International Journal of Environmental Science and Technology (2023) 20:11165–11176
https://doi.org/10.1007/s13762-023-05107-0

ORIGINAL PAPER

Merging treatability results and sustainability assessment: a segregated textile dyehouse effluent

K. Dogan[1] · B. Atilgan Turkmen[2] · F. Germirli Babuna[1] · O. Koba Ucun[1] · I. Arslan Alaton[1]

Received: 22 July 2022 / Revised: 3 July 2023 / Accepted: 13 July 2023 / Published online: 28 July 2023

Abstract

Treatability studies are performed on industrial wastewaters before defining a proper treatment scheme. Segregated effluents are of concern for industrial sectors such as textile, leather, metal etc. where wastewater characterization differs substantially depending on the various processes applied. Conclusions are drawn from the results obtained by checking the removal efficiencies. A treatment train is recommended based on the pollutant removal efficiencies. This type of inadequate evaluation is doomed to fail as it lacks the cross media effects and a whole spectrum of environmental impacts. In this context, the current study targets merging treatability results with the sustainability assessment. A segregated textile wastewater that contains hydrolyzed Reactive Black 5 dye (RB5) is subjected to treatability tests with UV-C activated persulfate (PS) and UV-C activated percarbonate (PC). The results that show 100% RB5 removal are evaluated via life cycle assessment (LCA). By doing so, the treatment alternative that yields minimal environmental impacts is stated. The life cycle assessment methodology used is structured according to the ISO 14040/14044 guidelines. The GaBi software version 7.3 is adopted. The CML is used to estimate the life cycle environmental impacts. The following environmental impact categories are investigated: Global warming potential (GWP), abiotic depletion potential (ADP fossils and elements), acidification potential (AP), eutrophication potential (EP), freshwater aquatic ecotoxicity potential (FAETP), human toxicity potential (HTP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP) and terrestrial ecotoxicity potential (TETP).

Keywords Environmental impacts · Industrial wastewater · Life cycle assessment · Photochemical oxidation · Reactive black 5 dye · Segregated effluents · Treatment

Introduction

The environment has become increasingly polluted as a result of the waste generated through industrial activities. Various natural and synthetic pollutants and heavy metals in wastewater are the major issues due to their negative effects on humans and other organisms (Ahmad et al. 2020, 2021; Akhtar et al. 2021; Briffa et al. 2020).

Treatment schemes for industrial effluents are shaped by referring to the results of treatability and modelling studies (Li et al. 2019; Germirli Babuna et al. 1998a; 1998b; 1999) that yields the lowest treatment costs (Ilhan et al. 2019; Erdogan et al., 2004). For some cases energy neutrality gains importance (Ødegaard, 2016) along with costs. In this sense, pollutant removal efficiencies obtained during treatability investigations together with the financial burdens usually dictate the applicable treatment train. However, such an approach concentrating only on the removal of pollutants yields inadequate conclusions as cross media effects

Editorial responsibility: SUNIL Kumar.

✉ F. Germirli Babuna
germirliba@itu.edu.tr

K. Dogan
kubradgn46@gmail.com

B. Atilgan Turkmen
burcin.atilganturkmen@bilecik.edu.tr

O. Koba Ucun
olgakoba24@gmail.com

I. Arslan Alaton
arslanid@itu.edu.tr

[1] Environmental Engineering Department, Civil Engineering Faculty, Istanbul Technical University, 34469 Maslak, Istanbul, Turkey

[2] Chemical Engineering Department, Bilecik Seyh Edebali University, 11230 Bilecik, Turkey

covering the whole spectrum of environmental impacts gain importance.

Segregated effluents with substantially different characterizations are produced in certain industrial sectors such as textile, leather, metal etc. as various auxiliaries are added during various operations under different conditions. Textile industry has a very complex nature in terms of the refractory wastewater constituents as quite a number of auxiliary chemicals are involved in the production of a variety of goods (Orhon et al. 2003). This complex nature reflects itself on the treatment schemes prescribed for textile effluents (Karahan et. al. 2002; Germirli et al. 1990). Effective industrial effluent management can be achieved by examining the treatment requirements of segregated wastewater streams having different natures (Dulkadiroglu et al. 2002, 2022; Orhon et al. 2002; Dogruel et al. 2003; Koyunluoglu et al. 2006; Arslan-Alaton et al. 2005; 2006; Oktay et al. 2007; Tezgel et al. 2014; Germirli Babuna et al. 2016).

It is a well-known fact that textile finishing mills generate effluents with color. As a consequence, standards with color limitations are developed for textile dyehouse wastewaters and treatment methodologies targeting color removal are adopted. Besides, only certain steps in textile preparation, dyeing and finishing operations produce colored segregated effluents. Proper environmental management dictates not mixing the segregated textile wastewaters containing color with the ones without color and solving the color problem by handling the colored streams separately. Various treatment alternatives are proposed in the literature to remove color in textile wastewaters (Bilińska & Gmurek, 2021; Collivignarelli et al. 2019; Maqbool et al. 2020; Samsami et al. 2020). It should be noted that commercial textile dyes are not toxic, their toxicity values are generally very low. They are only intentionally designed to resist biochemical as well as photolytic/photochemical/chemical degradation. As such, they remain in the treated dyehouse effluent without deterioration and advanced chemical treatment methods/conditions are needed to degrade the dyes/remove color from dyehouse effluent. However, during dye degradation with strong chemical oxidants such as ozone and ozone combined with hydrogen peroxide or ultra violet radiation forming advanced oxidation processes, it might be possible that degradation products which are more toxic than the original dyes (Arslan-Alaton and Akmehmet Balcioglu 2001; Arslan-Alaton 2003; Arslan-Alaton 2012; Bilinska et al. 2016; Freeman and Reife 2003).

The textile industry is a very water- and chemical-intensive industry. This sector is known for its extremely high water consumption (≥ 1000 m^3/d), the complexity and variety of dyes, surfactants, sequestering agents, dye auxiliary chemicals, organic/inorganic salts as well as acids/alkalis employed; producing rather difficult-to-treat, problematic waste streams (Grau 1991; Madhav et al. 2018). Conventional biological (activated sludge, attached growth, either aerobic or anaerobic/anoxic) and physicochemical treatment of textile effluent is routinely practiced, however, with limited success since characteristic pollution parameters of the textile industry such as COD, color and sulphur cannot be removed efficiently (Madhav et al. 2018; Periyasamy et al. 2018). Until now, several physical (adsorption, coagulation-flocculation, precipitation) and chemical (ozonation, wet air oxidation, sonolysis, advanced oxidation with the Fenton's reagent) treatment alternatives have proven to successfully remove color in dyehouse effluents and textile industry wastewater (Elwakeel 2009; Katheresan et al. 2018; Kokabian et al. 2013; Kusvuran et al. 2005). However, their real-scale application/implementation is most of the time economically not attractive and their performance in total and dissolved organic carbon (TOC and DOC) removal is relatively poor compared to color removal. Hence photochemical (mostly UV-C and UV-A-based) activation of oxidants or catalyst materials has recently become a promising alternative to improve biodegradability, remove color, organic carbon and eventually toxicity from textile wastewater (Cisneros et al., 2002; Raju et al. 2008). Among these photochemical advanced oxidation processes, the UV-C activation of peroxides such as persulfate and more recently percarbonate offers several advantages such as ease of operation, superior/efficient organic matter removal accompanied with rapid color abatement and detoxification, no sludge formation, no air emissions and the use of relatively green oxidants, namely peroxides (Fadaei et al. 2021; López Cisneros et al. 2002; Raju et al. 2008). The major operating cost is related to electric energy requirements to run the UV-C (short-UV) lamps, lamp replacement (around 20–30% of the electricity costs) as well as peroxide costs (Fadaei et al. 2021; López Cisneros et al. 2002; Yue-hua et al. 2011).

Speaking for the process chemistry, persulfate (PS) activation with UV-C mainly produces sulfate radicals ($SO_4\cdot^-$), whereas percarbonate (PC) activation with UV-C basically forms hydroxyl (HO·) as well as the more selective bicarbonate/carbonate radicals ($HCO_3\cdot/CO_3\cdot^-$) (Bennedsen et al. 2012; Liu et al. 2018; Miao et al. 2015; Yang et al. 2017). These react with dye molecules and dye assisting auxiliary chemicals to ultimately form mineralization end products of the dyehouse effluent ingredients. Bimolecular reaction rate constants are typically in the order of 10^{-6}–10^{-9} M^{-1} s^{-1} range for dyes and dye auxiliary chemicals (Bennedsen et al. 2012; López Cisneros et al. 2002; Raju et al. 2008). However, the high salinity and alkalinity of dyehouse effluent create a competitive inhibitory environment in the reaction solution and hence negatively affect oxidation efficiencies (Cooper & Zika 1983; Peyton 1993; Pignatello et al. 2006). Thus, process optimization in terms of pH and oxidant concentration is very critical for photochemically-driven advanced oxidation processes.

When applied to a product (Sezginer et al. 2022; Ozsahin et al. 2022), process (Ozkan et al. 2017; 2020) or service, life cycle assessment (LCA) methodology yields fruitful outcomes to envisage the environmental impacts. A wide spectrum of environmental impact categories can be covered ranging from global warming to various ecotoxicities with LCA. Besides, the whole life cycle or a certain life stage can be investigated in terms of impacts via LCA. There are LCA studies performed on treatment systems, such as operation and maintenance of industrial water purification systems (Yalamacilar, et al. 2021); operation of a wastewater treatment plant (Başkurt et al. 2017); construction (Elginoz et al 2019); and operation (Saad et al. 2019) of a water treatment plant. Putting LCA into use during treatability studies is of importance as decisions on treatment units are shaped based on the results of treatability.

In this context, the objective of this study is to develop a roadmap that merges the treatability results with the sustainability assessment. For this purpose, a segregated textile dyebath discharge that contains hydrolyzed Reactive Black 5 dye (RB5) is subjected to treatability tests with UV-C activated persulphate (PS) and UV-C activated percarbonate (PC). The results yielding 100% RB5 removal are evaluated via LCA to find out the treatment alternative with minimal environmental impacts. This research was performed between the years of 2020–2021 in Istanbul, Turkey.

Materials and methods

All the laboratory scale treatability experiments are conducted on simulated segregated textile wastewater. Separate applications of PC and PS together with UV-C are run.

Experimental

Preparation of the spent, reactive dyebath effluent

A spent (exhausted) reactive dyebath effluent was prepared by dissolving the reactive dye Reactive Black 5 (RB5) in T = 80 °C distilled water and increasing the reactive dye solution's pH values to above 11 (≈ 11.2–11.5) by adding caustic soda (NaOH; 6 N) to the RB5 solution. In this way, complete hydrolysis of RB5 dye was ensured. Caustic soda is frequently being used during the reactive dyeing process to release the vinyl sulphone group and initiate covalent bond formation between the dye molecule's reactive group and the cellulosate anions (Reife 2000).

Peroxide/UV-C experiments

The spent reactive dyebath was used in the peroxide/UV-C experiments after 50-fold dilution and pH re-adjustment to 8.0 with NaOH solutions (0.1 N and 1 N) to mimic the exact composition of a typical reactive dyehouse effluent (RB5 = 20 mg/L; TOC = 5.25 mg/L) after the textile dyeing, rinsing and finishing stages prior to discharge for dyehouse effluent treatment (Reife 2000). The peroxide/UV-C experiments were conducted in a 500 mL-capacity three-neck quartz flask (h = 10 cm; r = 4 cm) where the reaction solution was stirred at 100 rpm to ensure proper mixing and molecular oxygen saturation. The photochemical reaction chamber consisted of a LZC-ORG model (Luzchem Research Inc., Ontario, Canada) photoreactor (dimensions = 32 × 33 × 21 cm) equipped with a digitally controlled thermometer and a magnetic stirrer. Ten fluorescent UV-C lamps (8 W each) with a total incident light flux of $I_o = 1.3$ W/L measured with a UV-meter were used in the peroxide/UV-C experiments. Prior to the photochemical experiments, sodium percarbonate (SPC) or sodium persulphate (SPS) was added to the reaction solutions and the UV-C lamps were turned on 15–20 min before the start of the experiments to ensure a stable fluorescent UC-C light emission. Samples were taken at regular time intervals to measure color (peak absorbance at 600 nm) and total organic carbon (TOC). The pH was also followed during the experimental runs. The photoreactor set-up and experimental procedure are described elsewhere in more detail (Ozyildiz et al. 2019).

Statistical analysis was carried out for all instrumental measurements (color as peak absorbance and total organic carbon-TOC) as well as the calculation of color removal rate coefficients (in min^{-1}) using MS Office Excel software. Duplicates were assessed for color (peak absorbance) and TOC results. The significance level in all calculations was set as $p < 0.05$.

Life cycle assessment methodology

The life cycle assessment methodology used is structured according to the ISO 14040/14044 guidelines (ISO 2006a, 2006b). The GaBi software version 7.3 (Sphera 2017) is used. The background data is derived from the Ecoinvent 3.1 Database (Ecoinvent 2013).

Aim and scope of the study

The objective of this study is to evaluate the environmental effects of laboratory-scale decontamination studies performed in segregated textile wastewater streams and to determine which method and conditions are the most environmentally sustainable among the various alternatives.

This study focuses on the energy management and chemical usage of oxidation-based wastewater treatment processes. A comparison of potential environmental impact categories is made in the life cycle models based on energy

consumption and different amounts of chemicals used in wastewater treatment experiments.

In this study, "1 m^3 treated wastewater" is selected as the functional unit and all inventory data and environmental impacts are evaluated through this functional unit.

As illustrated in Fig. 1, the system boundaries include the production and transportation of chemicals to the facility, as well as the energy consumption used in experiments.

Inventory analysis

The data used in the study were obtained through experimental studies. The experimental results of the laboratory studies are tabulated in Table 1.

As can be seen from the Table 1, Run 1 and 2 yields the same outcome. Because of this, only Run 1 where a lower level of SPS is fed to the system is analysed with LCA. Similarly, among Runs 3 and 4, only Run 3 is selected for LCA as it requires less SPS input to produce the same removal. Besides Run 10 is also not included in LCA, since a similar outcome with lower SPC input is obtained in Run 9. To sum all up, LCA studies are not performed on Runs 2, 3 and 10, as it is possible to get the same output with fewer inputs.

A model for grid electricity in Turkey has been created using the Ecoinvent database (Ecoinvent Database, 2013) regarding electricity generation in Turkey 2019 (TEIAS 2019). The energy production in Turkey used in the study is based on fossil fuels, primarily hard coal (20%), natural gas (19%), lignite (15%) and hydropower (% 22).

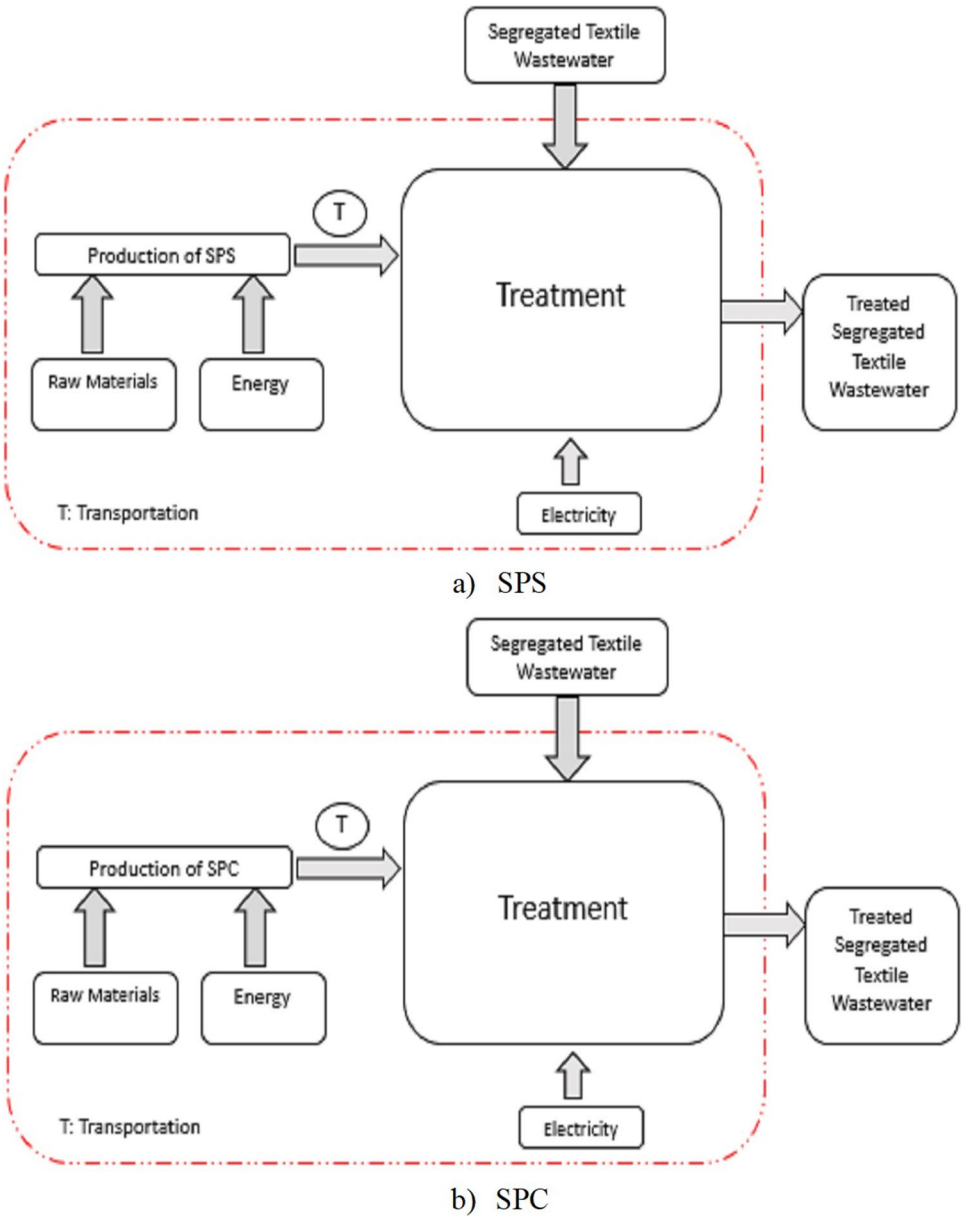

Fig. 1 System boundaries for treatment with **a** SPS; **b** SPC

Table 1 Data obtained on treatability studies for a) SPS b) SPC

Run number	SPS concentration (mg/L)	100% Peak absorbance (color) removal time (min)	Electricity requirement (kWh/m^3)
(a)			
1	35.7	60	1.340
2	59.5	60	1.340
3	95.2	30	0.670
4	119	30	0.670
5	238	10	0.223
Run number	SPC Concentration (mg/L)	100% Peak absorbance (color) removal time (min)	Electricity Requirement (kWh/m^3)
(b)			
6	39.25	60	1.340
7	78.5	30	0.670
8	157	20	0.447
9	235.5	15	0.335
10	314	15	0.335

Both of the chemicals used in treatability experiments are imported from China. Transportation distances for the chemicals are calculated using online distance measurements (FreeMapTools 2021) taking into account the location of production. Both SPS and SPC are imported from China, their transportation cover 19,668 km's of sea and 32 km's of highway.

Impact assessment

CML (Center for Environmental Science – University of Leiden, The Netherlands) (Guinee, 2001) methodology is adopted for life cycle impact assessment and the following environmental impact categories are investigated: Global warming potential (GWP), abiotic depletion potential (ADP fossils and elements), acidification potential (AP), eutrophication potential (EP), freshwater aquatic ecotoxicity (FAETP), human toxicity potential (HTP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP) and terrestrial ecotoxicity potential (TETP).

Results and discussion

The results of the LCA for the experimental runs are tabulated in Table 2.

The factors contributing to the environmental impacts given in Fig. 2 are different for each run. The share of

Table 2 Environmental impacts related to experimental runs

Impact Category	Run numbers						
	1	3	5	6	7	8	9
ADP elements (kg Sb-equiv.)	1.36E-06	2.89E-06	6.07E-06	1.88E-06	2.17E-06	3.62E-06	5.17E-06
ADP fossil (MJ)	8.85E+00	6.61E+00	7.32E+00	9.53E+00	6.33E+00	7.01E+00	8.38E+00
AP (kg SO_2-equiv.)	5.66E-03	4.57E-03	5.68E-03	5.95E-03	3.94E-03	4.34E-03	5.19E-03
EP (kg PO_4-equiv.)	3.39E-03	2.02E-03	1.44E-03	3.53E-03	2.07E-03	1.93E-03	2.05E-03
FAETP (kg DCB-equiv.)	7.86E-01	4.73E-01	3.44E-01	8.19E-01	4.75E-01	4.34E-01	4.57E-01
GWP (kg CO_2-Equiv.)	8.61E-01	5.79E-01	5.41E-01	9.18E-01	5.81E-01	6.06E-01	6.99E-01
HTP (kg DCB-Equiv.)	5.42E-01	4.04E-01	4.43E-01	5.83E-01	3.83E-01	4.19E-01	4.97E-01
MAETP (kg DCB-Equiv.)	1.91E+03	1.22E+03	1.01E+03	2.02E+03	1.23E+03	1.22E+03	1.36E+03
ODP (kg R11-Equiv.)	1.55E-08	4.59E-08	1.04E-07	1.66E-08	1.88E-08	3.12E-08	4.44E-08
POCP(kg C_2H_4-Equiv.)	2.87E-04	2.42E-04	3.16E-04	3.09E-04	2.16E-04	2.54E-04	3.14E-04
TETP (kg DCB-Equiv.)	6.29E-03	4.65E-03	5.05E-03	6.75E-03	4.41E-03	4.77E-03	5.63E-03

Fig. 2 Contribution of different factors to the total environmental impacts (**a** ADP elements, ADP fossil, AP, EP, FAETP, GWP; **b** HTP, MAETP, ODP, POCP, TETP)

electricity, transportation and chemical inputs in a total impact varies considerably for runs.

As indicated in Fig. 2, for Run 1 electricity requirement dominates ATP fossil, AP, EP, FAETP, GWP, HTTP, MAETP, POCP and TETP categories with more than 93% share on the total impacts mentioned. Approximately 78% of ATP elements is of electricity input and 21% from SPS production for Run 1. ODP of Run 1 is composed of, 61% from electricity, 30% from SPS input and 9% from transportation.

81% of ATP elements for Run 3 is generated by SPS input, where 18% comes from electricity requirement. For Run 3, ATP fossil is due to electricity (64% of the total) and SPS input (32%).

Contributions to AP of Run 3 is electricity (58%), SPS (32%) and the rest of transportation.

Electricity has 82% contribution on EP of Run 3, where 15% comes from SPS input. Similar percentages are also valid for FAETP. About 72 and 24% of GWP are due to electricity and SPS inputs, respectively for Run 3.

HTP of Run 3 is composed of electricity (64%) and SPS (33%) inputs.

About 77 and 23% of MAETP for Run 3 come from electricity and SPS introductions to the system.

SPS and electricity requirements have 82 and 10% shares in ODP of Run 3. On the other hand, 55 and 35% of POCP for Run 3 is composed of electricity and SPS.

TETP is of electricity (65%) and SPS (33%) origin for Run 3.

About 95% ATP elements of Run 5 is generated by SPS requirement. One can find more information on the share of factors for impacts arising from runs in Fig. 2.

Figure 3 illustrates a comparison of the environmental impacts for experimental runs by normalizing the results for Run 1.

Depending on which environmental impact category/categories are of importance, a proper treatment alternative can be quoted. When a detailed comparison between the runs is performed, the following findings arise:

For ADP elements, Run 1 yields the lowest impact. Approximately 115, 350, 40, 60, 170 and 280% elevations are obtained for Runs 3, 5, 6, 7, 8 and 9, respectively in comparison with Run 1. Therefore, if the level of ADP elements is important for the decision-makers, Run 1 with introducing 35.7 mg/L SPS and 1.340 kWh/m^3 energy requirement should be adopted over other experimental conditions.

For ADP fossil category, the lowest unwanted impacts are obtained for Run 3 and 7 with 25 to 28% reductions, namely, than Run 1. Thus, either 95.2 mg/L SPS and 0.670 kWh/m^3 energy input (Run 3) or 78.5 mg/L SPC and 0.670 kWh/m^3 energy requirement (Run 7) are stated as the optimal results in terms of ADP fossil impact category.

The same AP values are obtained for Runs 1 and 5. The lowest AP arises from Run 7, having 30% reduction in comparison with Run 1. Accordingly, 78.5 mg/L SPC and 0.670 kWh/m^3 energy input (Run 7) yields the lowest AP.

Run 1 and 6 generate close EP levels. Similarly Runs 3, 7, 8 and 9 yields approximately similar levels of EP having 40% reductions in comparison with Run 1. The lowest EP can be obtained when experimental conditions of Run 5 is adopted, as 238 mg/L SPS introduction with 0.223 kWh/m^3 energy input. In comparison with Run 1, it is possible to reduce EP by 60% with Run 5.

Similar levels of FAETP can be produced by Run 1 and 6. In comparison with Run 1, almost 40% reductions can be achieved with Runs 3, 7, 8 and 9. On the other hand, the lowest FAETP can be obtained with Run 5 where a 65% reduction than Run 1 is observed. Hence 238 mg/l

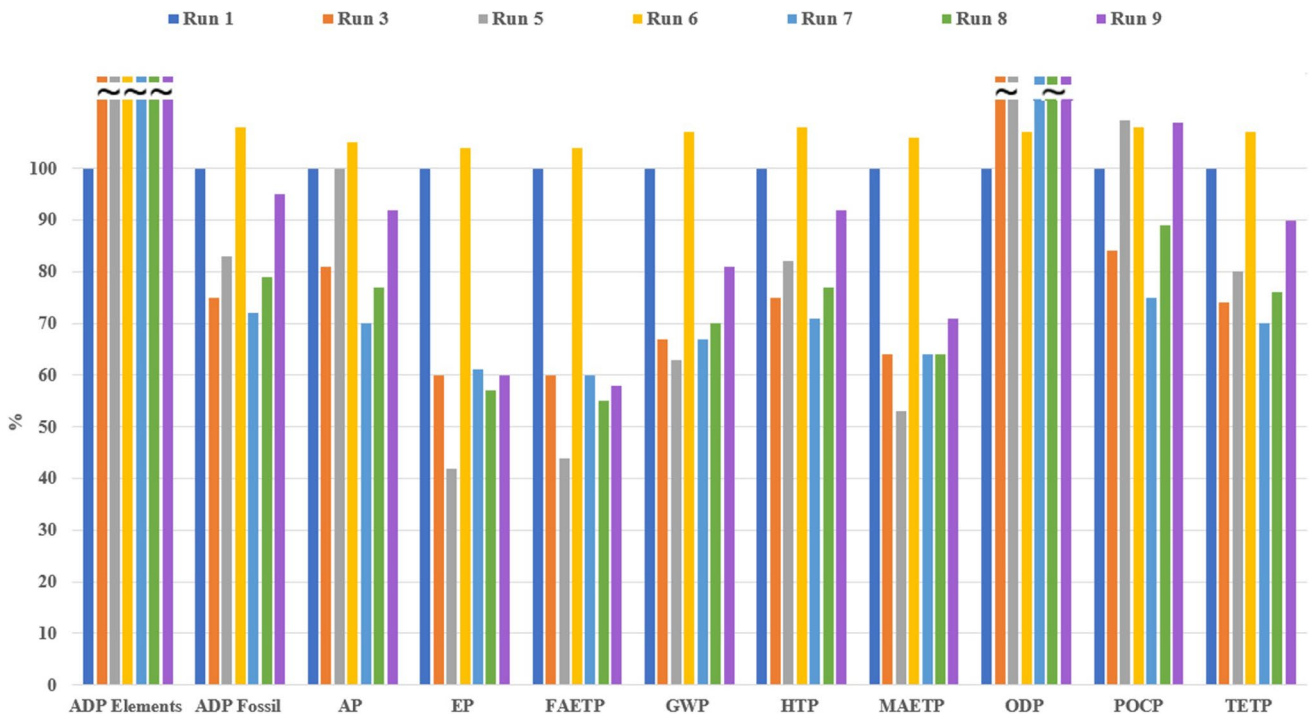

Fig. 3 Comparison of environmental impacts for experimental runs

SPS introduction with 0.223 kWh/m^3 energy input result in the lowest FAETP.

Run 6 results in slightly higher GWP than Run 1. The lowest GWP can be obtained by Run 5 where 38% reduction than Run 1 is getting. Although not as high reduction as Run 5, Runs 3, 7 and 8 have close outputs of GWP with more than 30% lowered GWP than Run 1. Consequently Run 5, involving 238 mg/l SPS introduction with 0.223 kWh/m^3 energy input, can be quoted as the lowest GWP yielding treatment alternative.

In terms of HTP, Run 7 yields the lowest impacts with a 30% reduction when compared with Run 1. Close results to Run 7 are obtained with Run 3 and 8.

For MAETP, almost 47% reduction can be achieved with Run 5 when compared to Run 1. Whereas 35% lower values than Run 1 can be obtained by Run Runs 3, 7 and 8.

All the runs result higher ODP levels than Run 1, however ODP of Run 6 is close to Run 1 with only 7% increase. In comparison with Run 1; 195, 570, 21, 100, 185% elevations are obtained for Runs 3, 5, 7, 8 and 9, respectively.

In comparison with Run 1, almost 10% higher POCP values are achieved for Runs 5, 6 and 9. However the lowest POCP is obtained with Run 7. Run 7 results in 25% reduction when compared to Run 1.

Run 7 yields the lowest TETP as a 30% reduction than Run 1 is obtained. A close result can be seen for Run 3.

As a summary of all the findings on the comparison of experimental runs, the following can be stated:

In terms of ADP elements and ODP categories the lowest impacts are obtained with Run 1. For ODP Run 6 yields close results to Run 1.

For ADP fossil, AP, HTP, POCP and TETP impact categories, most favourable outcomes are got by Run 7.

On the other hand, lowest EP, FAETP, GWP and MAETP impacts are obtained by Run 5.

Therefore, depending on which impact categories are of importance, the decision-makers can choose the right alternative. If ADP elements and ODP categories are prioritized over others Run 1 with introducing 35.7 mg/l SPS and 1.340 kWh/m^3 energy input should be selected. In case ADP fossil, AP, HTP, POCP and TETP categories are important, a treatment alternative composed of 78.5 mg/l SPC and 0.670 kWh/m^3 energy input (Run 7) should be adopted. Finally, if EP, FAETP, GWP and MAETP categories rank more important, then Run 5 having 238 mg/l SPS introduction with 0.223 kWh/m^3 energy requirement should be applied.

At this stage it should be noted that along with prioritizing the environmental impacts of concern, decision makers also consider financial burdens of the treatment options. Figure 4 outlines the costs related evaluation for alternative runs. The costs given are comprised of chemical costs and cost of electricity.

As can be clearly seen from Fig. 4, Run 7 with the lowest ADP fossil, AP, HTP, POCP and TETP, yields the lowest operating cost. On the other hand, Run 5 where lowest EP, FAETP, GWP and MAETP levels are obtained, has

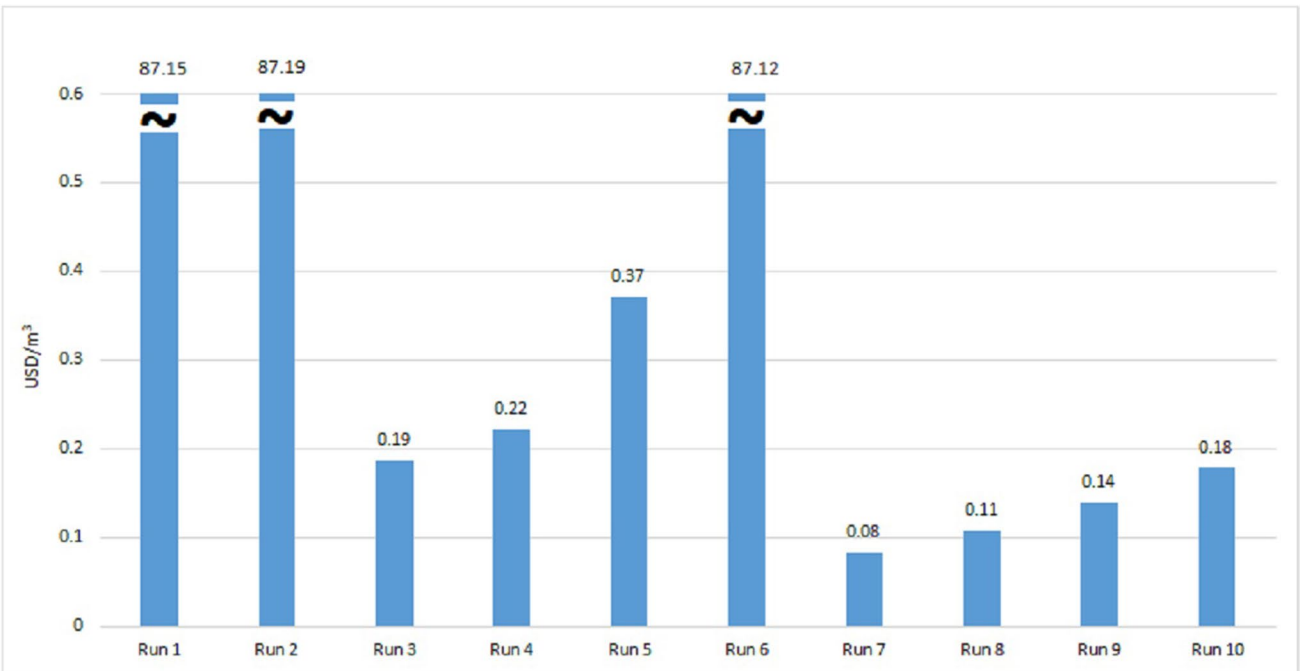

Fig. 4 Operating costs

an operating cost of 0.37 USD per treating a cubic meter wastewater.

A concise outline that shows the main reasons of getting environmental impacts for Run 1, 5 and 7 are stated in the following part.

ADP elements for Run 1 arises mainly due to non-renewable elements of copper (31%), cadmium and gold (both with 14% contribution) and lead (12%). ADP elements of Run 5 is of cadmium (20%), gold (19%), copper (15%) and lead (14%). Whereas ADP elements related to Run 7 is generated mainly because of copper and gold (each with 22% share).

ADP fossil for Run 1 is obtained mainly due to hard coal (40%), lignite (29%) and natural gas (25%) consumption. Petroleum and natural gas (each with around 32% contribution) and hard coal are producing the ADP fossil of Run 5. On the other hand, hard coal (36%), natural gas (30%) and lignite (22%) are the contributors to ADP fossil for Run 7.

AP is generated due to SO_2 and NO emissions for Runs 1, 5 and 7. The following contribution percentages for runs are obtained: Run 1: SO_2 (79%) and NO (18%); Run 5: SO_2 (81%) and NO (17%); Run 7: SO_2 (77%) and NO (19%).

Around 70, 56 and 63% of EP are generated due to phosphate emissions for Runs 1, 5 and 7, respectively.

FAETP of Runs 1, 5 and 7 are mainly caused by nickel, copper and beryllium emissions to water.

GWP, one of the most important environmental impact categories arise due to CO_2 emissions to atmosphere with more than 91% contribution for all the Runs 1, 5 and 7.

Selenium emissions to water is the main source of HTP for Runs 1 and 7. Whereas, arsenic and chromium (+ VI) emissions to atmosphere are the main reason of HTP for Run 5.

For Runs 1, 5 and 7, selenium emissions to water can be quoted as the main source of MAETP.

Halon and tetrachloromethane emissions to atmosphere are responsible for ODP of the runs.

SO_2 together with nitrous oxide emissions generate POCP for Runs 1, 5 and 7.

TETP arises mainly due to chromium (VI) emissions to soil.

Conclusion

This study concentrates on how to evaluate the treatability results with the sustainability assessment for a dye containing segregated textile stream. A segregated textile dyebath discharge that contains hydrolyzed Reactive Black 5 dye (RB5) is subjected to treatability tests with UV-C activated persulfate (PS) and UV-C activated percarbonate (PC) advanced oxidation processes. The outcomes yielding 100% RB5 (color; measured as peak absorbance) removal are further investigated through LCA to reveal the treatment alternative with minimal environmental impacts.

Based on the methodology adopted in this study, the application of the roadmap composed of the below given steps is recommended to find out the most environmentally sound treatment alternative with operating conditions:

- Running treatability studies
- Evaluating treatability results that yield the required efficiencies
- Based on laboratory studies, listing inputs and outputs for treatment alternatives yielding required efficiencies
- Running a modelling study though LCA methodology to find out the environmental impacts related to treatment alternatives
- Prioritizing environmental impact category/categories by considering their importance to decision-makers (eg. GWP for climate neutral actions)
- Cost assessment
- Addressing a treatment method and related operating conditions based on the prioritization of the environmental impacts and calculated costs.

The appraisal given in this study is based on laboratory scale treatability results. One should keep in mind that the impacts shown in the study will differ to some extent during scaling up to a full treatment plant. Nevertheless, the outcomes of this study yield a general comparative perspective on the environmental impacts of the treatment alternatives investigated.

Acknowledgements The Reactive Black 5 gift sample from Eksoy Chemicals (Adana, Turkey) is acknowledged.

Authors' contributions KD, BAT, FGB, OKU and IAA confirm responsibility for the following: Designing the study, data collection and modelling, analysis and interpretation of results, and manuscript preparation. KD, BAT, FGB, OKU and IAA read and approved the final manuscript.

Funding The authors did not receive support from any organization for the submitted work.

Declarations

Competing interests The authors declare that they have no competing interests.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

References

Arslan-Alaton I, Akmehmet Balcioglu I (2001) Photochemical and heterogeneous photocatalytic degradation of waste vinylsulphone dyes: a case study with hydrolyzed reactive black 5. J Photochem Photobiol A Chem 141:247–254. https://doi.org/10.1016/S1010-6030(01)00440-3

Arslan-Alaton I, Basar G, Olmez-Hanci T (2012) Ozonation of the reactive dye intermediate 2-naphthylamine 3,6,8-trisulphonic acid (K-acid): kinetic assessment, ozonation products and ecotoxicity. Color Technol 128:387–394. https://doi.org/10.1111/j.1478-4408.2012.00392.x

Arslan-Alaton I (2003) The effect of pre-ozonation on the biocompatibility of reactive dye hydrolysates. Chemosphere 51:825–833. https://doi.org/10.1016/S0045-6535(03)00231-5

Arslan-Alaton I, Germirli Babuna F, Iskender G (2022) Application of advanced oxidation processes to treat industrial wastewaters: sustainability and other recent challenges. Advanced oxidation processes for wastewater treatment, 1st edn. CRC Press, Boca Raton. https://doi.org/10.1201/9781003165958

Arslan-Alaton I, Insel G, Eremektar G, Germirli Babuna F, Orhon D (2006) Effect of textile auxiliaries on the biodegradation of dyehouse effluent in activated sludge. Chemosphere 62(9):1549–1557

Arslan-Alaton I, Eremektar G, Germirli Babuna F, Insel G, Selcuk H, Özerkan B, Teksoy S (2005) Advanced oxidation of commercial textile biocides in aqueous solution: effects on acute toxicity and biomass inhibition. Water Sci Technol 52(10–11):309–316

Ahmad K, Nazir MA, Qureshi AK, Hussain E, Najam T, Javed MS, Shah SSA, Tufail MK, Hussain S, Khan NA, Ashfaq M (2020) Engineering of Zirconium based metal-organic frameworks (Zr-MOFs) as efficient adsorbents. Mater Sci Eng: B 262:114766. https://doi.org/10.1016/j.mseb.2020.114766

Ahmad K, Ashfaq M, Shah SSA, Hussain E, Naseem HA, Ayub A (2021) Effect of metal atom in zeolitic imidazolate frameworks (ZIF-8 & 67) for removal of $Pb2^{+}$ & $Hg2^{+}$ from water. Food Chem Toxicol 149:112008. https://doi.org/10.1016/j.fct.2021.112008

Akhtar N, SyakirIshak MI, Bhawani SA, Umar K (2021) various natural and anthropogenic factors responsible for water quality degradation: a review. Water 13(19):2660

Başkurt M, Kocababuç I, Binici E, Dulekgurgen E, Özgün Karahan Ö, Taşlı R (2017) Life cycle assessment as a decision support tool in wastewater treatment plant design with renewable energy utilization. Desalin Water Treat 93:229–238

Bennedsen LR, Muff J, Søgaard EG (2012) Influence of chloride and carbonates on the reactivity of activated persulfate. Chemosphere 86(11):1092–1097. https://doi.org/10.1016/j.chemosphere.2011.12.011

Bilińska L, Gmurek M (2021) Novel trends in AOPs for textile wastewater treatment. Enhanced dye by-products removal by catalytic and synergistic actions. Water Resour Ind 26:100160. https://doi.org/10.1016/j.wri.2021.100160

Bilinska L, Gmurek M, Ledakowicz S (2016) Comparison between industrial and simulated textile wastewater treatment by AOPs – Biodegradability, toxicity and cost assessment. Chem Eng J 306:550–559. https://doi.org/10.1016/j.cej.2016.07.100

Briffa J, Sinagra E, Blundell R (2020) Heavy metal pollution in the environment and their toxicological effects on humans. Heliyon 6(9):e04691. https://doi.org/10.1016/j.heliyon.2020.e04691

Bruijn H, Duin R, Huijbregts MA, Guinee JB, Gorree M, Heijungs R, Huppes G, Kleijn R, Koning A, Oers L, Sleeswijk AW (2004) Life cycle assessment: operational guide to the ISO standards. Kluwer Academic Publishers, Dordrecht, The Netherlands

Collivignarelli MC, Abbà A, CarnevaleMiino M, Damiani S (2019) Treatments for color removal from wastewater: state of the art. J Environ Manage 236:727–745. https://doi.org/10.1016/j.jenvman.2018.11.094

Cooper WJ, Zika RG (1983) Photochemical formation of hydrogen peroxide in surface and ground waters exposed to sunlight. Science 220(4598):711–712. https://doi.org/10.1126/science.220.4598.711

Dogruel S, Germirli Babuna F, Kabdaşlı I, Insel G, Orhon D (2003) Effect of stream segregation on ozonation for the removal of significant COD fractions from textile wastewater. J Chem Technol Biotechnol 78:6–14. https://doi.org/10.1002/jctb.713

Dulkadiroğlu H, Eremektar G, Doğruel S, Üner H, Germirli Babuna F, Orhon D (2002) In-plant control applications and their effect on treatability of a textile mill wastewater. Water Sci Technol 45(12):287–295. https://doi.org/10.2166/wst.2002.0437

Ecoinvent (2013) Ecoinvent Database v3.1

Elginoz N, Alzaboot M, Germirli Babuna F, Iskender G (2019) Construction of a large water treatment plant: appraisal of environmental hotspots. Desalin Water Treat 172:309–315. https://doi.org/10.5004/dwt.2019.25107

Elwakeel KZ (2009) Removal of reactive black 5 from aqueous solutions using magnetic chitosan resins. J Hazard Mater 167(1):383–392. https://doi.org/10.1016/j.jhazmat.2009.01.051

Erdogan AO, Orhon HF, Dulkadiroglu H, Dogruel S, Eremektar G, Germirli Babuna F, Orhon D (2004) Feasibility analysis of in-plant control for water minimization and wastewater reuse in a wool finishing textile mill. J Environ Sci Health Part A 39(7):1819–1832. https://doi.org/10.1081/ESE-120037880

Fadaei S, Noorisepehr M, Pourzamani H, Salari M, Moradnia M, Darvishmotevalli M, Mengelizadeh N (2021) Heterogeneous activation of peroxymonosulfate with Fe3O4 magnetic nanoparticles for degradation of reactive black 5: batch and column study. J Environ Chem Eng 9(4):105414. https://doi.org/10.1016/j.jece.2021.105414

Freeman A, Reife HS (2003) Dyes, environmental chemistry. In: Kirk-othmer encyclopedia of chemical technology, 4th edn. John Wiley & Sons Inc., New Jersey

FreeMapTools. (2021). Measure Distance. Retrieved from https://www.freemaptools.com/measure-distance.htm

Germirli Babuna F, Turker C, Oguz Cabuk M, Olmez Hancı T (2016) biodegradability, toxicity and photochemical treatment of a textile surfactant. Desalin Water Treat. https://doi.org/10.1080/19443994.2016.1159995

Germirli F, Tunay O, Orhon D (1990) An overview of the textile industry in Turkey–pollution profiles and treatability characteristics. Water Sci Technol 22(9):265–274. https://doi.org/10.2166/wst.1990.0091

Germirli Babuna F, Orhon D, Ubay Çokgör E, Insel G, Yaprakli B (1998a) Modelling of activated sludge for textile wastewaters. Water Sci Technol 38(4–5):9–17. https://doi.org/10.1016/S0273-1223(98)00492-2

Germirli Babuna F, Eremektar G, Yapraklı B (1998b) Inert COD fractions of various textile dyeing wastewaters. Fresenius Environ Bull 7:959–966

Germirli Babuna F, Soyhan B, Eremektar G, Orhon D (1999) Evaluation of treatability for two textile mill effluents. Water Sci Technol 40(1):145–152. https://doi.org/10.1016/S0273-1223(99)00374-1

Grau P (1991) Textile industry wastewaters treatment. Water Sci Technol 24(1):97–103. https://doi.org/10.2166/wst.1991.0015

Ilhan F, Ulucan-Altuntas K, Avsar Y (2019) Electrocoagulation process for the treatment of metal-plating wastewater: kinetic modeling

and energy consumption. Front Environ Sci Eng 13:73. https://doi.org/10.1007/s11783-019-1152-1
ISO (2006a) Life cycle assessment-principles and framework. Retrieved from Geneva, Switzerland
ISO (2006b) Life cycle assessment-requirements and guidelines. Retrieved from Geneva, Switzerland
Karahan O, Dulkadiroglu H, Kabdasli I, Sozen S, Germirli Babuna F, Orhon D (2002) Effect of ozonation on the biological treatability of a textile mill effluent. Environ Technol 23(12):1325–1336. https://doi.org/10.1080/09593332508618440
Katheresan V, Kansedo J, Lau SY (2018) Efficiency of various recent wastewater dye removal methods: A review. J Environ Chem Eng 6(4):4676–4697. https://doi.org/10.1016/j.jece.2018.06.060
Kokabian B, Bonakdarpour B, Fazel S (2013) The effect of salt on the performance and characteristics of a combined anaerobic–aerobic biological process for the treatment of synthetic wastewaters containing reactive black 5. Chem Eng J 221:363–372. https://doi.org/10.1016/j.cej.2013.01.101
Koyunluoglu S, Arslan-Alaton I, Eremektar G, Germirli Babuna F (2006) Pre-ozonation of commercial textile tannins: effects on biodegradability and toxicity. J Environ Sci Health, Part A 41(9):1873–1886. https://doi.org/10.1080/10934520600779083
Kusvuran E, Irmak S, Yavuz HI, Samil A, Erbatur O (2005) Comparison of the treatment methods efficiency for decolorization and mineralization of reactive black 5 azo dye. J Hazard Mater 119(1):109–116. https://doi.org/10.1016/j.jhazmat.2004.11.017
Li H, Zhang H, Long J (2019) Combined fenton process and sulfide precipitation for removal of heavy metals from industrial wastewater: bench and pilot scale studies focusing on in-depth thallium removal. Front Environ Sci Eng 13:49. https://doi.org/10.1007/s11783-019-1130-7
Liu T, Yin K, Liu C, Luo J, Crittenden J, Zhang W, Zhang D (2018) The role of reactive oxygen species and carbonate radical in oxcarbazepine degradation via UV, UV/H2O2: kinetics, mechanisms and toxicity evaluation. Water Res 147:204–213. https://doi.org/10.1016/j.watres.2018.10.007
López Cisneros R, Gutarra Espinoza A, Litter MI (2002) Photodegradation of an azo dye of the textile industry. Chemosphere 48(4):393–399. https://doi.org/10.1016/S0045-6535(02)00117-0
Madhav S, Ahamad A, Singh P, Mishra PK (2018) A review of textile industry: wet processing, environmental impacts, and effluent treatment methods. Environ Qual Manage 27(3):31–41. https://doi.org/10.1002/tqem.21538
Maqbool Z, Shahid M, Azeem F, Shahzad T, Mahmood F, Rehman M, Ahmed T, Imran M, Hussain S (2020) Application of a dye-decolorizing pseudomonas aeruginosa strain ZM130 for remediation of textile wastewaters in aerobic/anaerobic sequential batch bioreactor and soil columns. Water, Air, Soil Pollut. https://doi.org/10.1007/s11270-020-04777-7
Miao Z, Gu X, Lu S-G, Dionysiou DD, Al-Abed SR, Zang X, Danish MJCEJ (2015) Mechanism of PCE oxidation by percarbonate in a chelated Fe(II)-based catalyzed system. Chem Eng J 275:53–62
Ødegaard H (2016) A road-map for energy-neutral wastewater treatment plants of the future based on compact technologies (including MBBR). Front Environ Sci Eng 10:2. https://doi.org/10.1007/s11783-016-0835-0
Oktay S, Iskender G, Germirli Babuna F, Kutluay G, Orhon D (2007) Improving the wastewater management for a beverage industry with in-plant control. Desalination 211(1–3):138–143. https://doi.org/10.1016/j.desal.2006.02.088
Orhon D, Dulkadiroğlu H, Doğruel S, Kabdaşli I, Sozen S, Germirli Babuna F (2002) Ozonation application in activated sludge systems for a textile mill effluent. Water Sci Technol 45(12):305–313 (**PMID: 12201116**)
Orhon D, Kabdasli I, Germirli Babuna F, Sozen S, Dulkadiroglu H, Dogruel S, Karahan Gul O, Insel G (2003) wastewater reuse for the minimization of fresh water demand in coastal areas—selected cases from the textile finishing industry. J Environ Sci Health, Part A 38(8):1641–1657. https://doi.org/10.1081/ESE-120021486
Ozkan E, Elginoz N, Germirli Babuna F (2017) Life cycle assessment of a printed circuit board manufacturing plant in Turkey. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-017-0280-z
Ozkan E, Bas B, Elginoz N, Germirli Babuna F (2020) Environmental sensitivity of printed circuit board manufacturing to Cu recycling rate, transportation and various energy sources. International Journal of Global Warming 20(3):237–248. https://doi.org/10.1504/IJGW.2020.106596
Ozsahin B, Elginoz N, Germirli Babuna F (2022) Life cycle assessment of a wind farm in Turkey. Environ Sci Pollut Res 29:71000–71013. https://doi.org/10.1007/s11356-022-20783-0
Ozyildiz G, Olmez-Hanci T, Arslan-Alaton I (2019) Effect of nanoscale, reduced graphene oxide on the degradation of bisphenol A in real tertiary treated wastewater with the persulfate/UV-C process. Appl Catal B 254:135–144. https://doi.org/10.1016/j.apcatb.2019.04.092
Periyasamy AP, Ramamoorthy SK, Rwawiire S, Zhao Y (2018) Sustainable wastewater treatment methods for textile industry. In: Muthu SS (ed) Sustainable innovations in apparel production. Springer, Singapore, pp 21–87
Peyton GR (1993) The free-radical chemistry of persulfate-based total organic carbon analyzers. Mar Chem 41(1):91–103. https://doi.org/10.1016/0304-4203(93)90108-Z
Pignatello JJ, Oliveros E, MacKay A (2006) Advanced oxidation processes for organic contaminant destruction based on the fenton reaction and related chemistry. Crit Rev Environ Sci Technol 36(1):1–84. https://doi.org/10.1080/10643380500326564
Raju GB, Karuppiah MT, Latha SS, Parvathy S, Prabhakar S (2008) Treatment of wastewater from synthetic textile industry by electrocoagulation–electrooxidation. Chem Eng J 144(1):51–58. https://doi.org/10.1016/j.cej.2008.01.008
Reife A (2000) Dyes, environmental chemistry. In: Kirk-othmer encyclopedia of chemical technology. John Wiley & Sons, New Jersey
Saad A, Elginoz N, Germirli Babuna F, Iskender G (2019) Life cycle assessment of a large water treatment plant in Turkey. Environ Sci Pollut Res 26(15):14823–14834. https://doi.org/10.1007/s11356-018-3826-9
Sezginer I, Atilgan Turkmen B, Germirli Babuna F (2022) Environmental impacts arising from the production of two surface coating formulations. Clean Technol Environ Policy. https://doi.org/10.1007/s10098-022-02288-z
Samsami S, Mohamadizaniani M, Sarrafzadeh M-H, Rene ER, Firoozbahr M (2020) Recent advances in the treatment of dye-containing wastewater from textile industries: Overview and perspectives. Process Saf Environ Prot 143:138–163. https://doi.org/10.1016/j.psep.2020.05.034
Sphera (2017) GaBi V7.3 software and database
TEIAS (2019) Electricity generation and transmission statistics of Turkey. Retrieved from http://www.teias.gov.tr/TurkiyeElektrikIstatistikleri.aspx
Tezgel T, Germirli Babuna F, Iskender G (2014) An evaluation of commercial textile tannins based on their inert COD content and toxicity. Glob NEST J 16(1):52–55
Yalamacilar B, Elginoz N, Germirli Babuna F (2021) Benchmarking industrial water purification systems with the aid of life cycle assessment. Desalin Water Treat 211:422–431

Yang Y, Lu X, Jiang J, Ma J, Liu G, Cao Y, Luo C (2017) Degradation of sulfamethoxazole by UV, UV/H2O2 and UV/persulfate (PDS): formation of oxidation products and effect of bicarbonate. Water Res 118:196–207. https://doi.org/10.1016/j.watres.2017.03.054

Yue-hua Z, Chun-Mei X, Chang-Hong G (2011) Application sodium percarbonate to oxidative degradation trichloroethylene contamination in groundwater. Procedia Environ Sci 10:1668–1673. https://doi.org/10.1016/j.proenv.2011.09.262