This is a post-peer-review, pre-copyedit version of an article published in Chemical Engineering Journal

December 2019

https://doi.org/10.1016/j.cej.2019.123696

LCA study of a new electrochemical and ultraviolet (EC-UV) combined system to decolourise and reuse textile saline effluents: Environmental evaluation and proposal to improve the production process

Maria-Dolores Alvarez, Valentina Buscio*, Víctor López-Grimau, Carmen Gutiérrez-Bouzán

Institute of Textile Research (INTEXTER), Universitat Politècnica de Catalunya-Barcelona Tech, Terrassa, Spain.

Corresponding author: Tel.: +34 93 739 82 60; fax: +34 93 739 82 72.

E-mail addresses: valentina.buscio-olivera@upc.edu

Abstract

In this work, the environmental performance of the reactive Jet dyeing process and the subsequent wastewater treatment currently carried out in the textile companies is compared with a new system. The developed system combines the application of an electrochemical process with ultraviolet irradiation (EC-UV) to remove colour of effluents containing reactive dyes. EC-UV system is also able to prepare the discoloured effluents for its subsequent reuse in a new dyeing process.

The developed system can operate in two modes: decolourisation and decolourisation plus reuse. This study compiles life cycle inventory data for both operation modes and compares their environmental impact with the conventional dyeing and wastewater treatment.

The results show that the EC-UV system, running in “decolourisation mode” (ED scenario), has a better environmental performance than conventional decolourisation (CD scenario), since the tertiary treatment is eliminated. The environmental assessment for CD and ED scenarios shows that the dyeing process has the largest contribution to all the impact categories, mainly caused by the consumption of Na_2CO_3 and NaCl. When EC-UV system is running to treat and reuse water and salt (EDR scenario), the reconstitution step process, necessary to reuse effluents, has a great contribution in most of the impact categories. Based on the obtained results, a modification in the dyeing process has also been evaluated. The proposed modification substitutes the use of Na_2CO_3 by NaOH in the dyeing process, causing a great environmental improvement in all the impact categories for the EDR scenario, being this scenario the one with better environmental performance.

Keywords: Life Cycle Assessment (LCA); Textile dyeing effluents; Saline effluents; Decolourisation; Electrochemical treatment; Water reuse

1. Introduction

The textile and clothing industry plays an important role in the global economy. However, it is considered one of the most polluting industrial sectors in the world mainly due to the use of high amount of water and chemicals, and the generation of waste [1,2].

According to Ellen MacArthur Foundation, 93 billion cubic metres of water are used annually in the production of textiles, of which 6.3 billion cubic metres are consumed in dyeing and finishing processes [3]. The discharge of high volume of wastewater characterized generally by high colouration must be also considered since the textile industry generates up to 20% of industrial wastewater worldwide [4]. It is important to highlight that the sales of textile products are expected to reach 160 million tonnes in 2050, therefore the negative environmental impact of the sector will also increase significantly [3].

In recent years, the interest of the textile industry in wastewater treatments for reuse purposes has increased in order to be more efficient in the use of natural resources and to reduce its environmental impact. Although conventional treatments such as biological and coagulation-flocculation processes are able to meet with the current regulations in terms of colour removal, they do not enable water reuse [5–8]. For this reason, the use of advanced oxidation processes (AOPs) either to replace or to combine with the current treatments has been studied [9–14].

Among the different AOPs, our research group has demonstrated the effectiveness of the indirect electro-oxidation assisted by UV irradiation (EC-UV) to treat effluents from the dyeing process with reactive dyes [15,16]. This kind of dyes requires the addition of high amount of salts to carry out the dyeing process. The salts already present in the effluents are used in the EC-UV treatment to generate oxidants able to degrade the dye molecules according to the equations (1) – (3) [17].

$$2Cl^- \rightarrow Cl_2 + 2e^- \quad (1)$$

$Cl_2 + H_2O \rightarrow HOCl + H^+ + Cl^-$ (2)

$HOCl \rightarrow H+ + OCl^-$ (3)

Consequently, the treatment is performed without adding any chemicals and no sludge is generated. The irradiation with UV light of effluents previously treated in the electrochemical cell allows to avoid the emission of chlorinated by-products [15, 16]. The EC-UV treatment was developed at industrial scale, optimized and installed in a Spanish textile mill. The EC-UV system achieves the complete colour removal and enables the reuse of 70% water and up to 72% salt in new dyeing processes [18].

In our previous work, Life Cycle Assessment (LCA) evidenced the clear environmental advantages of the new developed system. The environmental impact of the wastewater treatment plant was reduced up to 60% with respect to the current wastewater treatment applied in the selected textile mill [18]. This study was based on the environmental benefits provided by the EC-UV system for the treatment of the wastewater generated by all processes of the company. However, it is interesting to determine the effect not only on the wastewater treatment plant associated to the most coloured and problematic effluents but also on the dyeing process. In this work, LCA is used to evaluate the environmental benefits of applying the new industrial system versus the conventional dyeing and wastewater treatment currently performed in a textile company. Taking into account that the EC-UV system can be used in two modes (decolourisation or decolourisation plus reuse) both alternatives were evaluated in LCA study. The study compiles life cycle inventory data and compares the relative environmental performance of three scenarios: conventional decolourisation (CD), EC-UV for decolourisation (ED) and EC-UV for decolourisation plus reuse (EDR). Likewise, a modification in the dyeing process has been considered and assessed for all the studied scenarios.

The article is structured following the four basic phases of the life cycle assessment (LCA) methodology according to ISO 14040 [19] and ISO 14044 [20]: Goal and scope definition, Life cycle inventory and Life cycle impact assessment and interpretation.

2 Material and methods

2.1 EC-UV pilot plant description

The EC-UV system (Figure 1), fully automated, is able to treat $4m^3/h$. It is based on an indirect oxidation with active chlorine generated by means of an electrochemical treatment and assisted by UV irradiation.

The electrolytic cell is constituted by electrodes made of titanium covered with ruthenium and iridium oxides, with an active surface of 0.6 m^2 [21].

Figure 1. EC-UV system

This system was developed through the European project Eco-innovation (ECO/13/630452) and it is currently operating in a Spanish textile company.

2.2 Methodology

Life Cycle Assessment methodology (LCA) has been applied to perform the environmental comparison between treatment scenarios. A Cradle-to-Gate Life Cycle Assessment (LCA) was performed following the methodology ISO14040 [19]. SimaPro 7.3.3 software was used to perform the LCA, following the ReCiPe (H) V1.06 midpoint (problem-oriented approach) and endpoint (damage-oriented approach). The perspective selected was Hierarchist in order to seek consensus, as it is based on the most common policy principles and uses a medium timeframe of 100 years [22].

Both, the midpoint and endpoint impact categories have been considered since the midpoint indicators help identify issues of specific environmental concern, and endpoint or single score indicators can be very helpful in decision support [23]. The midpoint impact categories considered are: Climate change (CC), Ozone depletion (OD), Terrestrial acidification (TA), Freshwater eutrophication (FE), Marine eutrophication (ME), Human toxicity (HT), Photochemical oxidant formation (POF), Particulate matter formation (PMF), Terrestrial ecotoxicity (TET), Freshwater ecotoxicity (FET), Marine ecotoxicity (MET), Ionising radiation (IR), Agricultural land occupation (ALO), Urban land occupation (ULO), Natural land transformation (NLT), Water depletion (WD), Mineral resource depletion (MRD) and Fossil depletion (FD). The endpoint impact categories considered are: damage to Human Health, damage to Ecosystems diversity and damage to Resource availability.

2.2.1 Goal and scope

This study aims to evaluate from the environmental point of view the two alternatives technically feasible using the EC-UV system. These two scenarios are compared with the conventional processes used in the textile industry for the dyeing of cotton with reactive dyes and for the subsequent wastewater treatment of the effluents generated in this process. The results obtained will allow the identification of the main environmental impacts of each scenario and the proposal of some modifications on the dyeing process in order to improve its environmental performance, as explained and discussed in section 3.

The three studied scenarios in this work are referred hereinafter as:

- CD: Conventional colour removal and wastewater treatment.
- ED: Treatment of effluents with EC-UV for colour removal (Decolourisation mode scenario).
- EDR: Treatment of effluents with EC-UV for colour removal and reuse of treated effluents and salts (Reuse mode scenario).

To ensure the validity of the comparison the functional unit was selected on the basis of the following considerations:

- The EC-UV system can treat 4 m^3/h which represents 96 m^3/day (working 24h)
- 1 m^3 of coloured wastewater is generated from the production of 50 kg of dry dyed cotton in a conventional reactive Jet dyeing process.
- During the reactive dyeing process, 30% of water is absorbed by the fibre, which is subsequently removed in a drying process.

From the former points, it can be stated that the daily amount of EC-UV treated wastewater (96 m^3/day) corresponds to the dyeing of 4800 kg dry dyed cotton, which corresponds to *6240 kg of wet dyed cotton fabric.*

As a result, the functional unit selected for this study is: *6240 kg of wet cotton fabric dyed with reactive dyes in a Jet process*.

The CD scenario (see figure 2) consists mainly of three processes: (a) Dyeing of 4800kg of dry cotton fabric, carried out with softened tap water and large amount of salts (NaCl) in alkaline medium (adjusted with Na_2CO_3 solution). Dyeing liquor ratio 1:10 (1 kg dry fibre/10 L dye bath) was assumed. The first washing carried out after the dyeing step was also considered here due to its high coloration and salt content. At the end of this process, 6240 kg of wet dyed cotton fabric are produced; (b) Aerobic biological treatment of wastewater (dyeing process plus first washing step wastewater) with activated sludge; (c) Tertiary treatment, consisting in a coagulation-flocculation treatment to remove residual dyes.

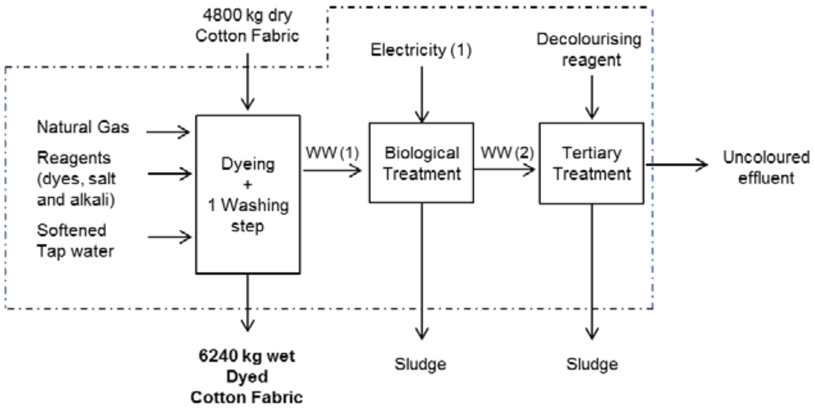

Figure 2- Flow chart and system boundary for the current dyeing and wastewater treatment (CD)

The ED scenario (see figure 3) also involves three processes: (a) the same current dyeing process with the first washing step defined for the CD scenario; (b) EC-UV system treatment. In our previous works [18] it has been stated that the removal of 60% colour of the dyeing effluent (67,2 m^3/day) is sufficient to achieve the decolouration of the whole mill wastewater (1000 m^3/day, mainly constituted by uncoloured water). Under these conditions, the system is also able to remove 10% of organic matter; (c) biological treatment with activated sludge to degrade the residual organic compounds. In this scenario, the biological process is shorter than in the CD scenario as 10% of organic matter was already removed in the previous process. Consequently, the electricity needed for the biological treatment is lower than in the CD scenario (10% lower).

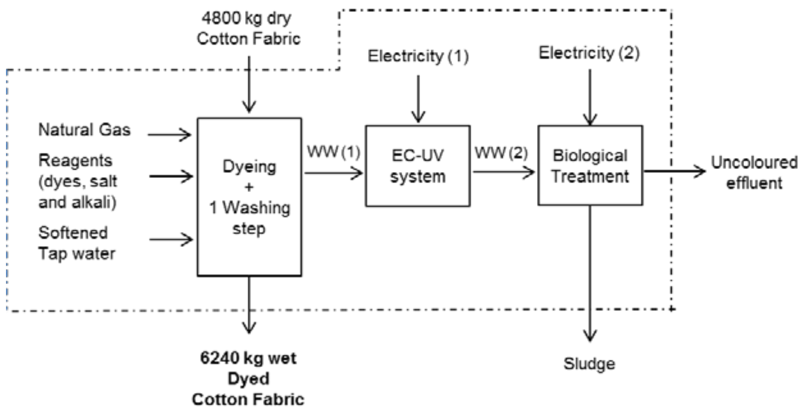

Figure 3- Flow chart and system boundary for ED scenario

In EDR scenario, wastewater treatment is not required as the EC-UV system is applied to both decolourise and reuse.

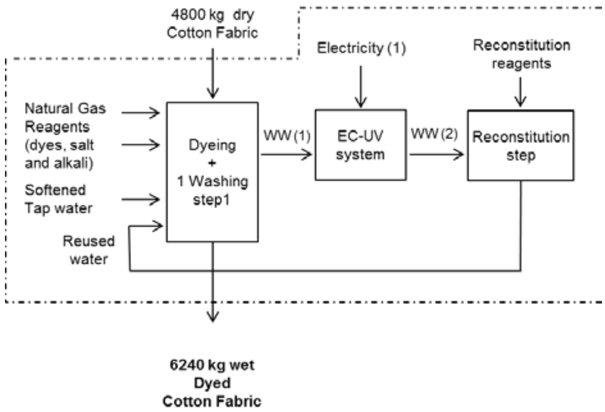

Figure 4 Flow chart and system boundary for EDR scenario

The EDR scenario (see figure 4), involves also 3 processes: (a) the dyeing process, which is similar to CD/ED scenarios but with the use of less water and salt since the EC-UV system enables the reuse of 70% water and 74% salt (NaCl); (b) EC-UV decolourisation treatment: in this case, it is applied to remove almost 80% colour in order to obtain an effluent able to be reused; (c) reconstitution of the treated effluent with the EC-UV system, instead of wastewater treatment. This process consists in the follow steps: (c1) decreasing the pH with HCl to remove carbonate as CO_2 gas; (c2) adjusting then the pH to 7 with NaOH; (c3) removal of the residual oxidants by adding a reducing agent.

To apply the LCA methodology, data for CD scenario are experimental data provided by a Spanish textile mill, where the conventional dyeing and waste water treatment had been carried out until the installation in this factory of the prototype pilot plant. Values used for ED and EDR calculations were estimated using annual average data from 2016. The following assumptions were made:

- The study is based on the dyeing and first washing in Jet process, including the subsequent wastewater treatment of the residual effluents.
- The company works 5 days/week and 24 hours/day.
- The electricity consumed comes from the Spanish grid at medium voltage.
- To obtain one Functional unit, the amount of water required to carry out the dyeing process is 96 m^3.
- 30% of the water is lost in the dyeing process (mainly by absorption on the fibre).
- The wastewater treated (decoloured effluent and reused water) is, in all the scenarios, 67.2 m^3.

- 25% of chlorides are adsorbed by the fabric in the dyeing process. Related to chloride concentration, although initially the EC-UV system consumes chlorides to convert them into chlorine or hypochlorite, these oxidants return to their chloride form once they have reacted. For this reason, the content in chlorides of output wastewater in CD and ED scenarios will be the same.
- The amount of sludge generated in the CD and ED scenarios are small (94.08 kg and 60.48 kg respectively, with a humidity of 90%, which means 9,408 kg and 6,048 kg of dry matter respectively). The EDR has not sludge generation. The inventory data published by Hospido et al. [24] for mechanical dewatering plus incineration of pasty sludge have been used and the characterization values for this sludge treatment has been calculated using the same assessing method (i.e. ReCipe midpoint). The results show that there is not a significant variation in any impact categories. For this reason, the treatment of the sludge generated in the CD and EC-UV scenarios (i.e. ED and EDR scenarios) has not been taken into account in this study.
- The infrastructures of construction and dismantling (EC-UV system pilot plant and conventional wastewater treatment plant) were excluded under the assumption that the impacts resulting from the operational phase are much higher [25]. In this sense, the average lifespan of electrodes for chloride generation is stablished in 10 years [26]. The electrodes in EC-UV treatment are mainly constituted by titanium being the presence of ruthenium and iridium oxides at level of traces. Nuss and Eckelman [27] performed a Life Cycle Assessment of metals (Cradle to gate) where they concluded that titanium has an environmental impact much lower than ruthenium and iridium. However, the content of Ru-IrO_2 in the coating of Ti electrodes is around 0.8 mg/cm^2 [28], which represents a total content of Ru-IrO_2 of 4.8 g, as the electrodes have a surface of 0.6 m^2. This low consumption of metals during the entire electrode lifespan ensures that their impact is not significant.
- The dyeing processes were carried out with four reactive dyes with chromophore azo: Remazol Black 133B (C.I. ReactiveBLack 5), Deep Red Remazol RGB, Ultra Yellow Remazol RGBN and Procion Navy H-EXL. Remazol dyes have reactive group bissulfatoethylsulfone, whereas the Procion dye has reactive group bismonochlorotriazine. The environmental impact due to the use of these dyes is not considered in any scenario since the quantity of dye is equal in any one of them, so the use of dye has the same contribution in all considered scenario. Furthermore,

finding the background data of this upstream process is quite difficult, since no data of these chemicals have been found in Ecoinvent data base.

Ecoinvent v 3.1 database provided background data on both upstream processes (chemical reagents, energy production, and softened tap water) and downstream process (wastewater emissions: COD and NaCl).

2.2.2 Life cycle inventory

As explained in section 2.2.1, the conventional dyeing and wastewater treatment flows data were provided by the textile mill. In addition, all the data related with the new EC-UV system flows were obtained from experimental assays performed with the prototype pilot plant installed in this textile mill.

The background data from Ecoinvent database v3.1 was used for chemical reagents and energy. The flow data and background sources are shown in Table 1 for the three considered scenarios. It should be stressed that the output wastewater from CD and ED scenario are not discharged directly to the sewage system. Previously to discharge, these effluents are mixed with other wastewaters generated in the mill in other processes. The COD and Chloride data showed in table 1 are the CD and ED scenario contributions to these parameters before mixing them with other effluents.

Table 1. Flow data and background data sources

Processes included in LCA			Amount	Unit	Ecoinvent unit process
CD Scenario					
Dyeing and first Washing					
	Inputs	NaCl	2880	kg	Sodium Chloride, powder (Glo)/market for/Alloc Def, U
		Na_2CO_3	816	kg	Soda ash, dense (Glo)/market for/Alloc Def, U
		Dye	168	kg	Not considered
		Softened tap water	96	m^3	Water, completely softened, from decarbonised water, at user (RER)/ production/ Alloc Def, U
		Natural gas	6.66	kWh	Heat, central or small-scale, natural gas (CH)/ heat production, natural gas, at boiler condensing modulating <100kW/Alloc Def, U
	Outputs	Wastewater (1)	67.2	m^3	
		Dyed cotton fabric	6240	kg	
Biological treatment					
	Inputs	Wastewater (1)	67.2	m^3	
		Electricity	235.2	kWh	Electricity, medium voltage (ES)/ market for/Alloc Def, U
	Outputs	Wastewater (2)	67.2	m^3	
Tertiary treatment					

Inputs	Wastewater (2)	67.2	m^3	
	Decolourising reagent	67.2	Kg	DTPA, diethylenetriaminepentaacetic acid (GLO)/ market for / Alloc Def, U
Outputs	Wastewater:	67.2	m^3	
	Chemical Oxygen Demand (COD)	22	kg	
	Chloride	2160	kg	
ED Scenario				
Dyeing and first Washing				
Inputs	NaCl	2880	kg	Sodium Chloride, powder (Glo)/market for/Alloc Def, U
	Na_2CO_3	816	kg	Soda ash, dense (Glo)/market for/Alloc Def, U
	Dye	168	kg	Not considered
	Softened tap water	96	m^3	Water, completely softened, from decarbonised water, at user (RER)/ production/ Alloc Def, U
	Natural gas	6.66[b]	kWh	Heat, central or small-scale, natural gas (CH)/ heat production, natural gas, at boiler condensing modulating <100kW/Alloc Def, U
Outputs	Wastewater (1)	67.2	m^3	
	Dyed cotton fabric	6240	kg	
EC-UV				

Inputs	Wastewater (1)	67.2	m^3	
	Electricity	284.9	kWh	Electricity, medium voltage (ES)/ market for/Alloc Def, U
Outputs	Wastewater (2)	67.2	m^3	
Biological treatment				
Inputs	Wastewater (2)	67.2	m^3	
	Electricity	211.7	kWh	Electricity, medium voltage (ES)/ market for/Alloc Def, U
Outputs	Wastewater:	67.2	m^3	
	Chemical Oxygen Demand (COD)	19.8	kg	
	Chloride	2160	kg	
EDR Scenario				
Dyeing and first Washing				
Inputs	NaCl	720	kg	Sodium Chloride, powder (Glo)/market for/Alloc Def, U
	Na_2CO_3	816	kg	Soda ash, dense (Glo)/market for/Alloc Def, U
	Dye	168	kg	Not considered
	Softened tap water	28.8	m^3	Water, completely softened, from decarbonised water, at user (RER)/ production/ Alloc Def, U
	Natural gas	6.66	kWh	Heat, central or small-scale, natural gas (CH)/ heat production, natural gas, at

				boiler condensing modulating <100kW/Alloc Def, U
Outputs	Wastewater (1)	67.2	m^3	
	Dyed cotton fabric	6240	kg	
EC-UV				
Inputs	Wastewater (1)	67.2	m^3	
	Electricity	571.2	kWh	Electricity, medium voltage (ES)/ market for/Alloc Def, U
Outputs	Wastewater (2)	67.2	m^3	
Reconstitution step				
Inputs	Wastewater (2)	67.2	m^3	
	HCl (30%)	1440	kg	Hydrochloric acid, without water, in 30% solution state (RER)/ market for/ Alloc Def, U
	NaOH (50%)	19.224	kg	Sodium hydroxide, without water, in 50% solution state (GLO)/ market for / Alloc Def, U
	$NaHSO_3$ (40%)	3.84	kg	Sodium hydrogen sulfite (GLO)/ market for/ Alloc Def, U
Outputs	Water to be reused			
	CO_2	401.8[a]	kg	

a Theoretical calculation taking into account the effluent carbonate content.

3 Results and discussion

In this section, the life cycle assessment of each scenario is presented and discussed. Subsequently, the three scenarios are studied comparatively. On the basis of these results, the best procedure to improve the environmental performance of the textile mill is selected. With the same purpose, a proposal of modification of the dyeing process is also suggested.

The contribution of each process involved in each scenario, for the different categories, is presented below.

The Figure 5 shows the ReCiPe midpoint characterization values, expressed in percentage, related to each of the processes involved in the CD Scenario (e.i. dyeing plus first washing, biological treatment and tertiary treatment).

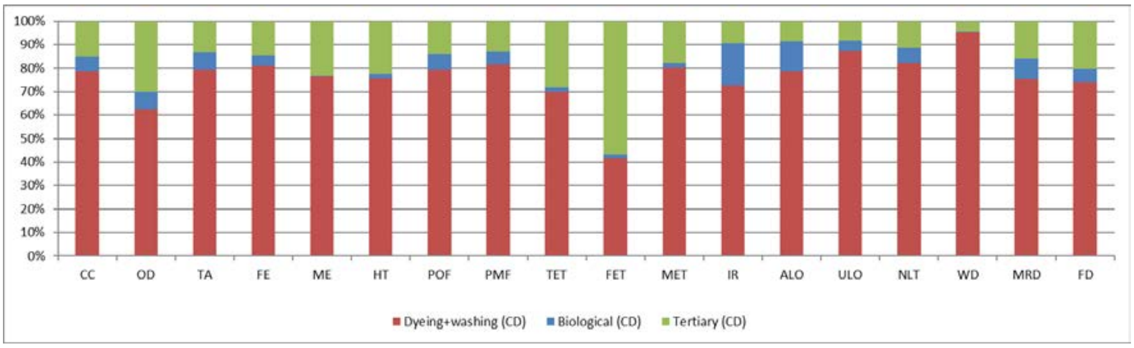

Figure 5 ReCipe midpoint characterization values for CD scenario.

The dyeing plus first washing is the process with the largest contribution to all the impact categories. A more detailed analysis of this fact is presented in figure 6, which shows the contribution of each input flow to the Dyeing plus washing process.

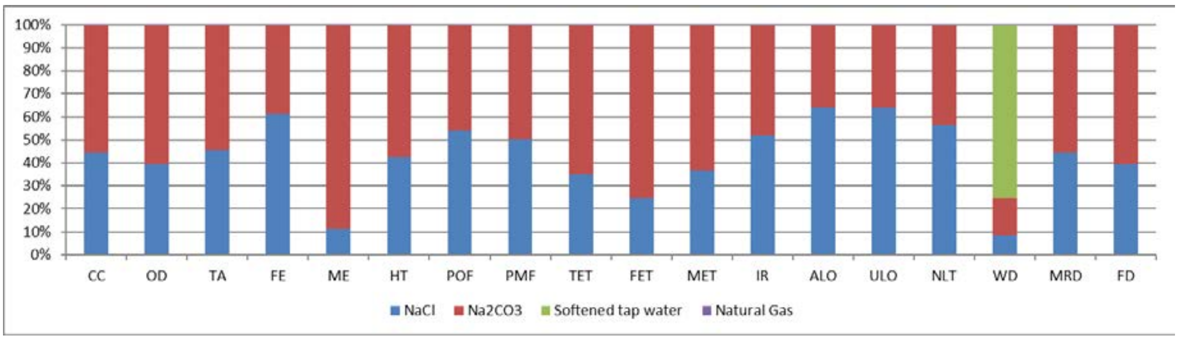

Figure 6. ReCipe midpoint characterization values for dyeing plus first washing process in CD scenario

The major contribution of all the impact categories is mainly due to the use of Na_2CO_3 and NaCl in the process. Obviously, for water depletion impact category (WD) the great contribution is due to the use of softened tap water in this process. The contribution of natural gas for dyeing is negligible for all the impact categories.

The figure 7 shows the characterization values, expressed in percentage, related to each of the processes involved in ED scenario (e.i. dyeing plus first washing, EC-UV decolourisation and biological treatment applied to the EC-UV outflow).

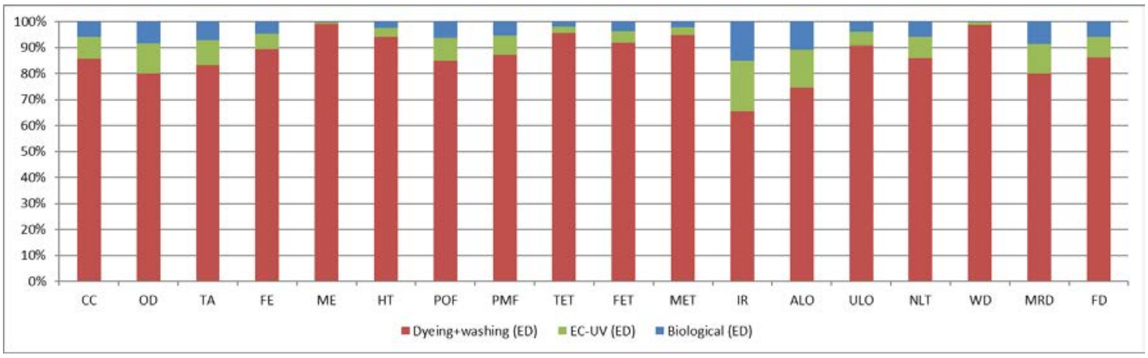

Figure 7. ReCipe midpoint characterization values for ED scenario

As in CD scenario, the dyeing plus first washing is the process with the largest contribution to all the impact categories, mainly due to the use of Na_2CO_3 and NaCl in the process.

The results obtained in each of the processes involved in EDR scenario are shown in the figure 8.

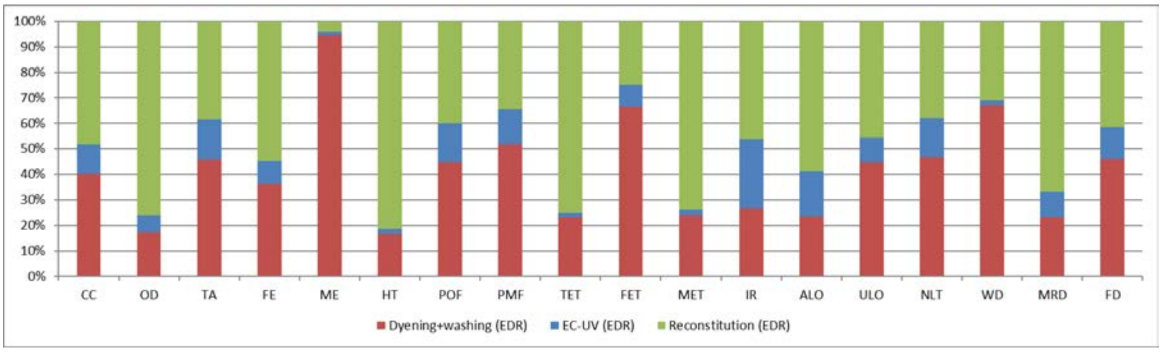

Figure 8. ReCipe midpoint characterization values for EDR scenario

As in the previous scenarios, the dyeing plus first washing process has an important contribution in some of the considered impact categories due to the use of Na_2CO_3 and NaCl. However, in this scenario, the reconstitution process shows a great contribution in most of the considered impact categories. In order to determine the contribution of each input and output flow in the impact of the reconstitution process, a detailed study on this process has been carried out (figure 9).

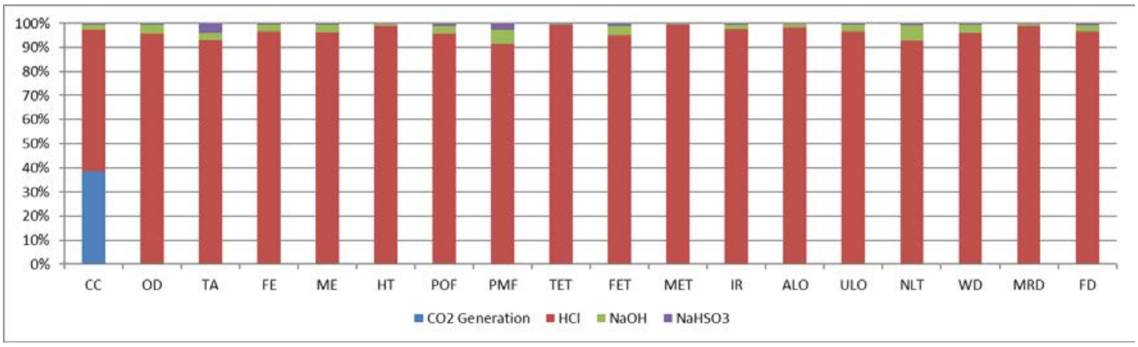

Figure 9 ReCipe midpoint characterization values for reconstitution process in EDR scenario

The use of chloride acid is the main responsible for the high impact of the reconstitution step. The acid is required to remove carbonates present in the effluent, which are converted to CO_2. The emission of CO_2 results in a great contribution to Climate change category.

The Table 2 shows the ReCipe midpoint characterization values for each scenario. As can be observed, the ED scenario presents lower impact values than the CD for all impact categories except for Ionising radiation (IR) and Agricultural land occupation (ALO). On the other hand, the ECRscenario shows higher impact values for most of impact categories.

Table 2- ReCipe midpoint characterization values

Impact categories	**Units**	**CD**	**ED**	**EDR**
CC	kg CO_2 eq	1.7E+03	1.5E+03	2.2E+03
OD	kg CFC-11 eq	1.9E-04	1.5E-04	4.8E-04
TA	kg SO_2 eq	8.4E+00	8.0E+00	9.6E+00
FE	kg P eq	7.3E-02	6.6E-02	8.9E-02
ME	kg N eq	3.7E+00	2.8E+00	2.7E+00
HT	kg 1,4-DB eq	1.1E+02	8.7E+01	3.3E+02
POF	kg NMVOC	4.9E+00	4.6E+00	5.1E+00
PMF	kg PM10 eq	3.8E+00	3.6E+00	3.7E+00
TET	kg 1,4-DB eq	2.4E-01	1.7E-01	5.3E-01

Impact categories	Units	CD	ED	EDR
FET	kg 1,4-DB eq	2.9E+00	1.3E+00	1.5E+00
MET	kg 1,4-DB eq	1.8E+00	1.5E+00	4.2E+00
IR	kBq U^{235} eq	9.1E+01	1.0E+02	1.5E+02
ALO	m^2·yr	6.4E+01	6.7E+01	1.1E+02
ULO	m^2·yr	1.1E+01	1.1E+01	1.1E+01
NLT	m^2	3.8E-02	3.6E-02	3.8E-02
WD	m^3	1.3E+02	1.2E+02	7.3E+01
MRD	kg Fe eq	7.2E+00	6.7E+00	1.6E+01
FD	kg oil eq	5.1E+02	4.4E+02	5.7E+02

The ED scenario presents a better environmental performance than CD scenario for all the impact categories considered except for Ionising radiation (IR) and Agricultural land occupation (ALO) where the values are similar. The EDR is the scenario with worse environmental performance for all the impact categories considered, except for ME, FET and WD. The ED and EDR scenarios present similar Marine Eutrophication and Freshwater Eutrophication values (ME and FE) due to the fact the dyeing process is the process, in both scenarios, with larger contribution to these impact categories. In CD scenario, the tertiary treatment has also, in addition, an important contribution to these impact categories.

Logically, the Water Depletion (WD) in EDR scenario is lower than in the other considered scenarios due to the water reuse after reconstitution step.

The use of Na_2CO_3 and NaCl in the dyeing process has and important environmental contribution in all the studied scenarios. In addition, the use of HCl in the EDR scenario, necessary in the reconstitution process to produce an adequate effluent to be reused in the dyeing process, presents a great contribution due to the use of chemical itself and due to the generation of CO_2. In order to improve the environmental performance in all the considered scenarios, and more specifically, in the EDR scenario, some modifications in the dyeing process have been studied.

Previous studies carried out by our research group conclude that is possible to substitute the use of Na_2CO_3 in the dyeing process by NaOH with no effect in the dyeing quality of the fabrics ~~[25]~~ [29]. Dyeings were performed in 100% cotton fabrics with the same kind of reactive dyes than the current study: Remazol (reactive group bissulfatoethylsulfone) and Procion (reactive group bismonochlorotriazine). This substitution avoids the CO_2 generation in the EDR scenario, caused by the elimination of carbonates.

This change in the dyeing process will affect all the studied scenarios since it is a common process in all scenarios. Experimental tests carried out by the authors in this study conclude that the quantity of NaOH to be used is 28.8 kg/FU instead of 816 kg/FU of Na_2CO_3.

Moreover, the substitution of Na_2CO_3 by NaOH in the dyeing process makes a lower consumption of HCl in the reconstitution step on EDR scenario (0.818 kg/FU instead 1440 kg/FU), and no CO_2 is generated in the reconstitution step.

As can be seen in figure 10, the use of NaOH instead of Na_2CO_3 in the dyeing process, causes a great environmental improvement in all the impact categories on all the considered scenarios. This decrease is especially significant in the case of the EDR scenario. The substitution of carbonates causes that its elimination is not required during the reconstitution step, reducing the generation of CO_2.

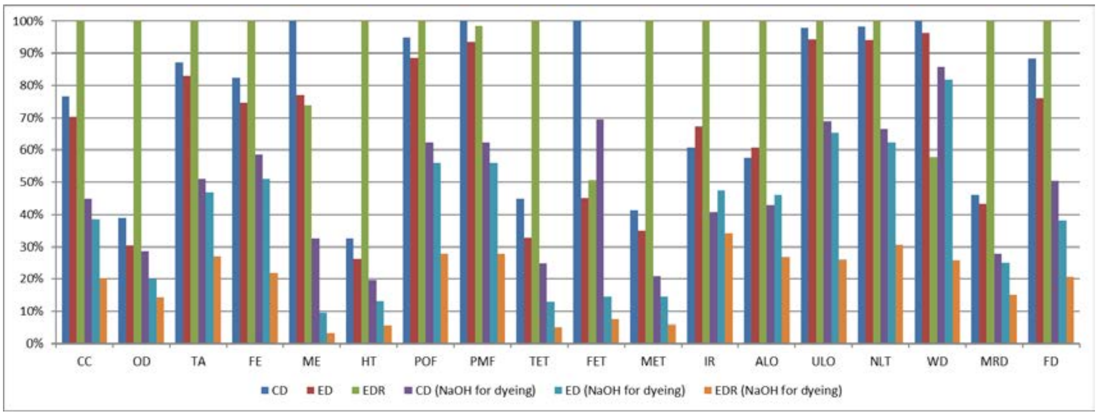

Figure 10. ReCipe midpoint characterization values for CD, ED and EDR scenarios, with and without modifications in the dyeing process.

A comparison of the three scenarios, taking into account the proposed modification, is presented in figure 11.

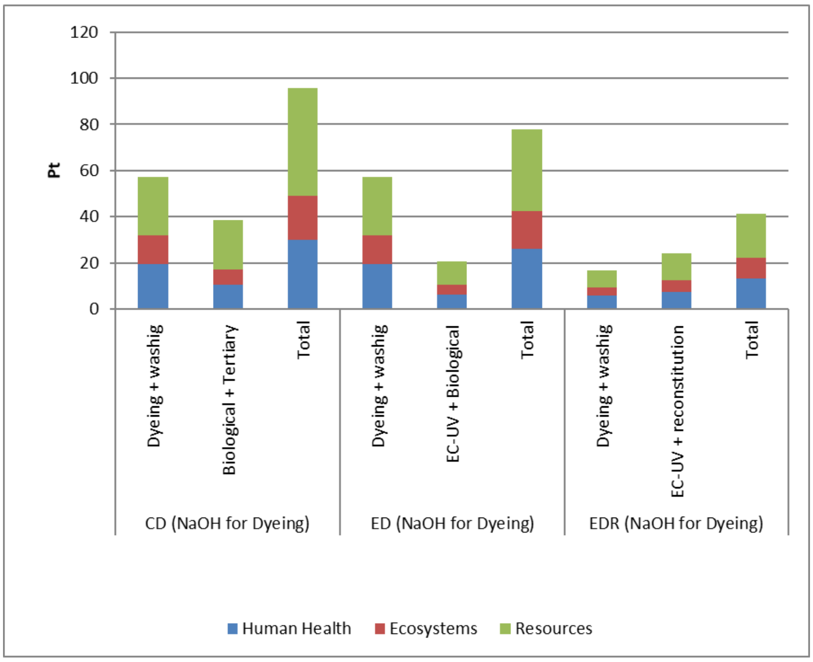

Figure 11. ReCipe single-score values for CD, ED and EDR scenarios, with modifications in dyeing process

In comparison to the conventional decolourisation (CD scenario), the use of the EC-UV system, running in "decolourisation mode" (ED scenario) provides a reduction of about 20% in the environmental impact, whereas when EC-UV system is running to treat and reuse water and salt (EDR scenario) the environmental impact of the wastewater treatment decreases in 60%.

4 Conclusion

The LCA methodology has been a useful tool to compare, evaluate, identify and propose improvements to the EC-UV system, a new developed technology to treat and reuse water and salt from a dyeing textile process.

The work shows that in CD scenario, the consumption of Na_2CO_3 and NaCl in the dyeing process is the largest contributor to the environmental impact. On the other hand, if we focus the analysis on the conventional wastewater treatment (biological and tertiary processes), the tertiary treatment is the process with the largest contribution to all the environmental categories. Therefore, the elimination of this stage of treatment is highly advisable. In this sense, the EC-UV system enables to remove this process.

In the ED scenario, the dyeing process is the same than in the CD scenario, as it is not affected by EC-UV system. Consequently, the consumption of Na_2CO_3 and NaCl are still the largest contributors to the environmental impact in this scenario. The ED scenario presents a better environmental performance than the CD one, since the tertiary treatment is eliminated. The EC-UV system running in decolouration mode (ED scenario) has been proved to be a technologically feasible and a better environmental alternative to conventional treatment (CD scenario).

The EC-UV system running in reuse mode is a technologically feasible alternative but it needs some modifications in the current dyeing process to imply a better environmental performance than the other considered scenarios. It should be noted that the addition of NaOH in substitution of high amounts of Na_2CO_3 in the dyeing process has been applied by a great number of textile mills at present. As the combination of NaOH with Na_2CO_3 involves a drastic reduction of Na_2CO_3 consumption to adjust pH at alkali conditions. The use of mixed alkali, or even the use of NaOH alone, allows to obtain acceptable dyeings in quality control tests [30]. Dye manufacturers recommend the of soda ash, caustic soda or mixed alkali, depending on the method [31].

Acknowledgements)

This project is co-funded by the European Commission within the CIP Eco-Innovation initiative of the Competitiveness and Innovation Framework Programme, CIP: ECUVal project (ECO/13/630452). For more information: www.ecuval.eu.

References

[1] M.R. Al-Mamun, S. Kader, M.S. Islam, M.Z.. Khan, Photocatalytic Activity Improvement and Application of UV-TiO2 Photocatalysis in Textile Wastewater Treatment: A Review, J. Environ. Chem. Eng. (2019). doi:https://doi.org/10.1016/j.jece.2019.103248.

[2] W. Leal Filho, D. Ellams, V.J. Boiten, A. Paco, H. Moora, S. Han, D. Tyler, A.-L. Balogun, A review of the socio-economic advantages of textile recycling, J. Clean. Prod. 218 (2019) 10–20. doi:10.1016/j.jclepro.2019.01.210.

[3] E.M. Foundation, A new textiles economy: Redesigning fashion’s future, 2016.

[4] T. Tavangar, K. Jalali, M. Amin, A. Shahmirzadi, M. Karimi, Toward real textile wastewater treatment : Membrane fouling control and effective fractionation of dyes / inorganic salts using a hybrid electrocoagulation – Nanofiltration process, Sep. Purif. Technol. 216 (2019) 115–125.

doi:10.1016/j.seppur.2019.01.070.

[5] T. Robinson, G. McMullan, R. Marchant, P. Nigam, Remediation of dyes in textile effluent: a critical review on current treatment technologies with a proposed alternative., Bioresour. Technol. 77 (2001) 247–55. http://www.ncbi.nlm.nih.gov/pubmed/11272011.

[6] Y. Zheng, S. Yu, S. Shuai, Q. Zhou, Q. Cheng, M. Liu, C. Gao, Color removal and COD reduction of biologically treated textile effluent through submerged filtration using hollow fiber nanofiltration membrane, Desalination. 314 (2013) 89–95. doi:10.1016/j.desal.2013.01.004.

[7] T. Freitas, C. Almeida, H. Lopes, M. Ferreira, J. García, Review of utilization plant-based coagulants as alternatives to textile wastewater treatment, in: M. Subramanian (Ed.), Detox Fash. Wastewater Treat., Springer, Singapore, 2018: pp. 27–79.

[8] M. Vilaseca, V. López-Grimau, C. Gutiérrez-Bouzán, Valorization of waste obtained from oil extraction in Moringa Oleifera seeds: Coagulation of reactive dyes in textile effluents, Materials (Basel). 7 (2014) 6569–6584. doi:10.3390/ma7096569.

[9] H. Zazou, H. Afanga, S. Akhouairi, H. Ouchtak, A.A. Addi, R.A. Akbour, A. Assabbane, J. Douch, A. Elmchaouri, J. Duplay, A. Jada, M. Hamdani, Treatment of textile industry wastewater by electrocoagulation coupled with electrochemical advanced oxidation process, J. Water Process Eng. 28 (2019) 214–221. doi:10.1016/j.jwpe.2019.02.006.

[10] J. Khatri, P.V. Nidheesh, T.S. Anantha Singh, M. Suresh Kumar, Advanced oxidation processes based on zero-valent aluminium for treating textile wastewater, Chem. Eng. J. 348 (2018) 67–73.

[11] U. Sathya, Keerthi, M. Nithya, N. Balasubramanian, Evaluation of advanced oxidation processes (AOPs) integrated membrane bioreactor (MBR) for the real textile wastewater treatment, J. Environ. Manage. 246 (2019) 768–775.

[12] W.L. Wang, H.Y. Hu, X. Liu, H.X. Shi, T.H. Zhou, C. Wang, Z.Y. Huo, Q.Y. Wu, Combination of catalytic ozonation by regenerated granular activated carbon (rGAC) and biological activated carbon in the advanced treatment of textile wastewater for reclamation, Chemosphere. 231 (2019) 369–377. doi:10.1016/j.chemosphere.2019.05.175.

[13] K. Pazdzior, L. Bilinska, S. Ledakowicz, A review of the existing and emerging technologies in the combination of AOPs and biological processes in industrial textile wastewater treatment, Chem. Eng. J. (n.d.). doi:https://doi.org/10.1016/j.cej.2018.12.057.

[14] L. Bilinska, K. Blus, M. Gmurek, S. Ledakowicz, Coupling of electrocoagulation and ozone

treatment for textile wastewater reuse, Chem. Eng. J. 358 (2019) 992–1001.

[15] M. Sala, V.V. López-Grimau, C. Gutiérrez-Bouzán, Photo-electrochemical treatment of reactive dyes in wastewater and reuse of the effluent: Method optimization, Materials (Basel). 7 (2014) 7349–7365. https://doi.org/10.3390/ma7117349.

[16] M. Sala, V. López-Grimau, C. Gutiérrez-Bouzán, Photoassisted Electrochemical Treatment of Azo and Phtalocyanine Reactive Dyes in the Presence of Surfactants, Materials (Basel). 9 (2016) 211. https://doi.org/10.3390/ma9030211.

[17] C.A. Martínez-Huitle, M. Panizza, Electrochemical oxidation of organic pollutants for wastewater treatment, Curr. Opin. Electrochem. 11 (2018) 62–71. doi:10.1016/j.coelec.2018.07.010.

[18] V. Buscio, V. López-Grimau, M.D. Álvarez, C. Gutiérrez-Bouzán, Reducing the environmental impact of textile industry by reusing residual salts and water: ECUVal system, Chem. Eng. J. 373 (2019) 161–170. doi:10.1016/j.cej.2019.04.146.

[19] AENOR, ISO 14040:2006: Environmental management - Life cycle assessment - Principles and framework, 2006.

[20] AENOR, ISO 14044 :2006: Environmental management - Life cycle assessment - Requirements and guidelines, 2006.

[21] M.C. Gutiérrez-Bouzán, J.A. Tornero-García, V. Buscio, M. Gutiérrez-Mérida, Procedimiento por lotes para tratamiento en continuo de efluentes líquidos por técnicas electroquímicas para su depuración., 201730750, 2017.

[22] ReCiPe, A life cycle impact assessment method which comprises harmonised category indicators at the midpoints and the endpoints level. Report I: Characterisation, 2008.

[23] T. Kägi, F. Dinkel, R. Frischknecht, Session “Midpoint, endpoint or single score for decision-making?”—SETAC Europe 25th Annual Meeting, May 5th, 2015, Int. J. Life Cycle Assess. 21 (2016) 129.

[24] A. Hospido, T. Moreira, M. Martín, M. Rigola, G. Feijoo, Environmental Evaluation of Different Treatment Processes for Sludge from Urban Wastewater Treatments: Anaerobic Digestion versus Thermal Processes, Int. J. Life Cycle Assess. 10 (2005) 336-345 https://doi.org/10.1065/lca2005.05.210

[25] X. Gabarrell, M. Font, T. Vicent, A comparative life cycle assessment of two treatment technologies for the Grey Lanaset G textile dye: biodegradation by Trametes versicolor and

granular activated carbon adsorption, Int. J. Life Cycle Assess. 17 (2012) 613.

[26] S. Trasatti, Electrocatalysis: understanding the success of DSA, Electrochim. Acta 45 (2000) 2377-2385 https://doi.org/10.1016/S0013-4686(00)00338-8

[27] P. Nuss, J.L. Eckelman, Life Cycle Assessment of metals: A scientific synthesis, PLoS ONE 9 (7) (2014) https://doi.org/10.1371/journal.pone.0101298

[28] J. Luo, Y. Wang, D. Cao, K. Xiao, T. Guo, X. Zhao, Enhanced photoelectrocatalytic degradation of 2,4-dichlorophenol by TiO_2/Ru-Ir-O_2 bifacial electrode, Chem. Eng. J. 343 (2018) 69-77. https://doi.org/10.1016/j.cej.2018.02.120

[29] M. Riera-Torres, M.C. Gutiérrez-Bouzán, J. Valldeperas, M. Lis, M. Crespi, Influence of electrochemical pre-treatment in dyeing wastewater reuse for five reactive dyes, Text. Res. J. 81 (2011) 1926–1939. https://doi.org/10.1177/0040517511413316

[30] Bhuiyan, M. A. R., Shahid, M. A., Hannan, M. A., and Kafi, M. A., 2012. Influence of Mixed Alkali on Fixation of Deep Shade on Single Jersey Cotton Fabrics with Reactive Dyes. Journal of Chemical Engineering IEB 27 (2012) 58-63. https://doi.org/10.3329/jce.v27i1.15860

[31] Anon. Novacron and Avitera SE reactive dyes; salt and alkali recommendations; rev 2013. Huntsman textile effects/R & T colors. Huntsman; 2013.