, the Autonomous Regional Corporation of Valle del Cauca (CVC) and the Valle del Cauca Aqueduct and Sewage Society S.A. (ACUAVALLE S.A.). In a complementary manner, some members of the neighboring community were also identified, whom, because of their close proximity to the tanneries, could provide valuable information to the research.

For the collection of information, semi-structured interviews were specifically designed and carried out for each type of social actor. Business owners were asked about the productive, economic and perception aspects of the solution alternatives to the pollution problem and the implementation of environmental management programs, cleaner production (CP) practices and biotechnological methods.

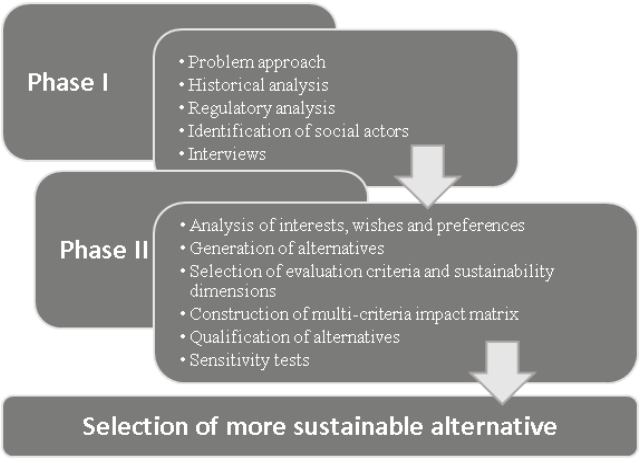

Figure 1. Scheme of the Social Multicriteria Evaluation method.
Source: The Authors.

Tannery workers were surveyed about their working conditions, their knowledge of the risks of Cr, and the implementation of environmental management and CP programs. In the case of public officials, the questions sought to identify their relationship with the tanneries and the most relevant aspects for tannery environmental improvement program implementation. Relative frequencies and measures of central tendency were calculated from the information. To analyze the relationship between some qualitative variables, Fisher's exact test was used. Statistical processing was performed using the R software version 3.2.2 (R Core Team, 2015) with a 5% significance level.

2.2.2. Phase II: Institutional Analysis

In the second phase, the information obtained in the first stage was analyzed by performing the multicriteria evaluation.

The first part of this analysis gave results concerning the interests, wishes and preferences of stakeholders about possible solutions known to them for chromium pollution reduction in the tanneries.

For the generation of alternatives, previous laboratory tests which demonstrated an efficiency of more than 95% in removing trivalent chromium from leather tanning wastewater using the native *Yarrowia lipolytica* and *Candida fluviatilis* yeast consortium were considered [14]. Based on the above multicriteria evaluation and laboratory results, experts were consulted, and possible solution alternatives were proposed.

Considering the three pillars of sustainable development, which seek to achieve balanced economic and social development along with environmental protection [15], these three dimensions (economic, social and environmental), along with the technical dimension, were selected for this evaluation. According to the dimensions defined, evaluation criteria for the alternatives under consideration were selected. The criteria corresponded to the technical attributes and social reality perception aspects obtained through interviews, conversations, and consultation with experts, which made it possible to define indicators that allowed the comparison between treatment options.

This step allowed for the construction of a multicriteria impact matrix, in which alternatives were interrelated with the scores given to the selected criteria.

A classification matrix of the alternatives under study was then constructed by applying a mathematical algorithm proposed by Munda and Russi [9] within the framework of the SMCE method that takes into account the "rule of Condorcet consistency", which consists of a matched comparison of all considered alternatives. In this sense, a concordance classification index is calculated, whose elements maintain the constant property of the sum. The pairs of selected criteria with concordance rates greater than 50% are selected. Given the transitive property, the final classification is determined. For better clarity, the rule of Condorcet consistency has the following properties:

Given a finite set of criteria, G = {gm}, m = 1.2, …, M, and a finite set of alternatives, A ={an}, n = 1.2, …, N, with respect to some evaluation criteria gm, based on an ordinal, interval or ratio measurement scale, the values with the highest scores are assumed to be preferred over the lowest (the best, the highest). Meaning:

$$\begin{aligned} \text{jPak} &\Leftrightarrow \text{gm(aj)} > \text{gm(ak)}, \\ \text{ajIak} &\Leftrightarrow \text{gm(aj)} \dagger = \text{gm} \end{aligned} \quad (1)$$

where, P and I indicate a relation between preference and indifference, respectively, and both meet the transitive property (if aiPak and aiPaj then aiPaj).

The weights of the criteria are calculated as:

$$\begin{gathered} \text{W} = \{\text{wm}\}, \text{m} = 1, 2, \ldots, \text{M} = \pi r^2, \text{with:} \\ \sum_{\text{m}=1}^{\text{M}} \text{Wm} = 1 \end{gathered} \quad (2)$$

which correspond to the coefficients of importance. The obtained information provides a rating of the relation between each pair of alternatives and of all the alternatives, depending on the preference or indifference. This process of mathematical aggregation can be divided into two main steps: (a) a comparison between pairs of alternatives according to the set of criteria used and (b) a classification of the alternatives in a complete preorder.

An *N x N* matrix, called evaluation matrix E, is constructed (Arrow and Raynaud; 1986; Roy, 1996), as cited by [9]. Any generic element of E -- ejk, ≠ k, is the result of the comparison by pairs according to all the M criteria among the alternatives j and k. Thus, the pair comparison is obtained by means of equation (3)

$$ejk = \sum_{m=1}^{M} \left(w_m \, \text{P}jk + \frac{1}{2} w_m \, \text{I}jk \right) \quad (3)$$

where WmIjk and WmPjk are the weights of the criteria that have a preference (P) and indifference (I) relation, respectively. In addition, clearly:

$$ejk + ekj = 1 \quad (4)$$

A sensitivity test is carried out by calculating the maximum likelihood scores of the alternatives, which correspond to the classification of the total number of pair comparisons of criteria summed from all the pairs of the alternatives considered. Formally, all comparisons N(N - 1) make up the evaluation matrix E. R is called to the set of all possible N! of the alternatives that make up the matrix, R = {rs}, 1, 2, …, N!. For each rs, the corresponding score φs is calculated as the sum of ejk's overall pairs j, k of the alternatives $\binom{N}{2}$. This is:

$$\varphi\text{s} = \sum ejk, \quad (5)$$

where: j ≠ k, s = 1, 2, …, N! and ejk ε Rs.

The final classification (r*) is given by the maximum value calculated from equation (5), that is:

$$\text{r}^* \Leftrightarrow \varphi^* = \max \sum ejk, \text{ where } ejk \, \epsilon \, R$$

Finally, a sensibility test was performed to compare the evaluated alternatives and determine what alternative met the criteria of sustainability. This was achieved by applying the same

coefficient of weight to the environmental, economic, social and technical dimensions previously defined to balance the maximum classification matrix.

3. Results

3.1. Institutional Analysis

The first tanneries in the El Cerrito municipality were founded in 1968 because of its strategic location at the edge of the El Cerrito river and near the existing railroad. This allowed the tannery sector to increase its production capacity and technology and to have a positive impact on the local economy during the following decades. However, at the beginning of the 2000s, the (CVC) environmental agency began to demand that tanners in the municipality of El Cerrito implement water pollution control systems. As a response to this demand, some business owners built wastewater treatment plants (WWTP) through significant financial investment. Due to these changes, today, 25% of the tanneries are found to have a complete WWTP infrastructure composed of pipelines separating liming, tanning and retanning effluents, tanks for sulfide oxidation, chromium bath recollection, homogenization and precipitation and sludge dehydration and sludge drying beds. Another 50% present an incomplete system composed of wastewater collection tanks and components for physicochemical treatment but without units for the recycling of chromium, while the remaining 25% have an incipient system consisting only of grease and solid waste traps [16].

In addition to the treatment of tannery effluents, authorities have also promoted contamination prevention programs. Towards the year 2003, the Regional Center for Cleaner Production (RCCP) ascribed to the CVC started a project for the implementation of a CP program that counted the active participation of El Cerrito tanneries of that time. In this sense, the Cinara Institute, the RCCP, the Corporation for the Productive Development of Leather, Footwear and Fine Leather Goods, together with the El Cerrito businesses, participated in a project that linked CP with competitiveness, with the aim of strengthening the leather sector at the national and international levels. With this effort, some improvements to the environmental performance of Valle del Cauca tanneries were made [17-19]. However, although the principles of pollution prevention were able to successfully be disseminated to some business owners through the concept of CP [17], at the present time, the problem continues to be latent, and efforts have been shown to be insufficient. The CP and environmental management programs have not had continuity in microenterprises over time.

Currently, the tanneries of El Cerrito are composed of a medium-size enterprise and 12 microenterprises. The medium-sized enterprise, called Curtipieles S.A.S., holds an infrastructure composed of 25-30 pieces of equipment, 70-75 pieces of machinery with modern technology (some imported), and a complete WWTP and has a workforce of 120 to 150 employees that lead to a current production of approximately 8000 skins/month (with a maximum production capacity of 16000 skins/month, depending on the market demand). Workers at Curtipieles make up 70% of the jobs in El Cerrito tanneries, are affiliated with health, pension and labor risks institutions, and are occasionally sent to train abroad.

In comparison, the microenterprises are characterized by having low-quality infrastructure made up of 1-7 pieces of obsolete equipment and 0-9 pieces of low-tech machinery, incomplete or incipient WWT systems and a production of less than 1000 skins/month in 58% of the cases. Although these companies hire between one to ten workers, the employment at the microenterprises is also of low quality when comparing their working conditions (contract duration, working hours, workday, social security, industrial security and training) to those of the medium-sized enterprise ($p=0.0147$). Working hours exceed 10 h/day ($p=0.01471$), and workers have little or no supply of industrial safety implements ($p=0.0037$) [16]). Moreover, very few of these companies affiliate their workers with health, pension and labor risks institutions.

Furthermore, the El Cerrito tannery sector is also composed of approximately 45 informal tanneries that possess very low capital, which is why they perform the tanning process by renting the facilities of other tanneries and hiring workers for work to be done, thus establishing an informal relationship with their workers [16]. The social groups that were interviewed replied differentially when asked about their perception of decontamination solution options for tanneries (Table 1). Business owners expressed being concerned about the high treatment costs, the complexity of the technology and the long periods of time required for the implementation of chromium-recycling physicochemical methods. They noted that this affects their product profitability and competitiveness when compared to companies that do not perform this treatment.

Tannery workers and the neighboring community highlighted the importance of preserving jobs at the tanneries, given that they are the source of income for several members of the community who have dedicated their lives to this trade of long history and tradition. This was stated although workers recognize that tanneries contribute to the deterioration of the air and water quality, a situation that has affected the cultural and landscape activities that used to be carried out in the past around the El Cerrito River.

These positions trigger a confrontation with the environmental authority (CVC), which must enforce the regulation that guarantees “the right of all people to enjoy a healthy environment and to plan for the management and exploitation of natural resources… having to prevent and control the factors of environmental deterioration, impose legal sanctions and demand repairs for the damages caused", in compliance with decree 3930 of 2010 [20].

Table 1.
Social actors involved and their interests in relation with the tanneries.

Actors Involved	Interests that emerge from the analysis
CVC Environmental Authority	Prevent and control water pollution according to current regulations
Business owners	Economic profitability and technological efficiency
Workers	Maintain employment
Tannery neighbors	Keep employment for people

Source: The Authors.

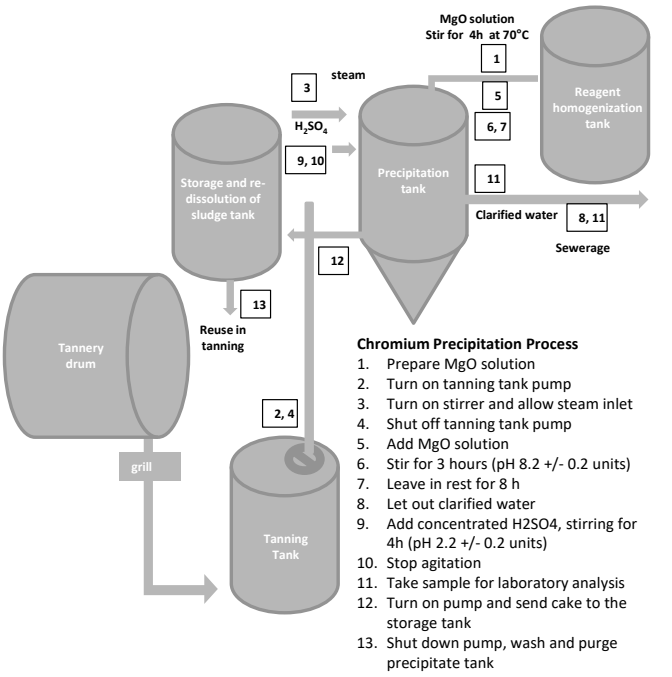

Figure 2. Diagram that summarizes the operation of the physicochemical alternative.
Source: The Authors.

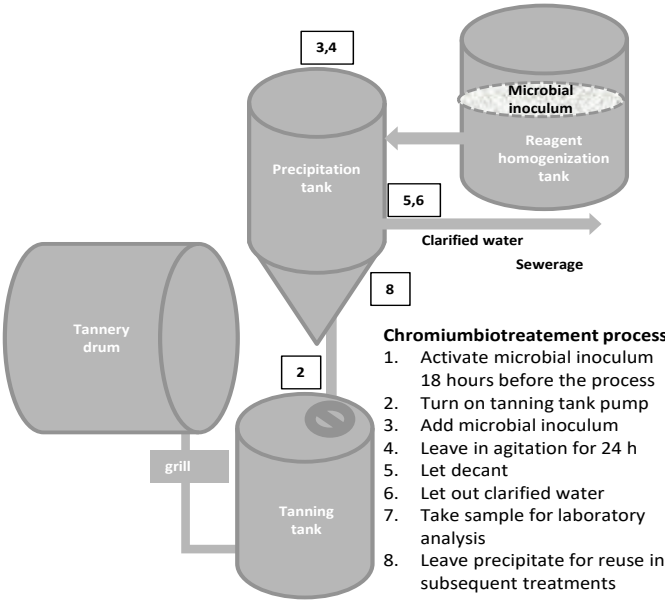

Figure 3. Diagram that summarizes the operation of the biotechnological alternative.
Source: The Authors.

3.2. Generation of alternatives

Three possible alternatives for reducing the pollution caused by chromium in El Cerrito tanneries were selected. The first was the physicochemical alternative, which consists of precipitating the metal through the application of MgO, which generates the so-called "cake" (a semisolid material that contains chromium precipitate). An acid redissolution is then performed, through which lower-chromium concentration baths are obtained, which in turn can be reused in the tanning of subproducts such as flesh splits but not in the production of leather [4]. This requires 4 to 5 days of operation and a high consumption of chemical inputs and energy for the generation of the steam and heat necessary to carry out this process [6]. Fig. 2 summarizes the operation of this alternative, which corresponds to the proposal made by the environmental agency based on the recycling of chromium liquors according to CP practices [21].

The second scenario corresponds to the biotechnological alternative, an option that requires the reduction of raw material consumption without affecting the efficiency of the tanning process while reducing chromium pollutant loads. This alternative is based on the experience of the medium sized-company Curtipieles S.A.S., which has succeeded in lowering its chromium sulphate consumption from 7.0% to 4.8% while preserving its leather quality and obtaining a total chromium effluent concentration of approximately 28.3 mg Cr/L [16]. This low chromium concentration does not allow the use of the physicochemical method of precipitation with MgO and acid redissolution, given that it does not produce the so-called "cake". The biotechnological alternative, on the contrary, is able to further reduce this concentration in such a way that it can reach the maximum allowable limit value (MALV), corresponding to 1.5 mg Cr/L according to the waste dumping regulation in Colombia [22].

In fact, the chromium concentration of the effluent to be treated can be approximately 1000 mg Cr/L, according to tests conducted for the consortium composed of native yeasts *Yarrowia lypolitica* and *Candida fluviatilis* [unpublished dates [14]. Another advantage of this method is that the selected yeast consortium acts naturally at acid pH, which reduces operational costs. In laboratory trials, this consortium has demonstrated the ability to remove trivalent chromium, in addition to offering the advantage of increasing the typically acid pH of tanning waters, reaching a final pH of 5.8 after the process of Cr(III) removal [14].

With regard to temperature, the optimal value for these microorganisms was established as between 23-30°C, a temperature range which matches El Cerrito municipality's environmental conditions [12], which is the reason why the process can be carried out at room temperature.

Furthermore, the presence of organic matter in tannery waters (coming from leather) guarantees the existence of electron donors that are necessary for the metabolic processes carried out by the inoculum composed of the consortium of *Yarrowia lipolytica* and *Candida fluviatilis.* The operation of the biotechnological alternative is summarized in Fig. 3.

The third option is the nontreatment alternative, which consists of carrying out screening of wastewaters by means of grids and grease traps for subsequent discharge into sewers. This corresponds to the present situation of the majority of El Cerrito microenterprises.

3.3. Construction of the multicriteria impact matrix

In accordance with the wishes and preferences of the social actors, consultations with experts and the information obtained in laboratory trials, a multicriteria impact matrix

was constructed, considering the environmental, economic, social and technical dimensions (Table 2) and in accordance with the sustainable development guidelines [15].

Table 3 lists the criteria considered for each dimension. Each criterion was subjected to a qualification process to evaluate the different alternatives proposed.

Within the environmental dimension, the qualification assigned to the criterion of pollution control and prevention was related to the expectation of minimizing water contamination.

Table 2.
Multicriteria impact matrix.

Criteria	Unit	Alternatives		
		Physico-chemical	Biotech-nological	Without treatment
Pollution prevention and control	mg Cr/L	1.5	1.5	1800 - 3100
Effect on flora and fauna	linguistics	none	none	high
Operation and maintenance costs	$US	170	60	0
Risk to human health	linguistics	low	low	high
Number of new jobs	number	0.25	0.75	0
Time of operation	days	4 to 5	3 to 4	long
Efficiency of technology	Linguistic	regular	good	none

Source: The Authors.

Table 3.
Dimensions and criteria considered.

Dimension	Criteria	Needs or expectations	Criterion scores
Environmental	Pollution prevention and control	Minimize chromium pollution	Criteria: VLMP Unit: 1.5 mgCr/L Direction: Minimize
	Effect on fauna and flora	No effects on the fauna and flora	Criteria: Quality Unit: Linguistics Direction: Minimize
Economic	Operation and maintenance costs	Low cost	Criteria: Cost Unit: $US Direction: Minimize
	Risk to human health	No effect on human health	Criteria: Quality Unit: Linguistics Direction: Minimize
Social	Number of new jobs	Reactivate the economy	Criteria: How many jobs Unit: Number Direction: Maximize
Technical	Time of operation	Short duration	Criteria: Time Unit: Days Direction: Minimize
	Efficiency of technology	Decrease chromium pollution	Criteria: Quality Unit: Linguistics Direction: Maximize

Source: The Authors.

Table 4.
Physicochemical analysis of wastewater from three El Cerrito tanneries.

Parameter	Units	WWT. 1	WWT. 2	WWT. 3	*MPLV
Temperature	°C	24.7	28.8	37.1	<40
pH	Units	**5.5**	**4.0**	**3.9**	6-9
BOD5	$mgO_{2/L}$	478.0	**1361.0**	**2725.0**	600
OD	mgO2/L	-	0.7	3.3	
COD	$mgO_{2/L}$	**4443.0**	**3229.0**	**8611.0**	1200
TSS	mg/L	104.0	220.0	**2035.0**	600
Chromium (as total)	mg/L	**3084.0**	**1470.9**	**1067.2**	1.5
Chromium (as CrVI)	mg/L	**1.0**	<0.05	<0.05	0.2

*Maximum permissible limit value for discharges of nondomestic wastewater to superficial waters and to public sewerage systems for the manufacture of leather articles, tanning and pickling of hides [22]. WWT. Wastewater tannery. Bold parameters are outside the norm.

Source: The Authors.

According to regulations, the minimum chromium concentration in the effluents corresponds to 1.5 mg/L [22], a value that is expected to be reached by both the physicochemical and biotechnological methods.

For the alternative without treatment, this value was established as within the range of 1800 - 3100 mg Cr/L based on physicochemical test results performed at three tanneries in El Cerrito (Table 4).

The criterion of the effect on fauna and flora was qualified by considering the high values of chromium in effluents discharged directly into water sources and/or sewage systems and the way these concentrations can affect aquatic flora and fauna, as has been documented in chromium toxicity research [23-26]. For this reason, the alternative without treatment was classified as high-impact, while the other options received a classification of no effect on this criterion, because they can produce an effluent within the MALV.

With respect to the economic dimension, for the criterion of cost estimation of the technologies, operation and maintenance values were calculated, discarding investment costs for buildings, because the proposal intends to draw on the existing infrastructure. This is why the evaluation of alternatives was directed towards companies that have a complete or partial WWTP already built, which in the case of El Cerrito tanneries, corresponds to 75% of the companies. For this calculation, the prices of chemical inputs, workforce and electrical energy were taken into account.

Table 5 shows the estimated costs of operation and maintenance of the evaluated alternatives. This was calculated on the basis of a production of 6000 kg of skin, equivalent to 240 medium-sized units (average weight/skin = 25 kg), which generate 24000 L of chrome tanning residual water at a concentration of 0.20 g/L. Calculations were made based on information provided by officials from the El Cerrito tanneries. The experimental data obtained with the *Y. lipolytica* and *C. fluviatilis* yeast consortium, whose speed of removal was established at 0.0043 g $CrL^{-1}h^{-1}$ (unpublished data), was also considered.

Table 5.
Operation and maintenance costs of different alternatives.

Alternative	Skins produced (kg)	$US/2400 L of wastewater	Difference (%)
Physicochemical	6000	143.21	61.54
Biotechnology	6000	55.08	

Source: The Authors.

3.4. Classification of alternatives

The classification of the alternatives was carried out by applying the classification algorithm called the *Rule of Condorcet consistency,* according to the specifications provided by [27,28]. This is a method which allows the comprehensive analysis of the qualitative and quantitative data obtained and guarantees the consistency and transparency of the analysis. The maximum classification matrix presented in Table 6 was obtained after applying this algorithm.

Each of the values in Table 6 indicates the result of a comparison between pairs of alternatives. The physicochemical option was observed to exceed the biotechnological alternative by 0.2 points and the no-treatment option by 0.9 points (note that the rating goes from 0 to 1). The biotechnological option surpassed the physicochemical alternative by 0.8 points and the nontreatment by 0.9 points. The alternative without treatment was left out of the classification, as it is below the established threshold, corresponding to the preference given to values higher than 50% of the criteria.

When testing the maximum likelihood to adjust to the model (Table 7), the biotechnological alternative remained the preferred option, with the nontreatment option being the worst. This preference can be explained by the behavior of the evaluated criteria, given that the biotechnological alternative surpassed the physicochemical alternative in the criteria of operation and maintenance costs, jobs linked to the productive process and efficiency of the technology.

Table 6.
Outranking matrix.

	Physicochemical	Biotechnological	No treatment
Physicochemical	0	0.2	0.9
Biotechnological	0.8	0	0.9
No treatment	0.1	0.1	0

Source: The Authors.

Table 7.
Maximum likelihood ranking of alternatives.

Biotechnological	Physicochemical	No treatment	2.5
Physicochemical	Biotechnology	No treatment	1.9
Biotechnological	No treatment	Physicochemical	1.8
Physicochemical	No treatment	Biotechnology	1.2
No treatment	Biotechnology	Physicochemical	1.1
No treatment	Physicochemical	Biotechnology	0.5

Source: The Authors.

Until this step, all the criteria were given the same weight of importance, but not all dimensions had the same number of criteria. The environmental, social and technical dimensions are composed of two criteria, while the economic dimension comprises a single criterion. For this reason, it was necessary to carry out a sensitivity test by giving equal weight to all of the dimensions considered. The previous results were reaffirmed with this test, as the preferred option remained the biotechnological alternative, followed by the physicochemical alternative (Table 8). The difference from the nontreatment alternative slightly decreased, but its rating continued to be the lowest, given that the only criterion that favored it was the costs of operation and maintenance, and this option remained inconvenient from the social, environmental and technical dimensional points of view.

In Fig. 4, the comparative influence of all the criteria on the evaluated alternatives can be observed. Note that in the biotechnological option, the obtained score showed a balance between the economic, social, environmental and technical dimensions, indicating its sustainability. This option was followed by the physicochemical alternative, which presented the greatest difficulty in the economic indicator. For the nontreatment alternative, the economic approach was the only favorable dimension, as demonstrated by the displacement of the graph, which showed an imbalance between the criteria and, as a result, the terrible sustainability of this option.

Table 8.
Sensitivity analysis of alternatives.

Biotechnological	Physicochemical	No treatment	2.3
Physicochemical	Biotechnological	No treatment	1.7
Biotechnological	No treatment	Physicochemical	1.8
Physicochemical	No treatment	Biotechnological	1.2
No treatment	Biotechnological	Physicochemical	1.3
No treatment	Physicochemical	Biotechnology	0.7

Source: The Authors.

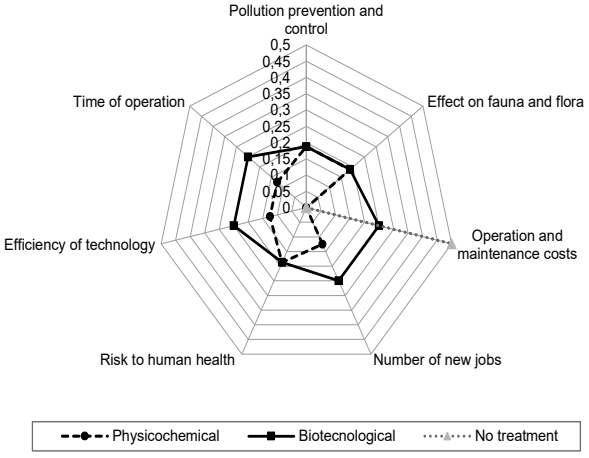

Figure 4.
Radial diagram that compares the three alternatives evaluated.
Source: The Authors.

4. Discussion

The obtained results confirmed that the nontreatment option is unsustainable because it only gives priority to the economic factor and leaves aside important aspects such as the social and the environmental factors by carrying out no intervention. The negative effects of this alternative are evident, and if continued in the same way, this situation can lead to magnification of the problem and to adverse consequences for the community, whose quality of life is threatened by the pollution of the natural environment, which affects their health and general well-being. In this same sense, workers expressed their discontent with the lack of preventive actions and intervention to solve the problem, noting the lack of actions to prevent the negative effects on their health and the absence of occupational safety and labor welfare programs in the microenterprises where they work. The threats to these companies' competitiveness will continue to grow because of the noncompliance with environmental regulations, which will translate into an inability to access international markets and a decrease in their acceptance in the national market in the present globalized world, which is becoming more demanding every day in terms of the care of the natural environment.

With regard to the physicochemical alternative, low sustainability was displayed, represented by the long operation times, low efficiency and, above all, high cost of the technology. The latter is a very negative aspect for the El Cerrito tanning sector, which is characterized by microenterprises that are not willing to use this technology because the large capital investments required to treat the effluent generated during their production process threaten their competitiveness, and, according to them, this would not generate any profitability [16].

The biotechnological alternative complemented with CP practices was selected as the most sustainable option, showing a balanced behavior between the different dimensions analyzed and including microbial bioremediation, which is recognized as environmentally friendly [29]. According to Ordóñez [14], the *Yarrowia lypolitica* and *Candida fluviatilis* consortium demonstrated efficiencies above 95% in the removal of trivalent chromium present in tanning effluents. This option demonstrated not only technical and environmental advantages but also social benefits by decreasing water contamination and providing the possibility of increasing the number of jobs generated to improve the treatment process efficiency. Not only does the cost of the technology decrease, but greater economic benefits can result by applying CP, with a focus on pollution prevention, better resources management and minimal production of pollutant wastes, since this alternative reduces the consumption of raw materials and produces effluents with low chromium concentrations that can be treated by biological methods [2,30].

Cleaner production considers the balance between social, economic and environmental issues in a comprehensive manner, relying on the definition of sustainable development [15]. In the case of the tanneries in Colombia, some emerging experiences have been reported by the Ministry of Environment and Territorial Development, such as the cases of the 'Curtigran' tannery and the 'Americana de curtidos' tannery [4], which have successfully implemented clean technology programs. These companies were able to reduce their environmental impact, improve employee working conditions and increase the productivity and quality of their products by introducing improvements based on an eco-efficiency program, thus demonstrating the benefits of the interaction between the productive process and the care for the natural environment. The new approach proposed in this paper, which complements CP practices with chromium bioremediation, is a novel one for the case of the tanneries in Colombia [30]. These methods can be replicated very well in other settings where a complex scenario predominates, characterized by elements that interact with the surrounding environment and flows of matter, energy, economic resources or information and influenced by regional, national and international policies, according to Garcia [31].

The multicriteria evaluation method used in this study made it possible to collect both qualitative and quantitative indicators, including the characteristics of the El Cerrito tanning sector, represented mainly by microenterprises, and the economic, environmental and technical issues, which were essential for the analysis of the different criteria and indicators used to qualify the evaluated alternatives. In this sense, Mahjouri *et al*. [32] highlighted the advantages of this method for decision-making in the implementation of wastewater treatment technologies in iron and steel industries, in which the topic was analyzed by a multidimensional approach that considered the specific sectors' characteristics and the interaction between social, environmental and technical aspects. Similarly, Rosen *et al*. [33] evaluated various alternatives for soil remediation and included social, economic and environmental indicators in their study, which enabled them to conclude that the method facilitates a comprehensive assessment of both the views of the stakeholders and experts, as well as the sustainability criteria, regardless of whether they are qualitative or quantitative.

From the practical point of view, there have been experiences that have responded very well to this approach. Such is the case of European tanneries, which have included ethical and social aspects accompanied by capital investment and have achieved efficiency in their processes and pollution control and prevention. It has been shown that the value given to social and environmental aspects keeps European tanneries at the forefront of international competition [34]. This approach has been gaining strength in developing countries, where this problem has begun to be studied based on the guidelines for sustainable development [21,35], which, in turn, have been the means of success in reducing the environmental impact, thanks to the integration of measures involving environmental, social and economic aspects.

This comprehensive approach also matches the SWITCH UNAL's team vision [7,36], which, based on studies carried out in the tanneries of Villapinzón and Chocontá in Colombia, recognizes the benefits of the CP strategies. In these localities, biophysical, sociocultural and economic aspects were integrated in conjunction with legal aspects and interinstitutional management to achieve successful

implementation in complex problems, such as the one studied in this research.

5. Conclusions

The integral and balanced analysis used to evaluate the selected alternatives was an essential aspect in this study because the technical factors and the wishes and social interests (such as the expectations to maintain employment, reactivate the economy, and reduce water pollution and the costs of the technology) were properties that were given the same weight in the analysis. These conditions made it possible to choose, based on a high degree of reliability, the biotechnological alternative complemented with CP practices as that with the highest sustainability.

Finally, for models such as the one implemented in this research to be replicable, the commitment of all social actors involved is required, as is promoted by the policies of CP. This social involvement leads to the transformation of the business activity, implementing new practices such as the reduction of raw materials, water and energy consumption and the recycling of byproducts. These practices can be accompanied by bioremediation methods that are highly efficient, beneficial to the environment due to their low waste production and more economical than the physicochemical method, as has been demonstrated in this research.

Acknowledgments

This research was financially supported by internal calls to doctorate students in 2014-2015 at the University of Valle.

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