Value chain upgrading in a textile dyeing industry

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Abstract

Eco-efficiency has been widely recognized during the last two decades as a suitable measure of a given system's progress towards a greener and sustainable development. It combines the economic welfare and the ecological impact of products or services throughout their lifecycle. The need for improving eco-efficiency leads to the development of appropriate metrics for measuring the performance of a given system and the identification of the most promising alternative solutions (eco-innovations). This paper briefly presents a methodological framework for the eco-efficiency assessment of water-use systems, using a life-cycle oriented approach and a set of selected eco-efficiency indicators. The environmental performance of the system is evaluated through the relevant midpoint environmental impact categories, while the economic performance is measured using the total value added to the system's final product due to water use.

The proposed framework is applied to the textile industry in Biella, Italy. The analysis reveals that the major environmental problems of the textile industry in the region are freshwater resource depletion, as well as human toxicity and ecotoxicity (both aquatic and terrestrial). The identification of the environmentally weak stages of the system has led to the selection of alternative actions, which could upgrade the whole value chain and improve the overall eco-efficiency. Six innovative technologies are examined and two alternative technology scenarios are formulated. The first scenario focuses on resource efficiency, while the second one focuses on reducing the emissions to water. The results show that all technologies could potentially improve the majority of the environmental performance indicators of the system. However, the scenario towards pollution prevention and control has proven to be not economically viable due to the high investment cost required and the current economic conditions, while the implementation of the scenario towards resource efficiency requires additional economic incentives and governmental support in order to be considered feasible by the industrial stakeholders.

Keywords: Eco-efficiency, water-use systems, textile industry, resource efficiency, pollution prevention

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1. INTRODUCTION

The concept of eco-efficiency was first introduced in 1989 and its main objective was to bring together the economic and environmental viability of a given system (Schaltegger and Sturm, 1989). It was formally defined in 1991 by the World Business Council for Sustainable Development as the ability of a business to deliver competitively priced goods/services while reducing ecological impact and resource use throughout their lifecycle (WBSCD, 2000). Since then, several definitions have been proposed (Huppes and Ishikawa, 2005), and several studies on eco-efficiency assessment have been carried out on a company, business unit (van Caneghem et al., 2010) or specific product (Michelsen et al., 2006) level. Their main objective was to support and to guide investment and management decisions in order to maximize profit and minimize environmental impact.

The OECD (1998) has provided a more generic definition, as the efficiency with which ecological resources are used to meet human needs and expressed it as the ratio of an output (the value of products and services produced by a firm, sector or economy as a whole) divided by the input required to produce it (the sum of environmental pressures generated by the firm, the sector or the economy). This definition has moved the concept of eco-efficiency outside the business context. Nowadays, eco-efficiency has been recognized as a measure of progress towards a greener and more sustainable economy, since it treats environmental matters as a critical component of the economic activity, and the environmental degradation is one of the basic problems that most countries around the world are facing. Eco-efficiency assessment has been already applied at the macro-level, either focusing on a sector of economic development (Ingaramo et al., 2004, Koskela, 2014) or at the regional (Mickwitz et al., 2006) and national level (Jollands et al., 2004, Wursthorn et al., 2011).

1.1 Assessing the eco-efficiency of a water use system

The paper briefly presents: (a) a methodological framework for the eco-efficiency assessment of a water use system, developed during the EcoWater project, and (b) its application to an industrial water use system. A life cycle oriented approach, which incorporates the principles of functional unit, life cycle inventory and life-cycle impact assessment (LCIA), is used to evaluate the environmental performance, while the economic performance is assessed through the total value added to the product as a result of water use. The proposed framework has been applied to the textile industry of the Biella region in Northern Italy.

The motivation for choosing water use systems as a common denominator of the analysis in the EcoWater project was based on the fact that water is a critical resource for all activities in a human society, with energy production, agricultural sector, urban water supply and industrial activities being the most important consumers (44%, 24%, 17% and 15% are the corresponding shares at an EU level). The continuous increase of the world population and the rapid urbanization and industrialization have led to a six fold increase in the global water use (Abra, 2012). More than 20 countries will face water shortage by 2025 and more than 50 could suffer from water stress, whereas more than 3 million premature deaths worldwide are due to lack of wastewater collection and treatment processes (UNWATER, 2009).

The textile industry was selected because it represents one of the bigger industrial water consuming sectors. Large amounts of freshwater are used along its entire value chain, while the wet processing operations (i.e. dyeing and finishing processes) utilize a large amount of freshwater for dissolving dyes and chemicals. Furthermore, the textile industry has a distinct environmental impact, particularly affecting the aquatic environment through pollution by discharging process wastewater. Thus, it is critical to monitor its environmental impact and its progress towards sustainable development, and to introduce the concepts of a lean and green industry and their connection with supply chain management.

Towards this end, several methodologies have been used by researchers. Allwood et al. (2008) have used scenario analysis to assess the sustainability of the clothing and textiles sector in the UK and have proposed a list of possible solutions towards a more sustainable production. A widely-used method for assessing the environmental performance of the textile industry is the eco-labelling system. However, there is a plethora of studies identifying problems in eco-labelling, among which are the increasing complexity of textile production processes and the limited resources that make difficult the satisfaction of the eco-regulations (You et al., 2009). The development of a framework based on environmental performance indicators, applicable to the textile industries, has also been widely studied. Nieminen et al. (2006) have assessed alternative technological options towards an improved environmental performance using Life Cycle Assessment (LCA) but also highlighted the limited significance of the results, since there are too many diverging parameters in the production process (technology, equipment or even formulas of dyes and additives. An LCA has been performed for comparing the eco-efficiency of an innovative technology (a new dyeing process) with the classical dyeing, using a set of environmental impact indicators (Parisi, et al, 2015).

However, all the above-mentioned studies focus mainly on the environmental impact of the industrial unit without assessing their influence on the environmental performance of the surrounding system and on the economic performance of the involved actors. The success, nevertheless, of a new and innovative technology is governed not only by processes within the micro level but also by developments at the level of the existing regimes and the macro level (Geels, 2002). Thus, eco-innovations will be successful and largely adopted only if they lead to an increase of the economic value added and a decrease of the environmental burden at different levels (businesses, sectors, regions and economy). Therefore, it becomes critical to develop eco-efficiency metrics for measuring the performance not only of the industrial unit but also of the whole system and of each actor involved separately.

2. METHODOLOGY

The proposed methodological approach aims to facilitate the uptake of innovative technologies in order to minimize the associated environmental impact or maximize the economic performance of a given system leading to an increase of its eco-efficiency. In particular, the developed systemic approach proposes a well-established set of eco-efficiency indicators, which can be effectively adapted to the textile industry by selecting the most relevant ones. The most important novelty is that the approach can, at the same time, assess the environmental performance of each stage, in order to identify the weakness or the so-called “environmental hotspots” of the system, and the economic performance of each actor separately, in order to address the distributional issues across the entire value chain.

These identified hotspots will guide the selection of innovative technologies which could potentially improve the eco-efficiency of the system. Eco-efficiency will be calculated as the ratio of the economic to the environmental performance. Thus, an improvement in the eco-efficiency compared to the baseline conditions can be a result of either an improved economic performance, a reduced environmental impact or even both. However, as already mentioned, the improvement of the eco-efficiency is not the only criterion for the selection of a specific technology (or set of technologies). Its implementation should also improve (or at least do not negatively affect) the economic output of all the actors involved in the system. The final step, after technology assessment, is the discussion with the all the actors in order to identify any non-technical constraints or barriers towards the implementation of these technologies, related to the special characteristics of the systems and the external environment.

According to the International Standard for eco-efficiency assessment to product systems (ISO, 2012), such a procedure, generally, comprises of five steps:

- Goal and scope definition;
- Environmental performance assessment;
- Value (or economic performance) assessment;
- Quantification of eco-efficiency; and
- Interpretation

2.1 Goal and Scope Definition

Before selecting and calculating the eco-efficiency indicators, the boundaries, the special characteristics of the studied system and the functional unit should be identified. A generic water use system (Figure 1) is represented as a network of unit processes, which convert generic materials (water, raw materials, energy and other supplementary resources) into products, while releasing emissions to the environment (air, land, water). The system is divided into two subsystems; foreground and background. The foreground system comprises of all processes whose selection or mode of operation is affected directly by decisions based on the study, and can be grouped in four stages, while the background includes other activities, which deliver energy and raw materials to the foreground system. The functional unit sets the scale for the comparison of two or more products or services delivered to the consumers. It depends on the reference flow selected each time and its main purpose is to provide a benchmark for the normalization and comparison of the results (ISO, 2006; JRC, 2010).

(Figure 1)

Figure 1. The generic water use system, divided into foreground and background sub-systems

2.2 Environmental Assessment

The most commonly used environmental performance indicators for the development of eco-efficiency metrics are structured to capture resource use in terms of production and consumption, and their corresponding environmental impact (UN ESCAP, 2009). In the proposed methodology, the environmental performance of the water-use system is assessed following a life-cycle oriented approach through the use of standardized midpoint impact categories, as recommended by JRC (2011). They were selected as a well-established and widely accepted set of environmental impact categories, covering all aspects of different impact on human health, natural environment and availability of resources.

The environmental performance assessment consists of two main steps. The first step creates an inventory of elementary flows from/to the environment and to/from all the unit processes involved in the system. The second step assigns the elementary flows to impact categories according to the contribution of the resource/emission to different environmental problems, using standard characterisation factors, and evaluates the significance of potential environmental impact. The environmental impact for impact category c is expressed as a score (ES_c) in a unit common to all contributions within the category and can be calculated as follows:

$$ES_c = \sum_r cf_{r,c} \times f_r + \sum_e cf_{e,c} \times f_e + \sum_r ef_{r,c} \times f_r \quad (1)$$

The first two terms refer to the impact of the foreground system while the third term refers to the impact of the background system. The elementary flows of resource *r* and emission *e* are represented by f_r and f_e respectively, while $cf_{r,c}$ is the characterisation factor of resource *r* for the impact category *c*, $cf_{e,c}$ the characterisation factor of emission *e* for the impact category *c* (both retrieved from LCA databases) and $ef_{r,c}$ the environmental impact factor representing the environmental impact from the production and/or transportation of one unit of a resource *r*.

The impact from the use of freshwater is neglected by most LCA studies and databases and as a result, there is no standardised environmental midpoint indicator for freshwater resource depletion (JRC, 2010). However, since water consumption is an important component of the studied system, freshwater depletion is taken into consideration, using the Freshwater Ecosystem Impact (*FEI*) indicator (Mila i Canals et al., 2009), which relates current freshwater use to the available freshwater resources, and is defined as:

$$FEI = f_{w,abs} \times WTA \quad (2)$$

where $f_{w,abs}$ is the flow of freshwater abstracted and *WTA* is the water withdrawal to availability ratio.

2.3 Value Assessment

The economic performance of a value chain can be assessed by using either a physical quantity or a financial term. In the first case, an indicator measuring the physical activity of the value chain can be used, such as the total volume of production or the total amount of services provided. Such an indicator is not easily applicable when various productions lines, with different products, are studied and compared, and thus, in this case, a financial term is more preferable. GDP is the most often used variable for measuring the economic performance of a system at the macro level, whereas turnover or net profit of an individual installation unit or from a single product can be used at the micro level.

In the case of a water use system, which combines a water supply chain and a production chain, and the emphasis is placed on the interactions among the two chains, the most appropriate indicator to express its economic performance is the Total Value Added (TVA) to the product due to water use. It is expressed in monetary units per period and per functional unit and can be estimated as:

$$TVA = EVU + VP_{BP} - TFC_{WS} - TFC_{WW} - TIC \quad (3)$$

where *EVU* is the total economic value from water use, VP_{BP} the income generated from any by-products of the system, TFC_{WS} the total financial cost related to water supply provision for rendering water suitable for the specific use, TFC_{WW} the total financial cost related to wastewater treatment and *TIC* the annual equivalent future cash flow generated by the introduction of new technologies in the system. The total economic value from water use can be calculated by subtracting the expenses for all the non-water inputs in the water use stage from the total value of the products.

In order to assess the economic performance of each actor, the Net Economic Output (NEO_i) of each directly involved actor *i* in the system is estimated as follows:

$$NEO_i = WS_i + VP_i - FC_i - IC_i \quad (4)$$

where WS_i represents the net revenues of actor *i* from the water services while VP_i, FC_i and IC_i are the value of product(s), financial costs and annual investment costs, respectively, incurred in the pertinent stages of actor *i*.

2.4 Eco-efficiency Indicators

The Eco-Efficiency Indicators (*EEI*) of the water use systems are defined as ratios of the economic performance indicator (Total Value Added, *TVA*), to the environmental performance metrics (environmental impact) of the system. There is one eco-efficiency indicator for each environmental impact category c:

$$EEI_C = \frac{TVA}{ES_C} \quad (5)$$

2.5 Value Chain Upgrading and Interpretation of the Results

Based on the results of the eco-efficiency assessment and the environmental weaknesses identified, alternative technological interventions are sought that may lead to an overall eco-efficiency improvement of the system, without deteriorating the economic performance of the involved actors. Each technology can be classified according to its primary objective and assessed based on its eco-efficiency. This initial screening can lead to the rejection of the technologies that may deteriorate the performance of the system. Using only the eco-efficient technologies, three alternative technology scenarios can be formulated:

- Pollution Prevention and Control Scenario, where end-of-pipe solutions are mainly adopted, in order to treat effluents or wastes, handle and dispose emissions and wastes, generated from the production process (pollution control) or interventions in the production process are implemented in order to improve the quality of the system's outflows and reduce the polluting load.
- Resource Efficiency Scenario, which includes technological interventions targeting at the optimum use of materials and energy.
- Circular Economy Scenario, where technologies focus on substituting the inputs with resources obtained through reuse or recovery technologies.

The assessment of the scenarios also takes into account the effect that the adoption of one technology upstream could have to the performance of another technology downstream of the production process. Moreover, the maximum impact that a selected set of technologies can have to the examined system can be estimated. When a scenario proves to be eco-efficient then the distributional issues must be addressed. If it has a positive impact on the TVA of the system and on the NEO of all actors then the scenario can be considered feasible. However, if the NEO of certain actors decreases, especially when those are the actors responsible for implementing the technologies, then additional policy instruments are required to promote the uptake of these eco-innovations.

3. THE CASE OF THE TEXTILE INDUSTRY IN BIELLA, ITALY

The proposed approach has been applied to the textile industry of Biella, a province of northern Italy located in the Piedmont Region. The province covers an area of 930 km^2, hosts 82 communities and is one of the most significant areas for the textile industry worldwide, especially with regard to wool and cashmere products. The Biella district has traditionally been an important wool processing and textile centre, and the first textile factory dates back to 1254. Famous industrial groups with long tradition, as well as many SMEs producing high quality products were located in the area.

During the last decade, the active textile units in Italy have decreased by 28%. The crisis of the textile sector is much more acute in Biella since nearly half of the factories closed down and 50% of the employees lost their jobs. However, despite the economic crisis, Biella remains one of the most prominent production centres of wool fabrics for clothing and fine fibres with more than 650 active textile industrial units (Industrial Union of Biella – Personal Communication; EcoWater, 2015).

The textile industry uses a large amount of freshwater, especially during wet processing operations, such as dyeing, as water is the medium in which dyes, chemicals and dyeing auxiliaries are dissolved. The textile wastewater is rated among the most polluting industrial waste. It contains toxic and stable pollutants, a significant amount of suspended solids, nutrients, salts, high chemical and biological oxygen demand (COD, BOD), as well as heavy metals and increased colour concentrations. The disposal of these contaminated effluents into receiving water bodies influences the aquatic and terrestrial ecosystem, and human health (Chequer, et al., 2013). In the Biella region, the textile industry has a critical impact on the environment, particularly by polluting river water through process effluents. On the other hand, the industry has a high economic significance on textile commerce and the local workforce, and subsequently affects quality of life and final consumer costs.

On the basis of the above described picture the analysis that follows is mainly focused on the study of the dyeing process. Prospects for improving the system's overall eco-efficiency are investigated. Through the identification of the environmentally weak stages of the system, as well as the selection and implementation of innovative technologies that would upgrade the value chain, two alternative technology scenarios are formulated and compared to the baseline scenario. The first scenario aims at increasing resource efficiency, while the second at reducing water pollution.

3.1 System boundaries & Functional unit

For the purposes of our analysis, two representative units of the textile industry are considered (Figure 2):

- A unit with in-house wastewater treatment plant, where the dyeing process is using standard chemical methods (Unit A); and
- A unit which uses both standard chemical dyes and natural herbal dyes (in separate production lines) and is connected to the municipal wastewater network (Unit B).

The system under study is divided into the foreground and the background sub-systems. The foreground system contains two different chains, the water supply and the water use chain. The water supply chain consists of four stages, namely water abstraction, distribution, use and wastewater treatment, defined in such way to enclose the relevant actors involved in the system and the interactions among them. The actors of the system, both directly and indirectly involved, are the following:

- The regional authorities, responsible for the water supply to industry;
- The textile industry, including the chemical and natural dyeing units; and
- The municipalities' consortium, which is responsible for the operation of the wastewater treatment plant and the sewage disposal network.

(Figure 2)

Figure 2. Schematic representation of the examined system

The background system consists of the production processes of the supplementary resources (electricity and natural gas) and raw materials (dyes, additives, wool). However, only the electricity and natural gas production processes are taken into consideration for the eco-efficiency assessment, due to lack of data for the other processes.

The functional unit depends on the reference flow selected each time and the purpose of the analysis. In the current study, two different cases are examined. When the objective is the comparison between the two units, then the flow of interest is the unit of product delivered and the functional unit is defined as 1 kg of dyed product. On the contrary, when alternative technologies are compared, the quantity of interest is the water used for the production purposes and the functional unit is 1 m^3 of water used in the dyeing process.

3.2 Baseline Scenario Assessment

Unit A, the standard chemical dyeing unit, has an annual output of 500,000 kg dyed product. The dyeing process, it is estimated that 1 kg of dyes and additives are required, while 1.02 kWh of electricity and 0.64 m^3 of natural gas are consumed per kg of wool. Furthermore, the dyeing process needs 0.15 m^3 of water per kg of wool, which is abstracted from private wells using electric groundwater pumps. The electricity consumption of each pump is estimated at 0.13 kWh per m^3 of water abstracted. Finally, the in-house wastewater treatment plant consumes 0.7 kWh of electricity per m^3 of wastewater treated.

Unit B, the unit with two separate production lines, produces annually 392,000 kg of chemically dyed product and 98,000 kg of naturally dyed product. The requirements of the chemical dyeing production line are the following: 0.32 kg of dyes and additives, 1.44 kWh of electricity, 0.59 m^3 of natural gas and 0.16 m^3 of water per kg of wool. The natural dyeing process requires less electricity (1.27 kWh per kg of wool) but higher quantities of dyes and water (0.5 kg of dyes and 0.19 m^3 of water per kg of wool), while the required amount of natural gas remains the same. In both cases, water is abstracted from Quargnasca Torrent (Cervo River Basin) and is pumped using electricity driven pumps, which consume 0.11 kWh per m^3 of water abstracted. Unit B also filters wastewater before sending it to the municipality consortium owned wastewater treatment plant. The filtering process consumes electricity (0.55 kWh per m^3 of wastewater treated) and produces solid waste (0.27 kg of sludge from the natural dyeing process per m^3 of wastewater treated).

3.2.1 Environmental assessment

The environmental performance of the system is assessed through eight environmental midpoint indicators, representative of the specific system and relevant to the textile industry. The background processes that are taken into account for the assessment of the environmental impact are electricity and natural gas production, as it was not possible to collect data for the other background processes, including wool, dyes and additives production. The characterisation factors included in the CML-IA database are used for the calculation of the environmental impact of the foreground system, while the factors for the background system are obtained from the EcoInvent database, using the CML 2001 Method (Guinee, et al., 2001).

Table 1. Contribution of the foreground and the background systems in the overall environmental impact for the baseline scenario

Midpoint Impact Category	Environmental Performance Indicator	Foreground Contribution	Background Contribution
Climate change	0.01 $kgCO_{2eq}/m^3$	51%	49%
Freshwater Resource Depletion	0.15 m^3/m^3	100%	0%
Eutrophication	0.02 $kgPO_4^{3-}{}_{,eq}/m^3$	90%	10%
Human toxicity	2.68 $kg1,4DCB_{,eq}/m^3$	73%	27%
Acidification	0.05 $kgSO_2^{-}{}_{,eq}/m^3$	28%	72%

Aquatic Ecotoxicity	22.45 kg1,4DCB$_{,eq}$/m^3	99%	1%
Terrestrial Ecotoxicity	1.94 kg1,4DCB$_{,eq}$/m^3	99%	1%
Photochemical Ozone Formation	0.003 kg $C_2H_{4,eq}$/m^3	25%	75%

The environmental assessment of the baseline scenario is summarized in Tables 1 and 2. Table 1 presents the normalized values of environmental indicators per volume of water used, for the entire system and the contribution of the foreground and the background system separately. It is obvious that the most significant environmental problems are toxicity related issues (including human toxicity and ecotoxicity), due to chemicals used in the dyeing process, and freshwater depletion.

Table 2. Comparison of the environmental performance between the two units for the baseline scenario

Midpoint Impact Category	**Unit**	**Ind. Unit A**	**Ind. Unit B**
Climate change	kgCO_{2eq}/kg product	0.002	0.003
Freshwater Resource Depletion	m^3/kg product	0.023	0.029
Eutrophication	kg$PO_4^{3-}$$_{,eq}$/kg product	0.003	0.003
Human toxicity	kg1,4DCB$_{,eq}$/kg product	0.440	0.482
Acidification	kg$SO^{2-}$$_{,eq}$/kg product	0.008	0.009
Aquatic Ecotoxicity	kg1,4DCB$_{,eq}$/kg product	3.865	3.856
Terrestrial Ecotoxicity	kg1,4DCB$_{,eq}$/kg product	0.352	0.334
Photochemical Ozone Formation	kg $C_2H_{4,eq}$/kg product	$<10^{-3}$	$<10^{-3}$

Table 2 displays the environmental performance of the two industrial units for the baseline scenario. The figures include both the foreground and the background system contribution. It is evident that Unit A has better performance in climate change, freshwater resource depletion and acidification, due to lower electricity and water consumption. On the contrary, Unit B has lower values in the two ecotoxicity indicators due to the natural dyeing production line which discharges cleaner wastewater. However, the human toxicity indicator does not follow the same pattern, because in that case the contribution of the background electricity production counterbalances the direct environmental impact from the water effluents of the dyeing process.

3.2.2 Value assessment

All financial costs required for the calculation of the TVA have been collected through the local stakeholders are summarized in Table 3. The purchase cost for all the supplementary resources (i.e. electricity, natural gas) is the same for both units. The main difference is the price of dyes, which is assumed to be 5-6 €/kg of chemical dye but may reach 11 €/kg for the natural dye. However, similar is the difference in the price of the finished dyed product. In the case of chemical dyeing processes, it ranges from 5.5 €/kg to 7 €/kg whereas a naturally dyed product can be sold for as much as 15 €/kg. Unit A has lower expenses for water abstraction (due to private wells) and wastewater treatment and disposal (due to in-house treatment) but requires an extra expenditure for sludge treatment and disposal. The TVA from water use to the dyed product is estimated to be 18.36 € per m^3 of water used. Furthermore, both industrial units have positive annual economic balance. The annual net economic output is 548,946 € for Industrial Unit A and 2,434,621 € for Industrial Unit B.

Table 3. Financial costs of the two industrial units

Expenditure	**Ind. Unit A**	**Ind. Unit B (Chemical)**	**Ind. Unit B (Natural)**
Electricity	0.18 €/kWh		
Natural Gas	0.45 €/m^3		
Dyes and Additives	5.2 €/kg	6.0€/kg	11.0€/kg
Water Abstraction	2,200 €/yr	50,000 €/yr	
Wastewater Treatment and Disposal	0.35 €/m^3	0.85 €/m^3	0.85 €/m^3
Sludge Treatment and Disposal	0.85 €/kg sludge	-	-
Operation and Maintenance Cost	0.16 €/kg product	0.21 €/kg product	

3.2.3 Eco-efficiency assessment

Table 4 presents the results of the baseline eco-efficiency assessment both for the overall system and for each industrial unit separately. It is confirmed that the major environmental impact of the studied system are toxicity related issues and freshwater resource depletion. The assessment also indicates a clear superiority of the Industrial Unit B concerning eco-efficiency, with higher values in all eight indicators and thus better performance. Both units have a similar environmental performance (as seen in Table 2), but Unit B is more eco-efficient because its NEO is higher, due to the higher price of the natural dyed product.

Table 4. Baseline eco-efficiency assessment

Midpoint Impact Category	**Unit**	**Overall**	**Ind. Unit A**	**Ind. Unit B**
Climate change	€/kgCO_{2eq}	1,351	516	2,122
Freshwater Resource Depletion	€/m^3	122	50.9	179
Eutrophication	€/kg$PO_4^{3-}$$_{,eq}$	1,025	377	1,667
Human toxicity	€/kg1,4DCB$_{,eq}$	6.85	2.60	10.8
Acidification	€/kg$SO^{2-}$$_{,eq}$	366	147	550
Aquatic Ecotoxicity	€/kg1,4DCB$_{,eq}$	0.82	0.30	1.35
Terrestrial Ecotoxicity	€/kg1,4DCB$_{,eq}$	9.45	3.43	15.6
Photochemical Ozone Formation	€/kg $C_2H_{4,eq}$	6,959	2,732	10,660

3.3 Value chain upgrading

The baseline eco-efficiency assessment and the identification of the systems' environmental weaknesses have led to the selection of innovative technologies, which can upgrade the value chain. Thus, based on the results, two main objectives are set for the upgrading of the studied system: (a) increase of resource efficiency, focusing on freshwater, and (b) pollution prevention and control, focusing on treatment of water effluents. After discussing with the directly involved actors (EcoWater, 2015) and reviewing the relevant literature, six alternative technologies are selected for implementation in the current system, which are briefly described in the following paragraphs whereas the assumptions used for modelling purposes are presented in Table 5.

Smart pumping systems are centrifugal pumps equipped with a special instrumentation package, a microprocessor that can operate at variable speed and a specific software. They can match effectively pump output to system conditions and they adjust themselves to system changes without manual intervention. The flow rate is constantly adjusted to the system's requirements, so that leakages and bursts can be prevented, potentially resulting in water savings. Through their application to a water abstraction process, a 30-40% reduction in energy consumption and a subsequent reduction in air emissions can be achieved. For the application in the Biella region, it is assumed that the smart pumping systems are installed in both chains.

Table 5. Technologies selected for implementation in the studied system

Technology	Environmental Performance	Economic Performance			Source
		Investment Cost	O&M Cost	Lifetime	
Smart Pumping Systems	30-40% reduction in energy consumption	15,000-20,000€	-	15 years	(Stavale, 2001)
Automatic Dispensing Systems	15% reduction in abstracted water, as well as in energy and dyes consumed	150,000-300,000€	20,000 €/year	15 years	(Cotton Inc., 2009)
LLR Jet Dyeing Machines	50% reduction water abstraction, 40% in energy consumption and 20% in the use of dyes and additives	150,000-300,000€	20,000 €/year	10 years	(Cotton Inc., 2009)
Use of Natural Dyes	50% reduction in additives, 15% in energy and 15% increase in water consumption	-	3x more expensive than synthetic	-	Local Experts
Advanced Oxidation Processes	55-65% reduction in COD and heavy metals in effluents	100,000€	0.29 €/m^3 wastewater	10 years	(Yonar, 2011)
Membrane Bioreactors	95-99% reduction of BOD, COD and heavy metals in effluents	2,800€/m^3 wastewater	1.70 €/m^3 wastewater	10 years	(Cheryan & Rajagopalan, 1998).

Automatic dye and chemical dispensing technology involves automatic and semi-automatic weighting, dissolving and measuring systems that enable the precise delivery of dyeing chemicals and auxiliaries to production machines. Systems of varying levels of automation are available for dispensing both liquid and powder dyes and chemicals. By integrating these systems in the industrial unit, there will be a significant improvement in the accuracy of material additions, as well as the consistency of production by reducing at the same time the amount of water abstracted

(Cotton Inc., 2009). For the application in the Biella region, it is assumed that automatic dye dispensing systems are installed only in the chemical dyeing processes.

Low-liquor-ratio (LLR) jet dyeing machines are based on the principle of accelerating water through a venturi constriction or nozzle to transport fabrics, and operate efficiently under high temperatures (maximum temperature ranges between 135 and 140°C) and ensures high quality with a very low liquor ratio (equal to or less than 8:1). The reduced liquor ratio guarantees optimum dyeing results in very short times, enhancing energy saving and reducing the consumption of water and auxiliary resources. Jet dyeing machines have been used commercially for 40 years and they can be considered as a mature technology (Cotton Inc., 2009). For the application in the Biella region, it is assumed that LLR dyeing machines are installed only in the chemical dyeing processes.

Natural dyes, derived from plants, minerals and animals, can make textile processes more sustainable. There are three primary categories of natural dyes; plant dyes (Indigo), animal dyes (Cochineal) and mineral dyes (Ocher). Taking into account the toxic effects of synthetic dyes, the use of natural dyes improves the environmental performance of the textile dyeing and finishing processes, regarding chemicals and energy consumption and eliminates heavy metals from the wastewater effluents. The price of natural dyes is higher than that of the standard chemical ones; however, the dyed product can be sold at a much higher price and the production cost can be controlled and reduced in terms of water savings and reduction of quantities of chemicals used. For their application to the studied system, it is assumed that Unit B increases the capacity of the natural dyeing production line, and 75% of its total production volume consists of natural dyed wool.

Advanced oxidation processes (AOPs) involve the generation and use of reactive but relatively non-selective free radicals (i.e. hydroxyl radicals), which in sufficient amounts oxidise most of the chemicals present in textile wastewater (Yonar, 2011). Among them, the Fenton process is a widely studied and used catalytic method, based on the generation of hydroxyl radicals (HO^-) from hydrogen peroxide with iron ions acting as a homogeneous catalyst at acidic pH and ambient conditions. Its basic advantages include high efficiency of the oxidation reaction, low cost, easily available substrates and simplicity of the procedure. The Fenton process can be used as a wastewater pre-treatment, achieving full decolourization and a 55-65% reduction in COD and heavy metals in textile effluents (Bautista, et al., 2008). It is assumed that the advanced oxidation process is implemented only in Unit A.

Membrane bioreactors (MBRs) consist of a suspended growth bioreactor, combined with membrane filtration equipment, typically microfiltration and ultrafiltration membranes, which perform a solid/liquid separation, requiring no secondary and tertiary clarifiers that are used in conventional activated sludge processes (Radjenović, et al., 2008). They are extensively used for industrial and municipal wastewater treatment, operating at high contaminant volumetric removal rates and flows. In general, they are characterised by higher energy consumption compared to other biological treatments, but also by lower sludge production and can lead to lower quantities of BOD, COD and heavy metals in the effluents (Bolzonella and Fatone, 2008; Badani, et al., 2005). It is assumed that the MBR is installed only in Unit A, thus improving the eutrophication and toxicity indicators and enabling the reclamation and reuse of the water.

A preliminary eco-efficiency assessment of the six selected technologies is presented in Figure 3 in order to potentially exclude those who deteriorate the performance of the system. However, in this case no technologies were excluded. It is also apparent that smart pumping systems and LLR jet dyeing systems improve significantly three of the indicators; namely climate change, freshwater resource depletion and acidification while natural dyes and MBR show greater improvement in aquatic and terrestrial ecotoxicity.

(Figure 3)

Figure 3. Eco-efficiency assessment of the six selected technologies

As a second step in the process of upgrading the value chain, two alternative technology scenarios are examined and assessed. The first one is characterised by the application of a set of technologies focusing primarily on resource efficiency, while the second scenario includes technologies oriented towards water pollution prevention. The combination of technologies used in each scenario is shown in Table 6. More specifically, the first scenario (RE Scenario) includes the implementation of the technologies that reduce the consumption of water and supplementary resources. The smart pumping system is applied to water abstraction, while the LLR jet dyeing machine and the automatic dye and chemical dispensing system are applied to the chemical dyeing process. The second scenario, focusing on pollution prevention and control (PPC Scenario), investigates the implementation of two technologies at the stage of wastewater treatment; one pre-treatment process and one for the main treatment, and the partial replacement of chemical dyeing processes with natural dyeing. There were no innovative technologies identified, with primary objective the promotion of circular economy, and thus only two alternative scenarios were developed.

Table 6. Alternative technology scenarios

Technology Scenario	**Technologies Included**
…towards Resource Efficiency	Smart Pumping Systems
	Automatic Dye and Chemical Dispensing
	Low-Liquor-Ratio Jet Dyeing Machines
…towards Pollution Prevention and Control	Use of Natural Dyes
	Advanced Oxidation Process (Fenton’s Reagent)
	Membrane Bioreactor

4. RESULTS

Table 7 summarizes the environmental performance of the two technology scenarios through the relative change in the eight environmental indicators of the upgraded system compared to the baseline scenario. An obvious observation is that the technology scenario towards resource efficiency significantly improves freshwater resource depletion (reduction by 52.8%) and slightly improves energy related indicators (acidification by 12.4%, climate change by 9.3% and photochemical ozone formation by 15.9%). On the contrary, all toxicity related indicators are significantly improved through the implementation of the technology scenario towards pollution prevention and control (reduction in aquatic ecotoxicity by 50.1%, terrestrial ecotoxicity by 53.4%, and human toxicity by 32.7%). Eutrophication is also slightly improved but all other indicators are not positively affected. However, it should be noted that the implementation of both scenarios does not have a negative impact on any of the indicators.

Figure 4 presents the eco-efficiency indicators for the two technology scenarios, confirming that both scenarios improve all eight eco-efficiency indicators. Furthermore, the total value added increases in both cases (49.52€/m^3 in the RE scenario, 23.12€/m^3 in the PP scenario). Thus, from a systemic point of view, the two scenarios show promising results, since they improve both the economic and the environmental performance of the entire value chain.

Table 7. Environmental performance assessment of the two alternative technology scenarios

Midpoint Impact Category	**Baseline**	**RE Scenario**	**PPC Scenario**
Climate Change	2,311 $kgCO_{2eq}$	−9.3%	−0.2%
Freshwater Resource Depletion	25,500 m^3	−52.8%	0.0%
Eutrophication	3,047 $kgPO_4^{3-}{}_{,eq}$	−1.9%	−20.3%
Human toxicity	455,971 $kg1,4DCB_{,eq}$	−4.2%	−32.7%
Acidification	8,527 $kgSO^{2-}{}_{,eq}$	−12.4%	−0.3%
Aquatic Ecotoxicity	3,817,041 $kg1,4DCB_{,eq}$	0.0%	−50.1%
Terrestrial Ecotoxicity	330,541 $kg1,4DCB_{,eq}$	−0.1%	−53.4%
Photochemical Ozone Formation	448 kg $C_2H_{4,eq}$	−15.9%	−0.3%

However, the economic performance of each actor should be also assessed before considering these two scenarios as candidates for implementation. Table 8 indicates that the NEO of all the directly involved actors increases or, in the worst case, remains constant, with the exception of the NEO of the Industrial Unit A in the technology towards pollution prevention and control (Table 7). More specifically, the economic performance of the Region is unaffected, as it depends on the net revenues from the water services provided to Units A and B, which are fixed on an annual basis (2,200 €/year and 50,00 0€/year respectively). The NEO of the Municipalities' Consortium mainly depends on the amount of wastewater treated on annual basis. Thus, it remains constant in the RE scenario but increases by about 6.7% in the PP scenario, since the introduction of natural dyeing lead to the production of greater quantities of wastewater.

(Figure 4)

Figure 4. Eco-efficiency assessment of the alternative technology scenarios

Table 8. Net economic output all the involved actors and the total valued added of the system

Actors	Net Economic Output		
	Baseline	**RE Scenario**	**PPC Scenario**
Industrial Unit A	548,946 €	1,365,876 €	512,832 €
Industrial Unit B	2,434,621 €	2,704,712 €	3,273,878 €
Region	52,200 €	52,200 €	52,200 €
Municipalities' Consortium	86,365 €	86,365 €	92,145 €
Total Value Added	3,122,132 €	4,209,153 €	3,931,055 €

The two most critical actors are the industrial units, which are also responsible for the implementation of the technologies. In the PP scenario, the NEO of Unit B increases but the NEO of Unit A is negatively affected, indicating that the economic profit from the installation of technologies towards pollution prevention and control, and particularly the advanced oxidation process and the MBR, is not high enough to counterbalance the high investment cost. Thus, this scenario should be considered as not economically feasible under the current conditions unless a significant economic incentive was offered to the industrial actors.

In the RE scenario, the NEO of both industrial units increases, but not significantly enough. After discussions with both industries and other important regional actors and policy makers (EcoWater, 2015), concerns were raised about the high investment cost required for its implementation, especially under the given economic conditions and the current crisis, which has led to the closing of more than half of the factories in the last ten years. All of them agreed that additional economic incentives, such as environmental taxes, tax exemption or subsidies, are required to make the scenario acceptable for the industries. Moreover, since more than 500 SMEs producing high quality textiles are still located in the Biella region, an alternative business model, such as the joint implementation of the WWTP upgrade by more than one actor, could be considered (either through industrial clustering or by collaborating with the municipalities' consortium). Even that, however, would require changes in the policy framework and in the existing operating mechanisms of the textile industry at a regional or even national level, in order to facilitate the uptake of such a joint scheme. The local stakeholders also suggested that all the above mentioned actions should be supplemented by a campaign led by the textile companies of Biella, and supported by local authorities, in order to promote the local environmentally friendly products, compared with imported textiles, and at the same time raise public awareness about public health issues related to clothes of very low quality and to dangerous chemical agents used for their production. The consensus among all the participants was that a radical eco-innovative shift in the production process requires strong support from the central government and the regional authorities.

5. CONCLUSIONS

This paper presents a methodological framework for the assessment of eco-efficiency in water use systems, which was applied to the textile industry in Biella, Italy. The main environmental problems of the area are freshwater resource depletion (due to waterintensive processes like dyeing and finishing) and toxicity of the effluents which are discharged in the river. To this end two alternative scenario were formulated, each one targeting at one of the two main regional issues, and their performance was compared with the current situation. More specifically, the first one investigated the implementation of a smart pumping system at the stage of water abstraction and a combination of technologies applied to the chemical dyeing process (automatic dye and chemical dispensing system and low-liquor-ratio jet dyeing),. The second scenario examined the prospect of improving the effectiveness of wastewater treatment by installing innovative technologies which are suitable for treating textile effluents, and the partial replacement of chemical dyeing processes with natural dyeing.

The results have showed that technically there is potential for improving the environmental performance of the system. More specifically, the first scenario is characterised by a significant improvement of the freshwater resource depletion, with a 3-fold increase in the respective eco-efficient indicator, whereas in the second scenario all eco-efficiency indicators were improved, and the higher impact was observed to the aquatic and terrestrial ecotoxicity categories. However, the necessity of a systemic approach was justified when the economic feasibility of the two scenarios was assessed. Although the overall economic performance was improved in both cases, the scenario towards pollution prevention and control reduces the economic output of the one industrial unit, rendering it economically viable. Furthermore, the discussion with the stakeholders and the analysis of the external environment has also revealed difficulties in implementing the scenario towards resource efficiency, although it is economically favourable for all involved actors. The main reason is the high investment cost, required from the private companies, combined with the current economic crisis, which has significantly affected the textile industry in Italy, and the ongoing competition with low price/low-quality imported textiles from developing countries. The two locally organized workshops have concluded that specific policies are required to facilitate the uptake of the proposed scenario. These could be in the form of either economic incentives (e.g. subsidies, tax exemptions), protective regulations/actions (e.g. public awareness campaign) or even informal industrial coordination on a regional level (e.g. memorandum of cooperation among industries towards the joint of implementation of the proposed scenario).

The presented case study was among the eight different case studies analysed during the EcoWater project. So, apart from the case-specific results and recommendations, the objective was also to test the applicability of the framework to several complex water use systems and identify the main challenges and weaknesses as well as areas for further improvement and research. Our experience has indicated that the proposed methodological framework can give reliable and accurate results and can be expanded and applied to other water use systems. The results are more meaningful when comparing two systems with similar products or even two different configurations of the same system. However, the comparison becomes more difficult when comparing two industrial systems with completely different production lines. It was also clear that a systemic approach is required in cases where multiple actors are involved and the overall assessment of the system's performance is not enough.

The main challenge faced during model development was related to the fact that the textile industry in the Biella region consists of more than 500 small and medium industrial units, each one with different production lines and different schemes concerning water supply (private pumping or connection to the regional network) and wastewater treatment (private treatment facilities or connection to the municipal WWTP). Thus, two industrial units were selected as the most representative ones among the ones willing to cooperate and provide numerical data, after consultation with local experts. This fact has highlighted the difficulties when attempting to model an industrial cluster with many small and remote industrial units, using the proposed framework.

Another difficulty, which was also brought up by other case studies, was the lack of publicly available impact factors for the background processes. Apart from the most common ones (production of fossil fuels and electricity), data for the production of case specific supplementary resourced (e.g. dyes, additives) could not be retrieved. It has been concluded that the approach should become more homogenous, especially concerning the definition of the boundaries of the system and the processes that are included in the background system. This will facilitate the comparison among case studies, and may lead to the estimation of a range of values for each indicator and of reference values for normalizing them. It will also allow technology benchmarking for each case study and lead to the identification of the most eco-efficient options for each sector.

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References

Abra, J., 2012. Innovation for sustainable water. Eco-Innovation Brief #2, Eco-innovation observatory.

Allwood, J.M., Laursen, S.E., Russell, S.N., Malvido de Rodríguez, C., Bocken, N.M.P., 2008. An approach to scenario analysis of the sustainability of an industrial sector applied to clothing and textiles in the UK, J. Clean. Prod. 16(12), 1234-1246. http://dx.doi.org/10.1016/j.jclepro.2007.06.014.

Badani, Z., Ait-Amar, H., Si-Salah, A., Brik, M., Fuchs, W., 2005. Treatment of textile waste water by membrane bioreactor and reuse. Desalination 185 (1-3), 411-417. http://dx.doi.org/10.1016/j.desal.2005.03.088.

Bautista, P., Mohedano, A.F., Casas, J.A., Zazo, J.A., Rodriguez, J.J., 2008. Review: An overview of the application of Fenton oxidation to industrial wastewaters treatment. J. Chem. Tech. Biotechnol. 83 (10), 1323-1338. http://dx.doi.org/10.1002/jctb.1988.

Bolzonella, D., Fatone, F., 2008. Application of the membrane bioreactor technology for wastewater treatment and reuse in the Mediterranean region, in Fried, J., Scherfig,

J. (Eds.), Proceedings of the International Conference on Water Scarcity, Global Changes and Groundwater Management Responses. Irvine, USA.

Chequer, F.M.D., De Oliveira, G.A.R., Ferraz, E.R.A., Cardoso, J.C., Zanoni, M.V.B., De Oliveira, D.P., 2013. Textile Dyes: Dyeing Process and Environmental Impact, in: Günay, M., (Ed.), Eco-Friendly Textile Dyeing and Finishing. pp. 151-176. http://dx.doi.org/10.5772/53659.

Cheryan, M., Rajagopalan, N., 1998. Membrane processing of oily streams. Wastewater treatment and waste reduction. J. Membr. Sci. 151 (1), 13-28. http://dx.doi.org/10.1016/S0376-7388(98)00190-2.

Cotton Inc. 2009. A World of Ideas: Technologies for Sustainable Cotton Textile Manufacturing. America's Cotton Producers and Importers.

EcoWater, 2015. Synthesis report from the 2nd Round of Case Study events, Public Deliverable 6.2 of the EcoWater Project.

Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Res. Pol. 31, 1257–1274. http://dx.doi.org/10.1016/S0048-7333(02)00062-8.

Guinée, J.B.; Gorrée, M.; Heijungs, R.; Huppes, G.; Kleijn, R.; Koning, A. de; Oers, L. van; Wegener Sleeswijk, A.; Suh, S.; Udo de Haes, H.A.; Bruijn, H. de; Duin, R. van; Huijbregts, M.A.J., 2002. Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background. Kluwer Academic Publishers, ISBN 1-4020-0228-9, Dordrecht.

Huppes, G., Ishikawa, M., 2005. Eco-efficiency and its terminology. J. Ind. Ecol. 9 (4), 43-46. http://dx.doi.org/10.1162/108819805775247891.

Ingaramo A., Heluane H., Colombo M., Cesca M., 2009. Water and wastewater eco-efficiency indicators for the sugar cane industry. J. Clean. Prod. 17 (4), 487-495. http://dx.doi.org/10.1016/j.jclepro.2008.08.018.

ISO, 2006. Environmental management – Life cycle assessment – Requirements and guidelines, ISO 14044:2006, Genève, Switzerland: International Organization for Standardization.

ISO, 2012. Environmental management – Eco-efficiency assessment of product systems – Principles, requirements and guidelines, ISO 14045:2012, Genève, Switzerland: International Organization for Standardization.

Jollands N., Lermit J. Patterson M., 2004. Aggregate eco-efficiency indicators for New Zealand – A principal components analysis. J. Environ. Manage. 73 (4), 293-305. http://dx.doi.org/10.1016/j.jenvman.2004.07.002.

JRC, 2010. International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Provisions and Action Steps. Luxembourg: Publications Office of the European Union.

Koskela, M., 2014. Measuring eco-efficiency in the Finnish forest industry using public data. J. Clean. Prod., Article in Press. http://dx.doi.org/10.1016/j.jclepro.2014.04.042.

Michelsen, O., Magerholm Fet, A., A., Dahlsrud, A., 2006. Eco-efficiency in extended supply chains: A case study of furniture production. J. Environ. Manage. 79 (3), 290-297. http://dx.doi.org/10.1016/j.jenvman.2005.07.007.

Mickwitz, P., Melanen, M., Rosenstro, U., Seppälä, J., 2006. Regional eco-efficiency indicators – a participatory approach. J. Clean. Prod. 14(18), 1603-1611. http://dx.doi.org/10.1016/j.jclepro.2005.05.025.

Mila i Canals, L., Chenoweth, J., Chapagain, A., Orr, S., Anton, A., Clift, R., 2009. Assessing freshwater use impacts in LCA: Part I - inventory modelling and characterisation factors for the main impact pathways. International Journal of Life Cycle Assessment 14 (1), 28-42. http://dx.doi.org/10.1007/s11367-008-0030-z.

Nieminen, E., Linke, M., Tobler, M., Vander Beke, B., 2007. EU COST Action 628: life cycle assessment (LCA) of textile products, eco-efficiency and definition of best available technology (BAT) of textile processing, J. Clean. Prod. 15(13-14), 1259-1270. http://dx.doi.org/10.1016/j.jclepro.2006.07.011.

OECD, 1998. Eco-efficiency. Paris: Organisation for Economic Co-operation and Development).

OECD, 2009. Sustainable Manufacturing and Eco-Innovation: Framework, Practices and Measurement. Synthesis Report, Paris.

Parisi, M.L., Fatarella, E., Spinelli, D., Pogni, R., Basosi, R., 2015. Environmental impact assessment of an eco-efficient production for coloured textiles, J. Clean. Prod. 108, 514-524. http://dx.doi.org/10.1016/j.jclepro.2015.06.032.

Radjenović, Jelena , Marin Matošić, Ivan Mijatović, Mira Petrović, Damià Barceló, 2008. Membrane Bioreactor (MBR) as an Advanced Wastewater Treatment Technology. The Handbook of Environmental Chemistry 5, 37-101. http://dx.doi.org/10.1007/698_5_093.

Schaltegger, S., Sturm, A., 1989. Ecology induced management decision support. Starting points for instrument formulation. WWZ-Discussion paper No. 8914, Wirtschaftswissenschaftliches Zentrum (WWZ), Universität Basel.

Stavale, A.E., 2001. Smart Pumping Systems: The Time is Now. Unpublished White Paper (ITT Industries, Fluid Technology Corporation).

UNWATER (2009) The United Nations World Water Development Report vol.3, Water in a Changing World. UNESCO Publishing.

Van Caneghem, J., Block, C., Cramm, P., Mortier, R., Vandecasteele, C., 2010. Improving eco-efficiency in the steel industry: The ArcelorMittal Gent case. J. Clean. Prod. 18 (8), 807-814. http://dx.doi.org/10.1016/j.jclepro.2009.12.016.

WBCSD., 2000. Eco-efficiency-Creating more value with less impact. World Business Council for Sustainable Development.

Wursthorn S., Poganietz W-R., Schebek L., 2011. Economic–environmental monitoring indicators for European countries: A disaggregated sector-based approach for monitoring eco-efficiency. Ecol. Econ. 70 (3), 487-496. http://dx.doi.org/10.1016/j.ecolecon.2010.09.033.

Yonar, T., 2011. Decolorization of Textile Dyeing Effluents Using Advanced Oxidation Processes, in: Hauser, P. (Ed.), Advances in Treating Textile. http://dx.doi.org/10.5772/18908.

You, S., Cheng, S., Yan, H., 2009. The impact of textile industry on China's environment. Int. J. Fash. Des. Technol. Educ. 2 (1), 33-34. http://dx.doi.org/10.1080/17543260903055141.

Highlights for Paper JCLEPRO-D-15-00978. Value chain upgrading in a textile dyeing industry

- A systemic approach has been used to assess the eco-efficiency of a textile industry.
- The two more significant issues are freshwater resource depletion and ecotoxicity.
- Alternative technologies have been assessed, indicating room for improvement.
- The high investment cost is the most notable prohibitory factor for their uptake.
- Government support and economic incentives are required to facilitate the uptake.