Process Safety and Environmental Protection 182 (2024) 903–917

Contents lists available at ScienceDirect

Process Safety and Environmental Protection

journal homepage: www.journals.elsevier.com/process-safety-and-environmental-protection

Occupational risk assessment in AOPs labs and management system that comply with UN sustainable development goals

Jaime Giménez [a,*], Bernardí Bayarri [a], Sixto Malato [b], José Peral [c], Santiago Esplugas [a]

[a] Departament d'Enginyeria Química i Química Analítica, Universitat de Barcelona, C/Martí i Franquès 1, 08028 Barcelona, Spain
[b] Plataforma Solar de Almería (CIEMAT), Carretera de Senes, km 4, 04200 Tabernas, Almería, Spain
[c] Departament de Química, Edifici Cn, Universitat Autònoma de Barcelona, Cerdanyola del Vallès, 08193 Bellaterra, Spain

ARTICLE INFO

Keywords:
Occupational risk indexes
Occupational safety costs
Root causes analysis
Occupational safety and health management system
UN-SDGs

ABSTRACT

Accidents in chemical laboratories are usually less significant than in the chemical industry but, sometime, they have serious consequences. As mandated by legislation, risk assessment is also needed at laboratory. In the present work, risk analysis is applied to laboratory dedicated to wastewater treatment by Advanced Oxidation Processes (AOPs). The analysis was carried out according to widely accepted methodologies, although innovative aspects, such as a new occupational risk index or the specific application to AOP laboratories, are introduced. Based on the hazards detected, a risk level with a normalized score between 0 and 10 is established. Based on the suggested prevention measures, their cost and their execution time, an annual cost and its relation to the previously assigned score are calculated. This gives a new index (another novelty) for the prioritization of preventive measures. To be able to identify the accident causes, Root Cause Analysis techniques were also included in the risk assessment. AcciMap, Why technique as well as the Ishikawa diagram, that shows the relationship between risk factors and accidents or occupational diseases have been used. This innovative risk assessment has been also framed in the implementation of management system for occupational health and safety, according to ISO 45001:2018. The here proposed improvements in safety are also a way of achieving the UN Sustainable Development Goals.

1. Introduction

Occupational safety is a goal of major concern worldwide, and particularly for the chemical industry. At the laboratory level, the consequences of an accident will typically be less serious than those expected from an industrial accident. Nevertheless, there are also several risks associated with laboratory work. Some of them have a broad and non-specific cause, such as falls, impacts, cuts, etc., and for chemical laboratories, there is also the specific risk associated with dangerous chemicals that may be toxic, corrosive, flammable, etc. To minimize these risks, it is necessary to carry out a risk assessment, and legislation in industrialized countries requires the evaluation of occupational hazards for every activity taken place in a company (Council Directive 89/391/EEC; Law 31/1995).

First of all, risk assessment involves detecting the possible hazards that exist in each workplace. For each identified hazard, the product of the possible accident consequences and its frequency provides the level of risk. When assessing possible accidents, it is not only necessary to focus on the hazardousness of the chemical products, but also to identify potential problems arising from an incorrect modus operandi: ignorance of the hazardous characteristics of substances, bad work habits, inherently dangerous work methods and procedures, inadequate or poor-quality laboratory materials, etc.

In previous works by this research group, indexes for the evaluation of environmental impacts associated to Advanced Oxidation Processes (AOPs) have been developed, and estimations of their costs have been carried out and (Giménez et al., 2015a, 2015b, 2019). The methodologies used were applied to AOPs at the laboratory and pilot plant scale but, with minor modifications, they could also be applied at industrial level.

It should be noted that in the field of AOPs, there are very few studies related to occupational safety, and therefore, there lies a wide research field to be explored.

A search in SCOPUS using the keywords *"occupational AND risk AND assessment AND in AND advanced AND oxidation AND processes",* and with no restriction of time frame, only showed four publications that

* Corresponding author.
E-mail address: j.gimenez.fa@ub.edu (J. Giménez).

https://doi.org/10.1016/j.psep.2023.12.033
Received 21 July 2023; Received in revised form 10 November 2023; Accepted 7 December 2023
Available online 16 December 2023

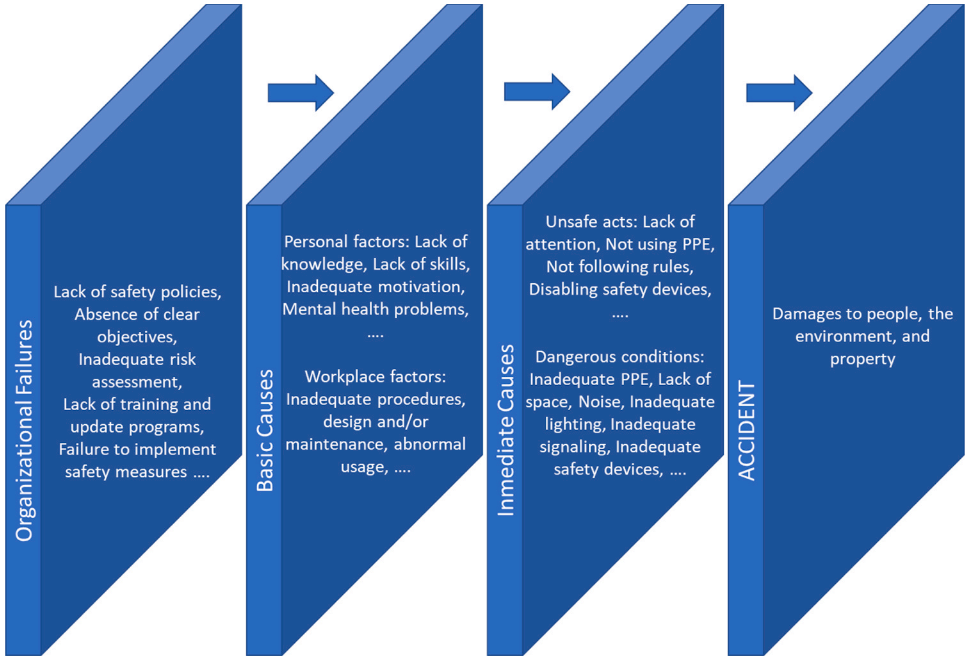

Fig. 1. Chain of causes driving to a final accident.

have no relation to risk analysis or the application of risk indices, since they only study some particular aspects related to health sciences (Chen et al., 2016; Falconer, 2006; IPCS - International Program on Chemical Safety, 2004; Zhang et al., 2013).

When the search in Scopus was limited to the keywords "*occupational AND risk AND assessment AND indexes*", and to the fields "*Chemical Engineering, Risk Assessment, Occupational Risk*", and within the time scope between 2018–2023, 25 citations were found, among which there were five that dealt with risk indexes, but in a rather general way and with a totally different approach to the topic than that the one in this work.

In this way, a paper by Lin et al. (Lin, Y.C. and Lin, Y.W., 2022) studies the effect on health of overwork in Taiwan, encompassing workers of retail stores and different manufacturing factories. Indexes were obtained related to burnout, cardiovascular, and cardiocerebral events, and other problems.

Another work (Noh et al., 2022) deals with the musculoskeletal disorders derived from ergonomic risk in the workers of a medical device industry in Malaysia. But this study is mainly focused on damage to workers' hands and fingers due to poor ergonomic positions.

The next paper (Noman et al., 2021) is centered on labor market assessment considering the OIW (Occupational Injuries of Workers) by means of indicators based on the injury rates by regionality, gender, occupational distribution, employment status, industry division, etc.

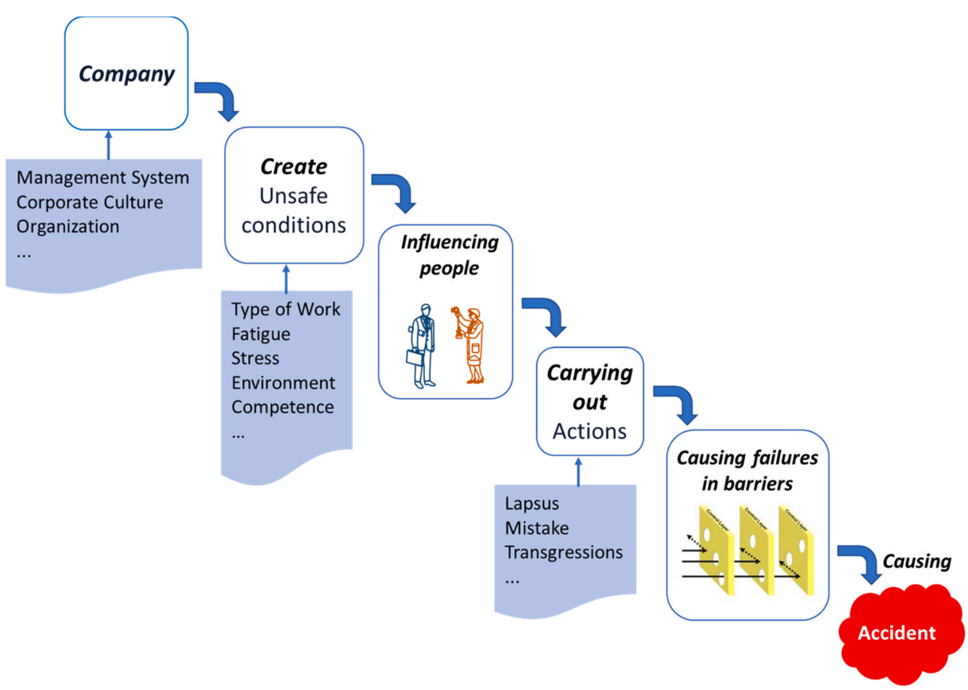

Fig. 2. Chain of errors from the high level of the company to the accident.

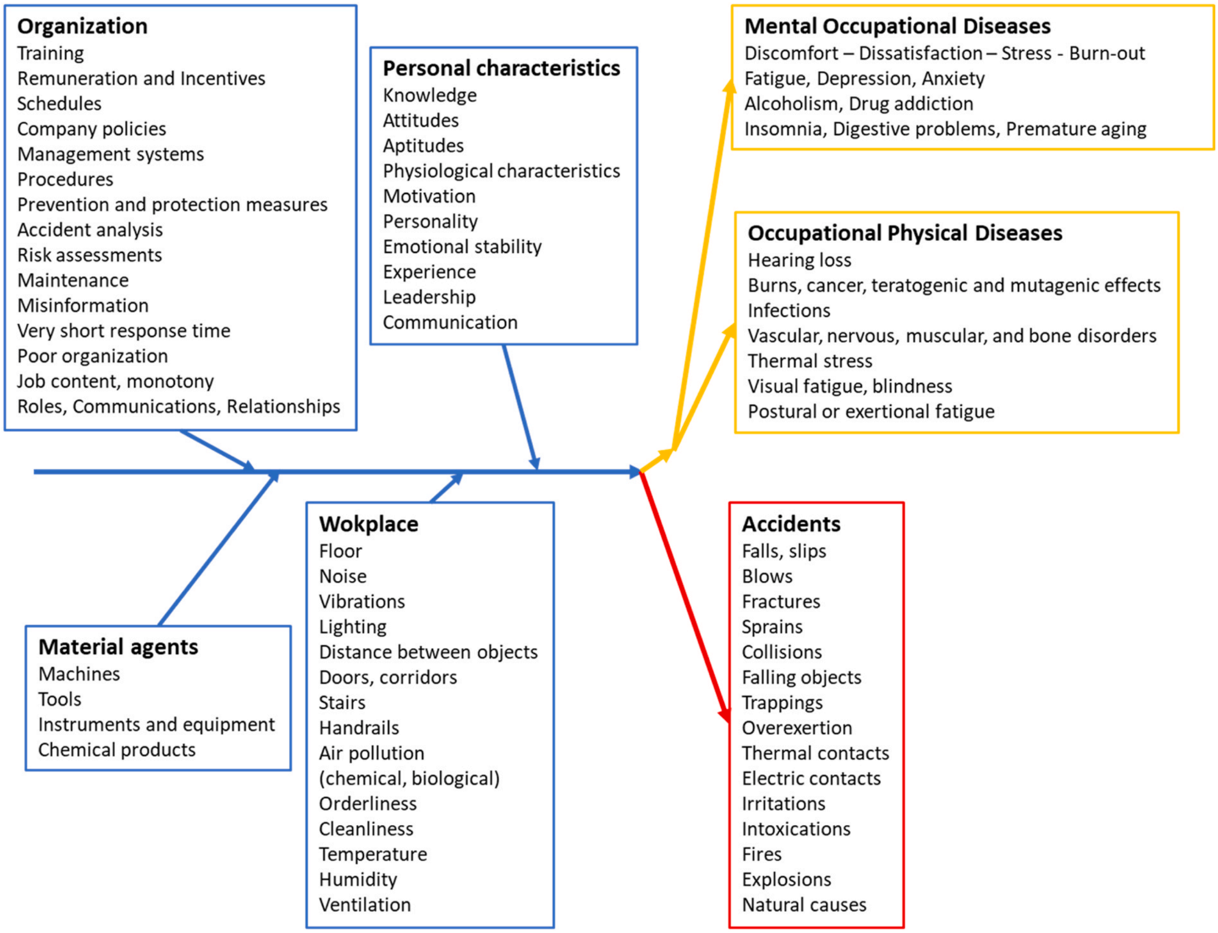

Fig. 3. Example of fishbone diagram assessing causes and consequences of an accident.

Ying So and coworkers (Ying So et al., 2021) integrate the indexes for the assessment of inherent hazards with layers of protection strategies for each hazard. Fundamentally, they consider the properties of the chemicals, along with some process variables such as pressure and temperature, during the research and development stage of two processes for the obtention of methyl methacrylate.

Finally, the last work, as the same authors (Ten et al., 2020) define, is focused on the introduction of a computer-aided molecular and process integrated design framework incorporating safety and health aspects.

As it can be observed, the previous works found in the literature, to the best of our knowledge and understanding, do not cover the field that is intended to be covered in this work with new proposed indexes. In this sense, the present work aims to provide a simple methodology to evaluate occupational risks, applied in this case to AOPs at the laboratory level. This work would be the natural continuation of previous studies, with the addition of indexes and parameters primarily related to occupational safety.

The implementation of an Occupational Health and Safety (OHS) Management System also involves the need to evaluate risks in all workplaces within the assessment scope. Thus, the ISO 45001:2018 devotes a large part of its section 6 to this issue, and specifically, section *6.1.2 - Hazard Identification and Risk Assessment and Opportunities*. Therefore, any company implementing a management system certified by ISO 45001:2018 must have conducted a risk assessment.

When an accident is analyzed, ~~t~~he use of techniques that allow to unveil its root causes are required. There are various Root Cause Analysis (RCA) techniques that enable the identification of the underlying causes of an accident by involving an analysis of the causal chain, as shown in Fig. 1. As it can be observed, organizational failures give rise to basic causes, which, under some circumstances, lead to immediate causes that can result in an accident (Cortés, 2002). These causes can be technical or human, as indicated in Fig. 1, and they can induce the entire system to collapse like a domino effect.

Similarly, the chain of errors encompasses all personnel within the company. Schematically, Fig. 2 illustrates how the chain of errors can propagate and how all personnel within the company are involved in it.

Among the RCA techniques, it is possible to mention well-known methodologies like Fishbone (Ishikawa diagram), WHY, Barriers, ECFCA (Events and Causal Factors Charting Analysis), Change analysis, ICAM (Incident Cause Analysis Method), Tripod (Stichting Tripod Foundation), AcciMap, etc. (IEC 62740:2015). Fig. 3 shows an example of a fishbone diagram where the causes of potential accidents and their consequences in the form of accidents or occupational diseases originated are related (Cortés, 2002; INSST, 1996, 2000, 2009. INSST is the Spanish acronym for "The National Institute for Labor Safety and Health").

From Fig. 3, a checklist of potential hazards posing a risk to workers in each workplace can be derived. Additionally, Fig. 3 shows the levels of impact that a worker may experience as a result of their work activity. On one hand, they may suffer accidents (cuts, breaks, etc.). On the other hand, they may acquire occupational diseases because of continuous exposure to certain hazards. These diseases can be purely physical (hearing loss, visual fatigue, thermal stress, etc.) or they can be mental illnesses that begin with discomfort, continue with dissatisfaction and stress, and eventually lead to burnout and premature aging. It should be noted that, according to the European Agency for Safety and Health at Work (EU-OSHA) and the International Labor Organization (ILO), mental illnesses are becoming increasingly prominent, as automation

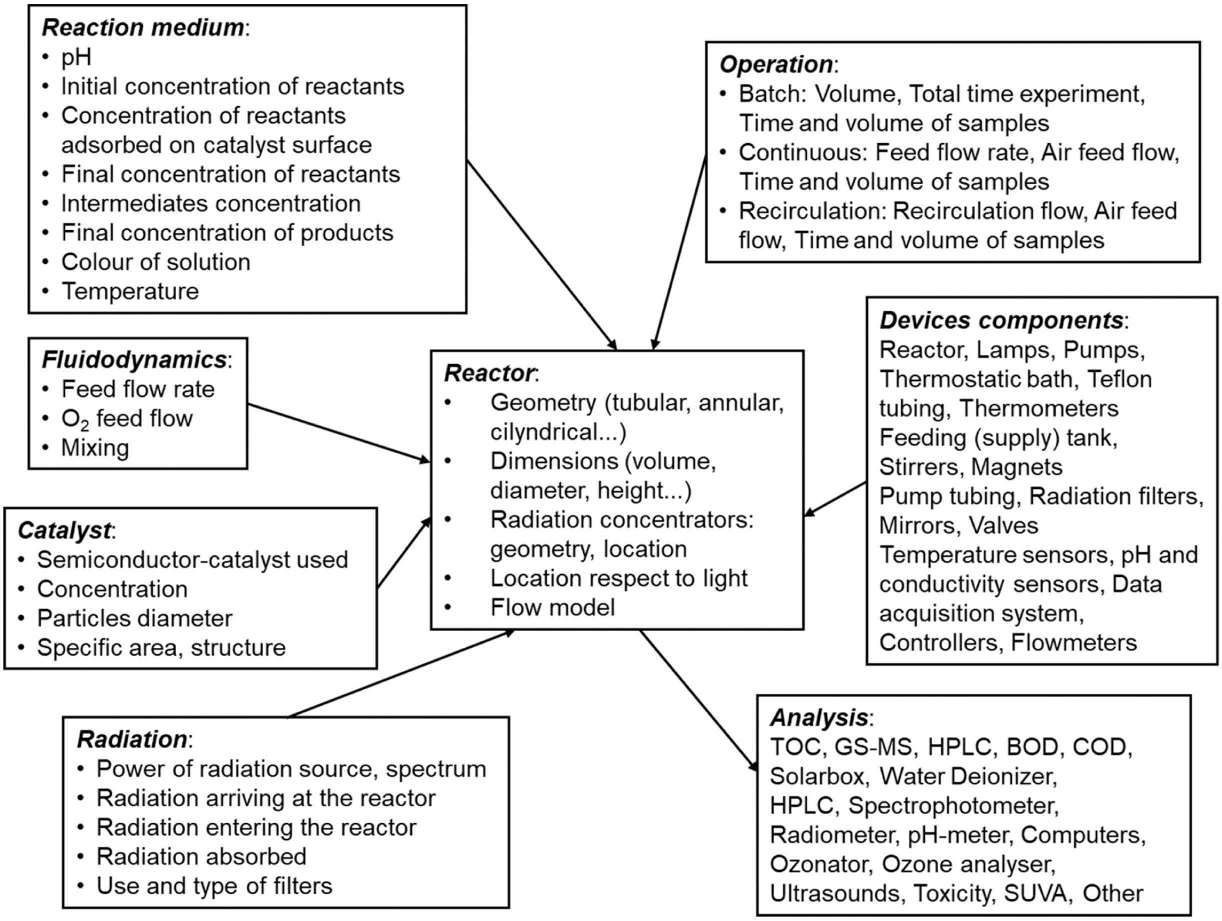

Fig. 4. Parameters and variables to be considered in AOPs experiments.

increases at the workplace and more mental work is involved (EU-OSHA-Research on psychosocial risks and mental health; ILO--Mental Health at Work).

To standardize operations, studies are carried out within the framework of an Occupational Safety and Health (OSH) management system. Likewise, RCA techniques are used to thoroughly analyze the causes of potential accidents. Finally, it should be noted that safe work practices also have environmental implications and help to fulfill some of the United Nations - Sustainable Development Goals (UN SDGs).

Therefore, this work will focus on the risks associated when working with AOPs at the laboratory level. It will propose indexes for the evaluation of hazards, and tools that facilitate the prioritization of measures, like root causes analysis, or implementing a robust management system. The Occupational Risk Index (S_{Oi}) for the considered operation will be obtained by adding the risks associated with each identified hazard, and the Global Occupational Risk Index (S_z) will be calculated by adding the S_{Oi} values obtained for each of the AOPs developed in a reference laboratory. The results can be normalized to compare operations, laboratories, processes, etc. Additionally, an estimation is given of the costs and the time it would take to implement the corrective and preventive measures. Thus, an interesting parameter is the ratio between the score obtained for a particular hazard and the cost (€/year). Finally, it can be said that the methodology used should be easily translated to any other type of experimental procedures and at any possible operation scale.

2. Experimental conditions

Fig. 4 displays the variables and parameters considered in many AOP experiments. The reactor, which is the central component of the setup, is pivotal to the entire figure.

Each AOP will require a facility with its own peculiarities, its instruments and equipment. In this case, risk analysis will be applied to a typical facility for carrying out photo-Fenton at the laboratory level. Two types of set-ups, either with a solar simulator (Solarbox), or with BLB lamps (Black Light Blue), will be evaluated. Those set-ups are used at the laboratories of the Advanced Oxidation Processes Engineering group of the Chemical Engineering and Analytical Chemistry Department at the University of Barcelona (from now, CED-UB). Both set-ups have already been extensively described in previous papers of the group (De la Cruz et al., 2013a; López et al., 2017; Méndez-Arriaga et al., 2008; Romero et al., 2016). However, to facilitate the reader's task, below we briefly describe the facilities, indicating their components.

In experiments using the Solarbox (from COFOMEGRA, Italy), the treated solution was recirculated using a peristaltic pump from a 1 L reservoir tank to a tubular photoreactor (26 cm length, 1.9 cm external diameter) located at the axis of a parabolic mirror at the bottom of a solar simulator. The setup was equipped with a Xe lamp (1 kW) that had a spectrum similar to the one of the sun in the UV range. The temperature of the feeding tank was controlled using a thermostatic bath. In the same tank, the mixture was homogenized using a magnetic stirrer. Additionally, the tank was equipped with ports for temperature reading and sample collection. The photon flux entering the reactor was $6.60 \cdot 10^{-7}$ Einstein s^{-1} and was measured using o-nitrobenzaldehyde actinometry (De la Cruz et al., 2013b; Kuhn et al., 2004).

The experiments with BLB lamps were conducted in a Pyrex-jacketed reactor, using 3 8 W BLB lamps. The temperature was kept constant using a thermostatic bath, and good mixing was ensured using a magnetic stirrer. The reactor lid was provided with ports for temperature measurement, sample collection, etc. The photon flux into the photoreactor was $6.71 \cdot 10^{-7}$ Einstein s^{-1} (De la Cruz et al., 2013b; Kuhn et al.,

Table 1
Average experimental conditions for photo-Fenton experiments.

Experimental conditions	Solarbox	BLB
Total volume (L)	1	2
Illuminated volume (L)	0.078	2
Lamp power (W)	1000	24
Temperature (°C)	25	25
Initial concentration of pollutant (mg/L)(1) (2)	50	50
Fe^{2+} (mg/L)(2)	10	10
H_2O_2 (mg/L)(2)	150	150
Conversion (%)	80	80
Experiments by year	50	50

(1) Some tested pollutants were metoprolol tartrate salt (MET), propranolol hydrochloride (PROP), sulfamethoxazole (SMX), diphenhydramine (DPH), ibuprofen, valproic acid sodium salt, trimethoprim and others.
(2) The values of concentrations are standard values, obviously they changed for different experiments.

2004).

First of all, the pollutant solutions were prepared according to the desired concentration and they were introduced into the reactor or into the feed tank. Iron and hydrogen peroxide were added and allowed to homogenize by stirring or recirculation. Finally, the lamp was turned on and samples were taken regularly and stored in vials for later analysis.

The experiments were conducted under different conditions (Giménez et al., 2015a; López et al., 2017; Romero et al., 2016). Table 1 presents the most significant conditions under which the experiments were carried out.

Regarding the used reagents, Table 2 shows a summary of them (for the case of MET), both along the experiments and in the various analyses carried out.

In Table 2, the reagents used for the analysis of typical parameters such as Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Organic Carbon (TOC), etc., are not included as they are well-known and need not to be specified. However, their possible hazards are also considered when conducting the risk analysis.

The most significant safety aspects of each compound have to be identified in order to know the potential risks that may emerge. As an example, the information collected for hydrogen peroxide is provided in Supporting Information (Fig. S1). This information has been obtained from the Safety Data Sheets (SDS) provided by the manufacturer of the products in accordance with REACH. In addition to the SDS, many alternative sources of information on substance properties and a variety of software are available for this purpose like, for example, Environmental Protection Agency (EPA), International Labor Organization (ILO), National Institute for Occupational Safety and Health (NIOSH), European Chemical Agency EPA, etc. (EPA - EPI SUITE; ILO - International Chemical Safety Cards (ICSCs); NIOSH - Pocket Guide to Chemical Hazards; EChA - Information on Chemicals).

3. Risk assessment and management

3.1. Risk assessment

For every detected hazard, it is necessary to establish the level of risk, considering that this is defined as the product of consequences (magnitude of damage caused) by the probability of the occurring event. To evaluate the different parameters (probability, consequences, risk), the ranges and numerical values shown in Tables 3a-3d are considered. Probability can be evaluated by considering the level of discrepancy with respect an accepted safe situation and the level of exposure. The Tables 3a-3d were developed based on the simplified accident risk evaluation system proposed by INSST (1993).

In addition to the risk values reported, in this work a score between 1 and 10 was added (Table 3d and Table 4). This extra rating is proposed by the authors to facilitate the assessment of the evaluated risks. Thus, taking into account the potential hazardous properties of chemical substances, Figs. 3 and 4, and various risk assessment manuals from official organizations (HSE, 2023; ICSSL, 2016; INSST, 1993, 1996, 2000, 2003, 2009, 2010, 2022), Table 4 has been developed. HSE means Health and Safety Executive - UK and ICSSL is the acronym of the Catalan Institute for Labor Safety and Health. Fundamentally, Table 4 was prepared according to international standards adopted by the INSST. This is the institution who sets the standards in everything related to safety and health at workplace in Spain and it collects practically all he hazards present in a chemical laboratory. INSST allows modifications in that table to adapt it to the special characteristics of

Table 3a
Probability levels.

Probability level (PL)	*Points*	*Meaning*
Very High	10	Poor situation (very dangerous) with continuous exposure or very poor situation with frequent exposure. Typically, the risk materializes frequently.
High	6	Poor situation with frequent or occasional exposure, or very poor situation with occasional or sporadic exposure. The risk may materialize several times throughout the work-life cycle.
Medium	3	Poor situation with sporadic exposure, or improvable situation with continuous or frequent exposure. The damage may occur at some point.
Low	1	Improvable situation with occasional or sporadic exposure. The risk is not expected to materialize, although it may be conceivable.

Table 3b
Consequences level.

Consequences level (CL)	*Points*	*Personal injuries*	*Material damages*
Mortal or Catastrophic	10	1 or more fatalities	Total system destruction (difficult to renew).
Very Serious	6	Serious injuries that may be irreparable.	Partial system destruction (complex and expensive repair).
Serious	3	Minor injuries that do not require hospitalization.	Process shutdown is required for repair.
Mild	1	Injuries resulting in temporary work disability.	Repairable without the need to stop the process.

Table 2
Chemicals used in photo-Fenton experiments.

Chemicals for experiments	Chemicals for analysis			Chemicals for Actinometries
	MET	H_2O_2	Fe	
Metoprolol tartrate salt $FeSO_4.7H_2O$ (7 mg/L Fe) H_2O_2 (100 mg/L) Ultrapure water	Acetonitrile water pH 3	Ammonium metavanadate H_2SO_4	Phenanthroline solution Ammonium acetate Acetic acid	o-Nitrobenzaldehyde Ethanol Formic acid Tert-butyl alcohol Benzoquinone Sodium hydroxide

Table 3c
Risk level (RL = PL x CL).

		Probability level (PL)			
		10	6	3	1
Consequences level (CL)	10	100	60	30	10
	6	60	36	18	6
	3	30	18	9	3
	1	10	6	3	1

Table 3d
Actions to do.

Risk	Score	Actions to do based on Risk Level
100	10	Quick correction of deficiencies. Very dangerous situation. In some cases, the operation will have to be stopped.
60	9	
36	8	
30	7	
18	6	To correct and adopt control measures.
10	5	
9	4	
6	3	There are things that can be improved, but they are not urgent and will also depend on economic feasibility.
3	2	
1	1	It is possible to continue under these conditions without any problem.

each organization. Here are so the reasons of the table contents. To fulfill the table, there are also methodologies recommended for INSST to estimate the probability and level of consequences and thus, the level of risk. In fact, Tables 3a, 3b, 3c and 3d are adaptations of these recommendations that allow obtaining normalized values for the risk level between 1 and 100 and, from there, and in order to work with more manageable values, we have proposed the use of new scores between 1 and 10. Thus, the person in charge of safety is the one who decides in each case the value of the probability level and the level of consequences assigned to each of the hazards that he considers to exist in the analyzed workplace. In the present case, the authors have assigned those values based on their knowledge of AOPs, knowledge of their laboratories, and their experience over many years about the detection of a greater or lesser probability for an accident to occur.

Table 4 shows an example of the application of the checklist to laboratory work in photo-Fenton experiments. Obviously, the values may vary slightly depending on the characteristics of the laboratory (type of floor, lighting, ventilation, etc.), experimental setup (volume, number of samples taken, operating mode), chemicals used and the analytics.

Items 114–115 and 201 may seem the same. However, the first two hazards refer to an isolated exposure to high concentrations of chemicals that can be traumatic, for example, a spill of sulfuric acid reaching an operator. Obviously, this will cause significant burns (trauma). On the other hand, item 201 refers to a long and continuous exposure to concentrations that could be tolerable but whose accumulation can eventually lead to occupational diseases.

The Occupational Risk Index S_{Oi} for the considered operation is obtained by adding the risks associated with each identified hazard (S_{ij}):

$$\sum (S_{ij})_O = S_{Oi} \tag{1}$$

Subindex O means Occupational, i indicates the considered AOP and j indicates the considered risk. In this case (Photo-Fenton experiment at the CED-UB labs), the value would be 108, as can be seen at the end of Table 4 (Total Score).

The same method would apply to all operations. Thus, the Global Occupational Risk Index S_z, is obtained by adding the S_{Oi} values obtained for each of the AOPs developed in the analyzed laboratory.

$$\left(\sum_{i=1}^{m} S_{Oi}\right)_z = S_z \tag{2}$$

Summarizing, for a given laboratory, two different indexes have been estimated: Occupational Risk Index (S_{Oi}) and Global Occupational Risk Index (S_z). These indexes allow comparisons between operations, laboratories, processes, etc. This methodology should be exportable to any laboratory with processes that differ from the one described here.

The results can be normalized to compare different operations. To do this, the percentage that the total score obtained represents over the possible maximum is evaluated. In this case, 46 items have been analyzed and, therefore, the maximum score that could be obtained would be 460 points. A value of 108 has been obtained (see Table 4 at the end), and therefore the normalized score would be:

$$Normalized \quad score = \frac{108}{460} \times 100 = 23.5 \tag{3}$$

Table 5 shows corrective and preventive measures that need to be implemented to reduce the level of risk for the proposed example. Additionally, the table provides an estimation of the costs and the time it would take to implement them or how often they need to be performed.

An interesting parameter displayed in Table 5 is the ratio between the score obtained for a particular hazard and the cost (€/year). This provides an estimation of the importance of that hazard and the priority to avoid it: the higher this ratio, the more risk points are corrected per euro invested.

The S/C ratio provides an idea of the relative importance of the assessed risk. Thus, a high score and a low cost will result in a high S/C ratio, indicating that high risk can be eliminated with a small cost. However, in each case, S and C must be analyzed to make a decision. For example, hazard 112 (thermal contacts) has a relatively low score of 2, but it also has a very low-cost analysis, resulting in a very high S/C ratio, which implies that it is worth to perform a preventive measure because it

Table 4
Check list for risk assessment in AOPs laboratory.

Code	Hazard	Probability	Consequences	Risk	Score
Final Consequence: ACCIDENT					
101	Falls by persons	1	3	3	2
102	Falling objects	3	3	9	4
103	Stepping on objects	1	1	1	1
104	Collisions with stationary objects	3	3	9	4
105	Collisions with moving objects	-	-	-	-
106	Strikes/cuts by objects or tools	3	3	9	4
107	Projection of fragments or particles	3	1	3	2
108	Entanglement by or between objects	-	-	-	-
109	Entanglement by machine rollover	-	-	-	-
110	Overexertion	1	3	3	2
111	Exposure to extreme ambient temperatures	-	-	-	-
112	Thermal contacts	1	3	3	2
113	Electric contacts	3	3	9	4
114	Exposure to harmful or toxic substances (ingestion or inhalation)	3	3	9	4
115	Contacts with caustic and/or corrosive substances	3	3	9	4
116	Exposure to radiation	3	3	9	4
117	Explosions	1	6	6	3
118	Fires	1	6	6	3
119	Noise	-	-	-	-
120	Accidents caused by living beings	-	-	-	-
121	Collisions or impacts with vehicles	-	-	-	-
122	Traffic accidents	-	-	-	-
123	Natural causes (heart attack, embolism, etc.)	1	6	6	3
124	Others	-	-	-	-
Final Consequence: OCCUPATIONAL DISEASE					
Code	***Hazard***	***Probability***	***Consequences***	***Risk***	***Score***
201	Exposures to Chemical Contaminants	6	3	18	6
202	Exposures to Biological Contaminants	1	3	3	2
203	Noise	3	3	9	4
204	Vibrations	-	-	-	-
205	Thermal Stress	-	-	-	-
206	Ionizing Radiations	-	-	-	-
207	Non-ionizing Radiations	3	3	9	4
208	Lighting	3	3	9	4
209	Visual Fatigue	3	3	9	4
210	Positional Fatigue	3	3	9	4
211	Displacement Fatigue	-	-	-	-
212	Effort Fatigue	-	-	-	-
213	Load Handling Fatigue	-	-	-	-
214	Caused by other circumstances	-	-	-	-
Final Consequence: DISCOMFORT, DISSATISFACTION, STRESS, BURNOUT					
Code	***Hazard***	***Probability***	***Consequences***	***Risk***	***Score***
301	Reception of Information	3	1	3	2
302	Response	3	3	9	4
303	Organizational Aspects	6	3	18	6
304	Content	3	1	3	2
305	Monotony	3	1	3	2
306	Roles	3	3	9	4
307	Communications	6	3	18	6
308	Relationships	3	3	9	4
309	Others	-	-	-	-
TOTAL SCORE					**108**

is very easy to implement. Hazard 116 (exposure to radiation) has a score of 4, indicating a higher level of risk than hazard 112, but its cost is also relatively low (20), resulting in an S/C ratio of 40, making it completely advisable to adopt that preventive measure.

On the other hand, the percentages (%) displayed in Table 5 are obtained by dividing the S/C ratio of a corrective measure by 280.45, the summation of all S/C ratios, and multiplying by 100.

Consequently, the S/C ratio and % allow, as mentioned before, the comparison and classification of evaluated risks according to their relative importance, and from there, the prioritization of preventive measures and the promptness with which they should be adopted.

Finally, from Table 5, the relative importance of the three negative consequences of occupational hazards can be deduced: accidents, physical illnesses, and mental illnesses, which are respectively 66.70%, 27.59%, and 5.71%. Therefore, as expected, accidents are the most concerning issue. This methodology enables the identification of various issues and establishes a grading system for their resolution.

Once all the hazards are identified, if feasible, they have to be eliminated, and if not, corrective and preventive measures have to be implemented. A fundamental principle to follow is that the workplace and, thus, corrective-preventive measures must be tailored as much as possible to the worker, including training. In this way, recommendations and the explanation of behavioral standards are basic tools for the training of workers and also students, in the case of teaching and public research laboratories. For example, the basic rule that no one should ever work alone in a laboratory must be frequently emphasized to avoid oblivion and the dangerous consequences that this can entail. Collective measures must be prioritized over individual measures. This means that, for example, extraction and ventilation systems must be considered first before compelling the use of Personal Protection Equipment (PPE). Risk assessment is an ongoing task involving the entire organization, from workers to top executives. The opinions of affected workers and direct managers are crucial, and risk assessment must also be reviewed periodically, with newer being conducted whenever there are changes in a job position.

3.2. Root causes analysis

Another important aspect of risk assessment is the analysis of the different hazard sources to identify the root causes. In fact, the Ishikawa diagram (Fishbone) has already been used (see Fig. 3). In this sense, the AcciMap technique (Baraza et al., 2022; Svedung et al., 2002) can be very useful as it analyzes not only the physical problems that may have caused the accident, but also organizational issues (Fig. 5).

One of the advantages of AcciMap is that it allows all information about the accident to be depicted in a diagram and enables visualization of all the factors that may contribute to its occurrence. Fig. 5 is focused on work in the laboratory, in this case in AOPs, and shows that administrations (European and National), universities and research centers, and even journals, as active agents, set the guidelines for research. From there, each research group decides on its own line of work and plans its experimental, but always considering the guidelines set by higher authorities in order to obtain funding. Then, considering safety regulations, center rules, individuals training and priorities, the research team plans laboratory work, i.e., the type and number of experiments (including concentrations of pollutants, Fe^{2+} or H_2O_2). Once everything is planned, the experimental work must be carried out. However, the researcher's performance is also influenced by the center policies and the research group own policies, as well as their personal characteristics, including their skills and abilities. Depending on all of this, the work the researcher produces will be more or less valuable. An erroneous action by the researcher can be favored by deficiencies in prevention measures or a poorly organized laboratory, with an excess of people, poor facility distribution, etc. In this regard, having a team of highly trained and prepared individuals will also decrease the probability of an accident, as shown in Fig. 5.

Table 5
Corrective and preventive measures, costs and priority.

Code	Score (S)	Corrective measures	Cost (€)	Time	Cost (C) (€/year)	(S/C)x100	%
ACCIDENT							
101	2	Change the type of soil (40 m^2), etc.	400	1 year	400	0.50	0.18
		Cost of labor (10 h x 45€/h)	450	1 year	450	0.44	0.16
102	4	To prevent hanging objects from the ceiling. (4 h x 45€/h)	180	Each year	180	2.22	0.79
103	1	Leaving the ground free of obstacles.	300	Each year	300	0.33	0.12
104	4	All objects have rounded edges and keep corridors free of objects.	200	Each year	200	2.00	0.71
105	-	-	-	-	-	-	-
106	4	Using protective elements such as gloves, etc.	250	Each 2 years	125	3.20	1.14
107	2	Using protective glasses or full-face masks.	200	Each 5 years	40	5.00	1.78
108	-	-	-	-	-	-	-
109	-	-	-	-	-	-	-
110	2	To use belts or waistbands.	150	Each 5 years	30	6.67	2.38
111	-	-	-	-	-	-	-
112	2	Placing signs in hot zones (20 €).	20	Each 10 years	2	100.00	35.66
		Using proper gloves (200 €).	200	Each 2 years	100	2.00	0.71
113	4	Ensuring that all electrical lines are safe: Inspections + plug replacements.	500	Each year	500	0.80	0.29
114	4	Working with fume hoods, ventilation, etc. **(1)**	220	Each year	220	3.64	1.30
		Using masks, filters, etc. **(2)**	110	Each year	110	7.27	2.59
115	4	Ensuring containers holding hazardous substances.	100	Each year	100	4.00	1.43
		Using appropriate protective equipment for handling **(3)**	480	Each 2 years	240	3.33	1.19
		Maintaining emergency showers, eye wash stations, etc.	75	Each 3 months	300	1.33	0.48
		Following SDS instructions and procedures. Increasing training courses.	850	Each year	850	0.47	0.17
116	4	Protective glasses for UV radiation **(4)**	100	Each 5 years	20	40.00	14.26
117	3	Using protective screens	400	1 year	400	0.75	0.27
		Maintaining bunkers	200	Each year	200	1.50	0.53
118	3	Maintaining fire extinguishers, detectors, etc.	300	Each year	300	1.00	0.36
119	-	-	-	-	-	-	-
120	-	-	-	-	-	-	-
121	-	-	-	-	-	-	-
122	-	-	-	-	-	-	-
123	3	Periodic medical reviews (10 researchers at €100/year of insurance for each one) **(5)**	1000	Each year	1000	0.60	0.21
124	-	-	-	-	-	-	-
Subtotal ACCIDENT					**6067**	**187.06**	**66.70**
OCCUPATIONAL DISEASE							
Code	***Score (S)***	***Corrective measures***	***Cost (€)***	***Time***	***Cost (C) (€/year)***	**(S/C)x100**	**%**
201	6	Working with fume hoods, ventilation, etc. **(1)**	220	Each year	220	5.45	1.94
		Using masks, filters, etc. **(2)**	110	Each year	110	10.91	3.89
		Using appropriate protective equipment for handling **(3)**	480	Each 2 years	240	5.00	1.78
202	2	Protective equipment, masks, gloves, etc.	200	Each year	200	1.00	0.36
203	4	Controlling noise levels, using headphones, etc.	100	Each 2 years	50	8.00	2.85
		Regular visits to the otolaryngologist, etc. **(5)**	1000	Each year	1000	0.80	0.29
204	-	-	-	-	-	-	-
205	-	-	-	-	-	-	-
206	-	-	-	-	-	-	-
207	4	Minimize the exposure time and use protective elements against UV radiation (similar to 116) (4)	100	Each 5 years	20	40.00	14.26
208	4	Avoid direct light and ensure sufficient illumination.	250	Each year	250	1.60	0.57
209	4	Computer screen is of appropriate size and brightness. Periodic breaks.	300	Each year	300	1.33	0.48
210	4	Use ergonomic furniture.	350	Each 2 years	175	2.29	0.82
		Encourage correct working postures	400	Each year	400	1.00	0.36
211	-	-	-	-	-	-	-
212	-	-	-	-	-	-	-
213	-	-	-	-	-	-	-
214	-	-	-	-	-	-	-
Subtotal DISEASES					**2965**	**77.38**	**27.59**
DISCOMFORT, DISSATISFACTION, STRESS, BURNOUT							
Code	***Score (S)***	***Corrective measures***	***Cost (€)***	***Time***	***Cost (C) (€/year)***	**(S/C)x100**	**%**
301	2	Supply it in the appropriate form and time Formation and planning	1500	Each year	1500	1.07	0.38
302	4	Sufficient time to complete tasks				2.13	0.76
303	6	Good distribution of time, tasks, and personnel				3.20	1.14
304	2	Work appropriate to the researcher's training				1.07	0.38
305	2	Avoid repetitive work and switch tasks				1.07	0.38
306	4	Everyone should know their role				2.13	0.76
307	6	Information should flow smoothly				3.20	1.14
308	4	Good working environment				2.13	0.76
309	-	-	-	-	-	-	-
Subtotal DISCONFORT					**1500**	**16.00**	**5.71**
ANNUAL TOTAL COSTS					**10532**	**280.45**	**100**

(1), (2), (3), (4) and (5): If different AOPs are carried out simultaneously, certain costs can be shared. Thus, the costs of codes 114 and 115 are shared with the costs of code 201. In the section on "DISCOMFORT, DISSATISFACTION, STRESS, BURNOUT," something similar happens, the €1500 that should be invested could be evenly distributed among the 8 items in the section (301-308).

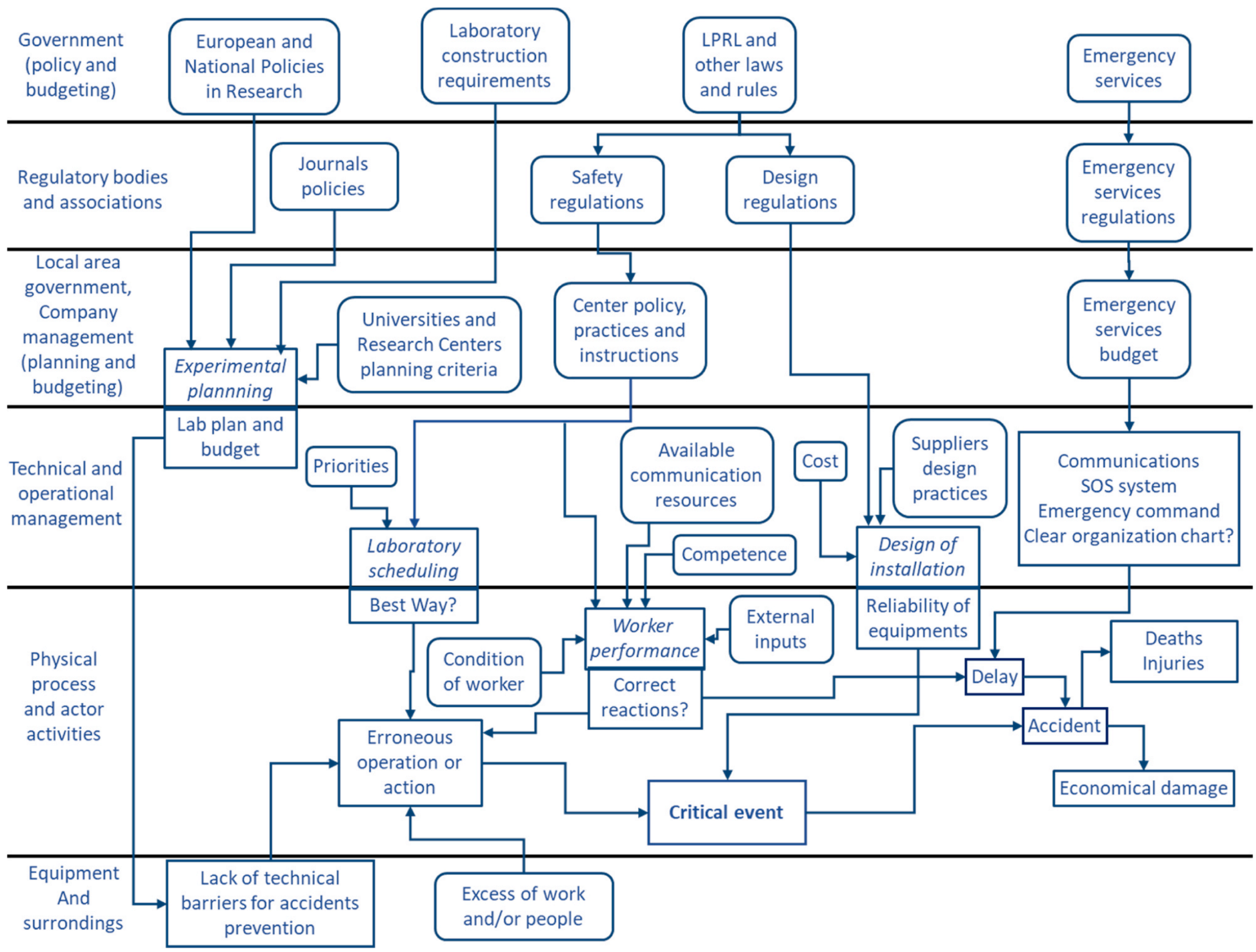

Fig. 5. AcciMap for laboratory AOPs. Six levels are considered: from government policies to laboratory accident. As can be seen, this scheme is applicable to many types of laboratories, not just AOPs. In each case, each box will have to be developed to account for the specificities of AOPs.

An erroneous operation can lead to a critical situation, but this will also depend on the design of the facilities, their reliability, and the safety measures with which they are equipped. Clearly, this requires adequate funding.

Summarizing, AcciMap shows that an accident and its consequences can depend on multiple causes located at different levels, and erroneous decisions or behaviors at different levels, as the ones shown in Fig. 5, can lead to errors that can ultimately produce an accident.

For simple operations, there is no need to use techniques like AcciMap, and there are other suitable RCA techniques such as the WHY technique, useful to identify a particular problem. For instance, in photo-Fenton experiments, sulfuric acid is used, which is known for its corrosive properties. So, if a person suffers burns on his hands due to sulfuric acid spillage, a WHY process could be initiated, as shown in Fig. 6. Usually, with five WHYs, the root cause can be identified.

Obviously, other RCA techniques could have been used, but the two chosen techniques AcciMap and WHY are quite representative of this type of analysis. Both represent two extreme methodologies: AcciMap is more complex, while WHY is suitable for simpler cases. It should be noted that this is an increasingly accepted trend when investigating and reaching the ultimate causes of accidents.

3.3. Safety and health management system

Fig. 5 provides the link to another very important topic in occupational health and safety, which is the topic of safety and health management. Nowadays, management systems could be very helpful in the proper functioning of AOPs laboratories. In addition, it should be noted that ISO 9001:2015, ISO 14001:2015, and ISO 45001:2018 are high-level standards, which means that they have an identical structure and, therefore, allow the implementation of the three management systems (quality, environment, and occupational health and safety) at the same time. This entails greater simplification in the documentation and standardization of the three systems. Table 6 shows in a schematic way all the actions that must be carried out to implement a management system, in accordance with the ISO 45001:2018 standard.

Table 6, applied to an AOPs laboratory, means that each AOP can be perfectly documented, including the organization of the laboratory, from the distribution of spaces to the location of equipment, devices, instruments, and products. This laboratory organization includes safety measures and the necessary tools to ensure that everything is done according to plan.

From all this, it can be deduced, as in any management system, that there must be procedures and/or instructions that perfectly describe

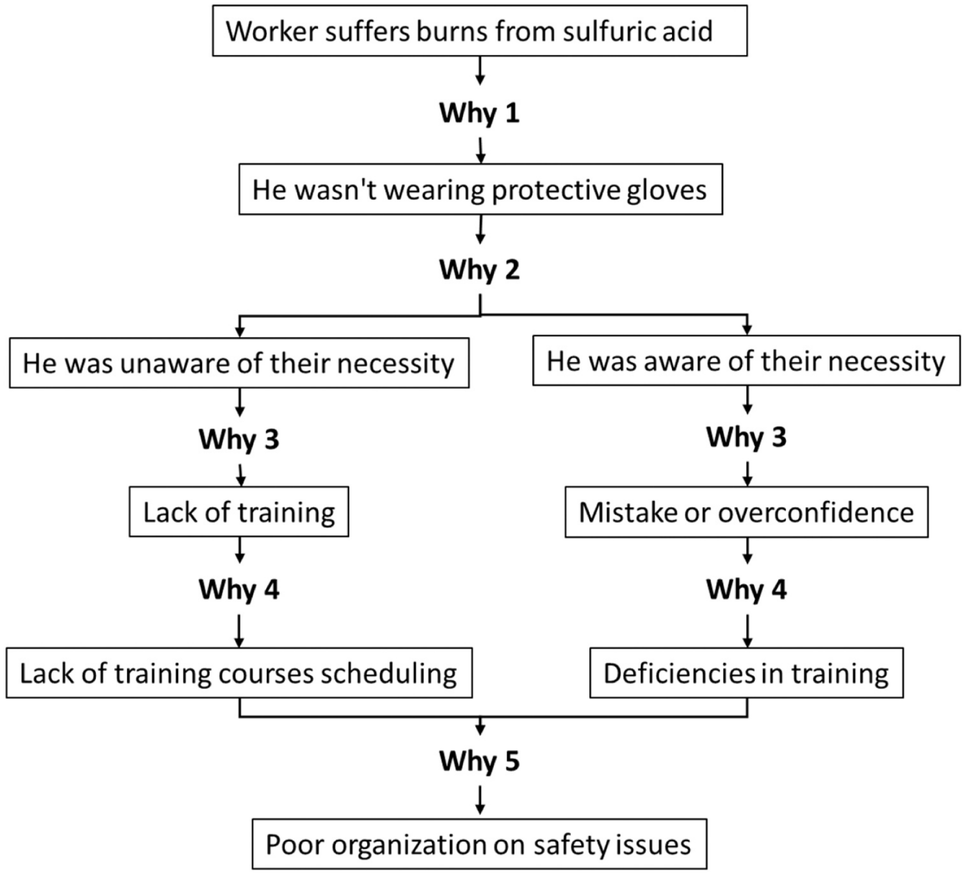

Fig. 6. Application of RCA WHY technique to a simple laboratory operation.

how to carry out each experiment, how each piece of equipment and apparatus works, how calibrations should be carried out, how to take samples, etc. This implies that all operations carried out in the laboratory are perfectly described to avoid errors and bad practices. As previously indicated, these standardized procedures (WSP) should be developed in collaboration with the operators and tested with them to ensure that they are viable and that there are no deviations between the theoretical procedure and the actual procedure. All this also facilitates subsequent audits and the diagnosis of possible errors. There must be procedures and/or instructions for all aspects related to laboratory work and organizational work, for example, for researcher training, safety instructions, organization of documentation, pH meter operation, GC operation, photo-Fenton experiment, use of analytical balances, TOC measurement, BOD measurement, thermostatic bath, etc. Only a few examples have been mentioned here..

The structures of the procedures are very similar and, roughly, their outline could be as follows:

- Introduction
- Aim and scope
- Application field
- Definitions
- Responsibilities
- Safety
- Equipment description
- Instructions - Development
- Wastes management
- Calibration - Checking
- Maintenance
- Related documents
- References

Likewise, it is very useful to have a card of these procedures, as shown in Table 7, where everything that needs to be done is summarized. In this case, the record corresponds to photo-Fenton experiments, but it could be applicable to any other type of AOP experiments..

As shown in Fig. 7, all the steps of the experiment are specified, from preparation to emptying and cleaning of the installation and waste treatment. The figure also specifies where the Work Standard Procedures (WSP) need to be used (orange WSP labels), and the data that must be taken and stored.

Laboratory safety management requires not only procedures, as previously mentioned, but also indicators whose function is to detect easily, quickly, and affordably the good or poor performance of the system.

Possible indicators of organizational topics include: time taken to solve incidents, number of annual incidents, number of annual accidents, rate of facility renewal, provision of training courses, and effectiveness of safety measures. Indicators related to experiment development can also be established, such as mass of eliminated contaminant/mass of catalyst, used kWh/mass of eliminated contaminant, contaminant conversion/experimental time, etc. Note that many of these indicators are also presented in Table 7.

It is advisable to create a dashboard with the most significant indicators, so that the research supervisor can easily detect the good or poor development of experiments. Some of these key indicators could be related to costs, providing an economic estimate. In this sense, some examples could be found in previous works of the authors (Giménez et al., 2015a, 2019; Haranaka-Funai et al., 2017; López et al., 2018).

With all the information received through the Occupational Safety and Health Management System, laboratory operations enter the circle of continuous improvement. Usually, the well-known PDCA (Plan, Do, Check, and Act) methodology is followed. Therefore, based on the

Table 6
Implementation of ISO 45001:2018.

MANAGEMENT SYSTEM		
OBJECTIVES	ACTIONS	Section on ISO 45001:2018
Understanding the organization what to achieve	Understanding the **context** in which the organization operates, in this case, CED-UB (Chemical Engineering Department - University of Barcelona). This context can be analyzed by using a SWOT analysis which allows to know internal (strengths and weaknesses) and external elements (opportunities and threats). The last ones can be completed with a PESTEL analysis (political, economic, social, technological, ecological, legislative aspects). In the case of CED-UB: Strengths: good training of teachers, good scientific level, easy access to information, safety culture and respect for the environment, teamwork, evaluation of the research activity of the staff, etc. Weaknesses: aging of the teaching staff, occasional lack of coordination, age of laboratories, slow procedures and decisions, inflexible schedules, etc. Opportunities: greater influence of universities in political decisions, increase of stable staff positions, search for external sources of financing, start-ups, speed networking, social awareness of the need for a good university research, etc. Threats: lack of generational change, rise of neoliberal policies, decrease in financing of public universities, little investment in R&D&I, little concern for education, few scholarships, huge structure, slowness, fear of change, excessive regulations, etc.	4.1
	Knowing the **requirements** that must be met (needs and expectations of workers and other stakeholders). These can be: Students: quality training, personalized attention, support, guidance, material resources, easy access to information, financial aid, etc. Professors: stabilization and promotion, material resources to support research, work conciliation measures, etc. University: resources for management, teaching and research, satisfactory results and performance, improvement in innovation and research, improvement in coordination and communication, etc. Government: global improvement of the university system, efficiency and effectiveness in research, productivity at low cost, adequate training offer, applicability of research, patents, etc. Society: improvement in innovation, positive impact of knowledge, quality university system, job insertion, good administration and money management, professionals with ethics and responsibility, etc. Employers: personally and professionally competent staff, training offer, greater ease for agreements, etc.	4.2
	Having strong **leadership** from management and establishing the chain of tasks and **responsibilities**. Consulting with workers. Defining the organization's **policy**. In our case that means having clear scientific lines of our group in the short, medium and long term and providing the means and organization to achieve it, through the achievement of research projects, good publications, collaborations with companies, etc.	5
	Objectives, taking into account risks and opportunities. Analysis of occupational risks. Complying with legal requirements.	4.4 (annual objectives) 6.2 (management system objectives) 6.1 (risks and opportunities)
	What are going to do? **PROCESS MAP**:Fig. 7 can also be an example of a simplified process map for carrying out an experiment in the laboratory.	4.4
Planning, resources, design, operational control	**Resources** (people, infrastructure, knowledge, environment,.), competence, awareness, communication, documented information.	7
	How **operate**: planning, requirements, process design, development and control. Reduce health and safety risks. Response to emergencies.	8
System behavior and continuous improvement	Demonstrate that everything is done correctly and that there is **documented information** for everything.	7.5 4.4
	Evaluate entire system: indicators, surveys, records, audits, review by management.	9
	Improve the system: non-conformities and corrective actions, continuous improvement.	10

results obtained, problems will be detected, possible improvements will be proposed and put into action, their effectiveness will be checked, and necessary corrections will be made. PDCA is a never-ending process, but it allows for good laboratory management and increases the likelihood of accidents and incidents decreasing. Fig. 8 shows a PDCA diagram.

The concepts appearing in Fig. 8 adapted to AOPs at the laboratory level are as follows. **Customer** would be any person who is working in AOPs laboratories or who can read and/or receive our research papers. **Stakeholder** could be the whole of society, but in particular the Institutions that invest the money to investigate. **Leadership** includes actions like establishing safety policy, determine roles and responsibilities, encourage participation or demonstrate leadership and commitment. **Context** refers to the multidimensional space where the organization moves and must be clearly defined: What supports and

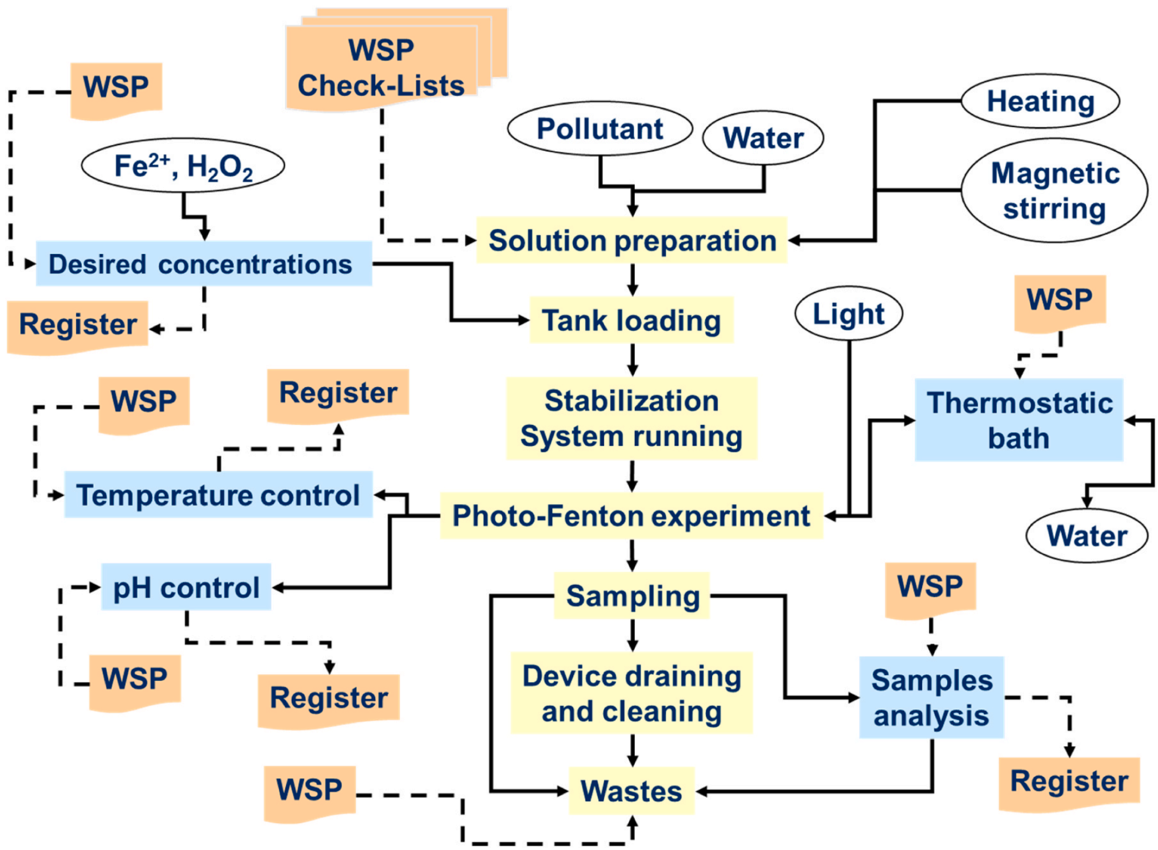

Fig. 7. Flowchart summarizing a WSP for the steps (yellow labels) of the removal of a pollutant by photo-Fenton: a) in orange, standardized processes, b) in white, reagents and energy, c) in yellow, main steps and d) in blue, secondary equipment/actions.

resources it has? What role it plays in its environment? A SWOT and PESTEL analysis can aid in this task (see Supplementary Material Tables S1 and S2). **Planning** includes the hazard identification and risk analysis, the compliance with all legal requirements, the objectives definition, the experiments preparation. **Support and operation**: Laboratories, facilities, material and reagents necessary to carry out the experiments. Supervision of the training of people. Establishment of control systems. Get hold of all the necessary documentation: procedures, records, etc. Emergency response. **Performance Evaluation**: Analyze the results of the experiments, see if they can lead to valid conclusions. Investigate potential accidents and incidents. Carrying out audits. **Improvement**: Introduce the necessary corrective actions to correct the non-conformities. Make all appropriate modifications both in facilities and in methodology to improve the results obtained. Continuous improvement.

Indicators can be a good tool for the continuous improvement process, as well as internal audits and surveys of all staff. It is important that all laboratory personnel are aware of this process and are involved in it. To achieve this, it is important to regularly communicate information in a very visual way (graphs, etc.).

3.4. UN sustainable development goals

The number of accidents at work in the EU in 2020 was 2735566, of which 3359 were fatal. If we look at the activity sectors on which this article focuses, according to the EUROSTAT (Statistical Office of the European Union) classification, 1.5% of total accidents and 1.85% of fatal accidents occurred in the *Professional, scientific and technical activities* sector, while the *Education* sector was the scene of 2.8% of total accidents and 0.45% of fatal accidents. In total, between these two sectors there were 117,630 accidents, being 77 fatal accidents. Despite that part of the accidents that occurred in the chemical industry could have been included in this counting, the figures are still quite significant.

On the other hand, the fact of lacking good laboratory practices implies the unnecessary repetition of experiments, with the corresponding increase of raw materials and energy consumption. As previously shown by this group (Giménez et al., 2015b), each photo-Fenton experiment could involve a consumption of about 400 mg of reactants (contaminant to be treated + $FeSO_4.7\ H_2O + H_2O_2$), in addition to 1 L of ultrapure water. The consumption of reagents for analysis (about 215 mL in total: acetonitrile for HPLC, acidified water for HPLC, dichromate for COD, H_2SO_4 for COD, reagents for H_2O_2 determination, phenanthroline for Fe determination) must also be added. Furthermore, synthetic air is needed for TOC quantification, and the corresponding reagents if BOD or toxicity tests are carried out. These values correspond to mean values for a photo-Fenton experiment, but obviously, they can vary depending on the pollutant treated, number of samples analyzed, etc. In the same work (Giménez et al., 2015b), the energy consumption was estimated for an average photo-Fenton experiment, including all the equipment (lamp, pump, stirrer, thermostatic bath, HPLC, TOC analyzer, spectrophotometer, etc.). This consumption was around 23 kWh, assuming 5.5 h and 12 samples per experiment. It is clear that a null experiment implies throwing away all that amount of raw materials and energy. According to Web of Science, when introducing the keywords "Advanced Oxidation Processes" and "Photo-Fenton", 5514 and 717 publications were obtained, respectively, for 2022. If there are 717 papers and an average of 20 experiments are used for each article, it implies that 14340 experiments were done. Assuming that between 10% and 20% of the experiments tend to go wrong, the required total number of them was 16491 (1.15 $\times$14340, assuming that 15% went wrong). Consequently, the resources of 2151 experiments (16491 - 14340) were thrown away. Taking into account, as mentioned before, that in each

Table 7
Photo-Fenton procedure (WSP) card.

PROCESS CARD Version: … Date: … Pages: 1			
PROCESS	**PHOTO-FENTON** Experiment on the degradation of an organic compound by photo-Fenton		
RESPONSIBLE	Laboratory technicians, maintenance personnel, and any facility user.		
AIM AND SCOPE	Performing this experiment in a manner that ensures appropriate conditions of safety, quality, and environmental respect, guaranteeing the total care of individuals' health, reproducibility of experimental results, and integrity of the equipment involved.		
APPLICATION FIELD	Any user of the facility. However, he/she must contact the laboratory manager responsible for conducting the experiments before their initial use.		
REACTIVES	Water, contaminant, ultrapure water, Fe^{2+}, H_2O_2, energy, air.	**SUPPLIER OF MATERIALS**	Laboratory and/or equipment manager.
PRODUCTS	Liquid waste (product solution) and/or solid and/or gaseous waste.	**CUSTOMERS**	Users of the facilities.
REVISION	**Responsible**	Laboratory responsible	
	Control variables	Temperature Reactant concentration Cooling flow rate and temperature Fe^{2+}, H_2O_2 concentrations/amounts Reaction time Residence time pH Air flow rate Light intensity	
	Indicators	Energy consumed per gram of removed pollutant. Pollutant conversion (%) Mass of pollutant removed per mass of Fe^{2+} or H_2O_2. Mass of total organic carbon (TOC) removed per mass of Fe^{2+} or H_2O_2. Energy consumed per mas of removed TOC. TOC conversion (%)	
REFERENCES	WSPs for the equipment and processes involved in the experiment, service form, …		
REGISTERS	Output record, incidents record		

One of the key aspects of an experiment, and therefore of a procedure, is the development stage, where all the steps are detailed. In this sense, Table 8 and Fig. 7 are crucial.

Table 8
Development of a photo-Fenton experiment: what, who, how, when.

PREPARATION, CONDUCT AND CONTROL OF AN EXPERIMENT			
What ***What needs to be done?***	**Who** ***Who must do it?***	**How** ***How should it be done?***	**When** ***When should it be done?***
Check the lamp of the installation	Responsible for lamps	Verifying the intensity and emission of power	Each 6 months
Check the analytical balances	Responsible for instruments	Checking that the weight displayed is right	Each month
Check the temperature probes, pH probes, etc.	Responsible for instruments	Verifying the correct measurement	Each month
Sampling	Researcher	Following the established procedure	Always
Temperature Reading	Researcher	Following the established procedure	Always
…	…	…	…

This development of an experiment can also be explained through a flowchart (see Fig. 7).

experiment 400 mg of reactants, 1 L of ultrapure water, 215 mL of reagents used for analysis, and 23 kWh are consumed, then 860 g of reactants, 2151 L of water ultrapure, 462 L of reagents for analysis and 49470 kWh were wasted. The reader can imagine how these figures increase when considering all investigation laboratories around the world.

The last aspect to comment is related to the economy. It is not a trivial issue, especially when considering that a very important part of the money allocated to research comes from public funds. In previous studies by this research team (Giménez et al., 2019), it was calculated that the cost of an average photo-Fenton experiment in a solar box was around €118 and one with a BLB lamp around €115. In both cases, amortization of facility costs, cost of reagents, cost of analysis, etc. were included. The average value of an experiment would then be €116.5. Assuming that, on average, about 20 experiments are used to make a paper, this would mean that the average value of a paper is €2324. Assuming that 15% of the experiments, as mentioned before, are unsuccessful, the cost associated to the wasteful experiments needed for the 717 research works published in 2020 would be almost €250,000 ($0.15 \times 717 \times 2324$). Reducing this useless expense would allow the money to be used for other things of public interest, also contributing to a more efficient investigation.

The implementation of risk analysis and an Occupational Health and Safety Management System in research laboratories and, specifically in AOPs laboratories, ensures a better preparation of the people, the improvement of operating procedures, and a more sound and structured execution of the experiments, implying a reduction in the probability and number of accidents. Thus, environmental and economic impact can be reduced, according to the figures discussed before. This fully affects different points of the *Sustainable Development Goals adopted by all UN Member States in 2015, as part of the 2030 Agenda for Sustainable Development* (UN-SDG) (see Supplementary Material, Fig. S2 and Table S3). It is obvious that working safely reduces the risks in the handling of chemical products, and also reduces emissions and spills, resulting in a safer and cleaner work environment (UN-SDG 8), being also a pathway towards sustainable development (UN-SDG 9) that benefits the health and well-being of individuals (UN-SDG 3). Finally, risk analysis ensures a better environmental performance and consequently, a more sustainable way of production (UN-SDG 12). In summary, as just mentioned, occupational risk analysis and the promotion of safety and health at work are also a path towards achieving the UN proposed Sustainable Development Goals (SDGs).

4. Conclusions

A novel risk level has been obtained and normalized between 0 and 10, giving a score (S), applied to photo-Fenton experiments carried out in an AOPs laboratory. Annual cost (C) of the proposed measures to mitigate risks has been estimated. S/C ratio has been deemed as adequate index to asses priorities. S/C ratio allows establishing those risks that can lead to accidents, as their S/C ratio is almost 65% of the total, while 30% and 5% are associated to occupational diseases and stress, respectively.

Although these values correspond to photo-Fenton experiments in the laboratory, the methodology could also be applied to AOP experiments at different scales or topics.

Furthermore, the effectiveness of using RCA techniques has shown to be of great help when delving deep into the causes of accidents and reach the organizational causes of them.

The paper also emphasizes the importance of having an Occupational Health and Safety management system, including indicators to verify the effectiveness and efficiency of the experiments. As a final goal, the implementation of a management system allows for a continuous general improvement of all laboratory procedures.

It has been demonstrated that this way of working contributes to achieve the UN Sustainable Development Goals (SDGs), because it

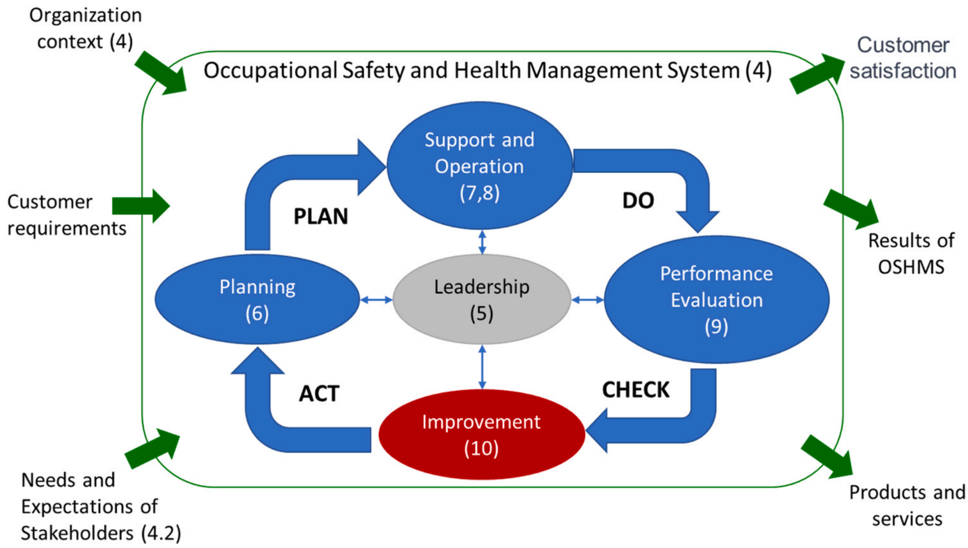

Fig. 8. Flowchart corresponding to an Occupational Safety and Health Management System. The numbers in parentheses indicate the corresponding point of the ISO 45001:2018.

creates a safer and cleaner work environment, promoting the health and well-being of individuals.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Jaime Giménez, Santiago Esplugas and Bernardí Bayarri are grateful to the Ministry of Science and Innovation (projects PID2020–112674RB-I00, TED2021–131569B-I00, MINECO/FEDER, UE) for funds received to carry out this work. Sixto Malato and José Peral wish to thank the Grant PID2021–126400OB-C33 (AquaEnAgri) funded by MCIN/AEI/10.13039/501100011033 and, by “ERDF A way of making Europe”.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.psep.2023.12.033.

References

Baraza, X., Giménez, J., Pey, A., Rubiales, M., 2022. Lessons learned from the Barracas accident: ammonium nitrate explosion during road transport. Process Saf. Prog. 41 (3), 519–530. https://doi.org/10.1002/prs.12396.

Chen, J., Huang, Y., Li, G., An, T., Hu, Y., Li, Y., 2016. VOCs elimination and health risk reduction in e-waste dismantling workshop using integrated techniques of electrostatic precipitation with advanced oxidation technologies. J. Hazard. Mater. 302, 395–403. https://doi.org/10.1016/j.jhazmat.2015.10.006.

Cortés, J.M., 2002. Técnicas de prevención de riesgos laborales. Seguridad e higiene del trabajo, fifth ed., Tébar, Madrid.

Council Directive 89/391/EEC of 12 June, 1989. on the introduction of measures to encourage improvements in the safety and health of workers at work. Off. J. Eur. Communities, 29/6/1989, No L 183/1-8.

De la Cruz, N., Dantas, R.F., Giménez, J., Esplugas, S., 2013a. Photolysis and TiO_2 photocatalysis of the pharmaceutical propranolol: solar and artificial light. Appl. Catal. B-Environ. 130-131, 249–256. https://doi.org/10.1016/j.apcatb.2012.10.003.

De la Cruz, N., Romero, V., Dantas, R.F., Marco, P., Bayarri, B., Giménez, J., Esplugas, S., 2013b. O-Nitrobenzaldehyde actinometry in the presence of suspended TiO_2 for photocatalytic reactors. Catal. Today 209, 209–214. https://doi.org/10.1016/j.cattod.2012.08.035.

EChA - Information on Chemicals. https://echa.europa.eu/information-on-chemicals/registered-substances (Accessed 26 October 2023).

EPA - EPI SUITE. http://www.epa.gov/tsca-screening-tools/epi-suitetm-estimation-program-interface (Accessed 23 October 2023).

EU-OSHA-Research on psychosocial risks and mental health. https://osha.europa.eu/en/themes/psychosocial-risks-and-mental-health/research (Accessed 26 October 2023).

EUROSTAT. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Accidents_at_work_statistics (Accessed 30 June 2023).

Falconer, Ian R., 2006. Are endocrine disrupting compounds a health risk in drinking water? Int. J. Environ. Res. Public Health 3 (2), 180–184, 10.3390/ijerph2006030020.

Giménez, J., Bayarri, B., González, O., Malato, S., Peral, J., Esplugas, S., 2015a. Advanced oxidation processes at laboratory scale: environmental and economic impacts. ACS Sustain. Chem. Eng. 3, 3188–3196, 10.1021/acssuschemeng.5b00778.

Giménez, J., Bayarri, B., González, O., Malato, S., Peral, J., Esplugas, S., 2015b. A comparison of the environmental impact of different AOPs: risk indexes. Molecules 20, 503–518. https://doi.org/10.3390/molecules20010503.

Giménez, J., Esplugas, S., Malato, S., Peral, J., 2019. Economical assessment and possible industrial application of a (photo)catalytic process: a case study. In: Palmisano, L., Marcí, G. (Eds.), Heterogeneous Photocatalysis. Relationships with Heterogeneous Catalysis and Perspectives. Elsevier, Amsterdam, pp. 235–267.

Haranaka-Funai, D., Didier, F., Giménez, J., Marco, P., Esplugas, S., Machulek Jr, A., 2017. Photocatalytic treatment of valproic acid sodium salt with TiO_2 in different experimental devices: an economic and energetic comparison. Chem. Eng. J. 327, 656–665. https://doi.org/10.1016/j.cej.2017.06.148.

HSE (Health and Safety Executive, UK), 2023. Managing risks and risk assessment at work. https://www.hse.gov.uk/simple-health-safety/risk/index.htm (Accessed 27 June 2023).

ICSSL (Institut Català de Seguretat i Salut Laboral), 2016. Detecció i avaluació general de riscos. Generalitat de Catalunya. http://treball.gencat.cat/ca/ambits/seguretat_i_salut_laboral/publicacions/gestio_prevencio/manual_id_av_riscos_laborals/ (Accessed 23 June 2023).

IEC 62740:2015 Root cause analysis (RCA).

ILO - International Chemical Safety Cards (ICSCs). https://www.ilo.org/dyn/icsc/showcard.home(Accessed 26 October 2023).

ILO-Mental Health at Work. https://www.ilo.org/global/topics/safety-and-health-at-work/areasofwork/mental-health-at-work/lang–en/index.htm (Accessed 26 October 2023).

INSST, 1993. NTP 330: Sistema simplificado de evaluación de riesgos de accidente. Barcelona. https://www.insst.es/documents/94886/326853/ntp_330.pdf/e0ba3d17-b43d-4521–905d-863fc7cb800b?version=1.1&t=1676626723671 (Accessed 29 June 2023).

INSST, 1996. Evaluación de Riesgos Laborales. Barcelona. https://www.insst.es/documents/94886/96076/Evaluacion_riesgos.pdf/1371c8cb-7321–48c0–880b-611f6f380c1d (Accessed 30 June 2023).

INSST, 2000. Evaluación de las condiciones de trabajo en pequeñas y medianas empresas. Barcelona. ⟨https://www.insst.es/documentacion/catalogo-de-publicaciones/evaluacion-de-las-condiciones-de-trabajo-en-pequenas-y-medianas-empresas⟩ (Accessed 3 July 2023).

INSST, 2003. Manual de procedimientos de prevención de riesgos laborales. Guía de elaboración. Barcelona. ⟨https://www.insst.es/documentacion/catalogo-de-publicaciones/manual-de-procedimientos-de-prevencion-de-riesgos-laborales.-guia-de-elaboracion⟩ (Accessed 3 July 2023).

INSST, 2009. Gestión de la prevención de riesgos laborales en la pequeña y mediana empresa. Barcelona. ⟨https://www.insst.es/documentacion/catalogo-de-publicaciones/gestion-de-la-prevencion-de-riesgos-laborales-en-la-pequena-y-mediana-empresa-ano-2009⟩ (Accessed 27 July 2023).

INSST, 2010. Riesgo químico: sistemática para la evaluación higiénica. Barcelona. ⟨https://www.insst.es/documentacion/catalogo-de-publicaciones/riesgo-quimico-sistematica-para-la-evaluacion-higienica⟩ (Accessed 3 July 2023).

INSST, 2022. Directrices básicas para la evaluación de riesgos laborales. Barcelona. ⟨https://www.insst.es/documentacion/catalogo-de-publicaciones/directrices-basicas-para-la-evaluacion-de-riesgos-laborales⟩ (Accessed 30 June 2023).

IPCS - International Programme on Chemical Safety, 2004. IPCS Concise International Chemical Assessment Documents 57: Glyoxal. https://www.inchem.org/documents/cicads/cicads/cicad57.htm (Accessed 27 October 2023).

ISO 14001:2015 Environmental management systems - Requirements with guidance for use.

ISO 45001:2018 Occupational health and safety management systems - Requirements with guidance for use.

ISO 9001:2015 Quality management systems - Requirements.

Kuhn, H.J., Braslavsky, S.E., Scmidt, R., 2004. Chemical actinometry (IUPAC technical report). Pure Appl. Chem. 76, 2105–2146. https://doi.org/10.1351/pac200476122105.

Law 31/1995, of November 8, on Occupational Risk Prevention. BOE nº 269, de 10 de noviembre de 1995, pp. 32590–32611. This Law transposes Council Directive 89/391/EEC.

Lin, Y.C., Lin, Y.W., 2022. An index to assess overwork-related adverse effects on employees under the occupational safety and health act in Taiwan. Saf. Health Work. 13 (4), 401–407. https://doi.org/10.1016/j.shaw.2022.10.002.

López, N., Plaza, S., Afkhami, A., Marco, P., Giménez, J., Esplugas, S., 2017. Treatment of diphenhydramine with different AOPs including photo-Fenton at circumneutral pH. Chem. Eng. J. 318, 112–120. https://doi.org/10.1016/j.cej.2016.05.127.

López, N., Marco, P., Giménez, J., Esplugas, S., 2018. Photocatalytic diphenhydramine degradation under different radiation sources: kinetic studies and energetic comparison. Appl. Catal. B Environ. 220, 497–505. https://doi.org/10.1016/j.apcatb.2017.08.077.

Méndez-Arriaga, F., Esplugas, S., Giménez, J., 2008. Photocatalytic degradation of non-steroidal anti-inflammatory drugs with TiO_2 and simulated solar irradiation. Water Res. 42, 585–594. https://doi.org/10.1016/j.watres.2007.08.002.

NIOSH Pocket Guide to Chemical Hazards. http://www.cdc.gov/niosh/npg/ (Accessed 23 October 2023).

Noh, M.S., Che Ghani, S.A., Muhammad Sidik, M.H., 2022. Investigation of ergonomics risk assessment among manual assembly manufacturing workers in medical device industry. In: Hassan, M.H.A., et al. (Eds.), Human-Centered Technology for a Better Tomorrow. Lecture Notes in Mechanical Engineering. Springer, Singapore https://doi-org.sire.ub.edu/10.1007/978-981-16-4115-2_56.

Noman, M., Mujahid, N., Fatima, A., 2021. The assessment of occupational injuries of workers in Pakistan. Saf. Health Work. 12 (4), 452–461. https://doi.org/10.1016/j.shaw.2021.06.001.

REACH - Regulation (EC) No 1907/2006 of The European Parliament and of The Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC.

Romero, V., González, O., Bayarri, B., Marco, P., Giménez, J., Esplugas, S., 2016. Degradation of metoprolol by photo-fenton: comparison of different photoreactors performance. Chem. Eng. J. 283, 639–648. https://doi.org/10.1016/j.cej.2015.07.091.

Svedung, I., Rasmussen, J., 2002. Graphic representation of accident scenarios: mapping system structure and the causation of accidents. Saf. Sci. 40, 397–417. https://doi.org/10.1016/S0925-7535(00)00036-9.

Ten, J.Y., Hassim, M.H., Chemmangattuvalappil, N.G., 2020. Integration of safety and health aspects in a simultaneous process and molecular design framework. Chem. Eng. Res. Des. 153, 849–864. https://doi.org/10.1016/j.cherd.2019.11.018.

UN-SDG (United Nations - Sustainable Development Goals). https://www.un.org/sustainabledevelopment/ (Accessed 30 June 2023).

Ying So, W., Hassim, M.H., Ahmad, S.I., Rashid, R., 2021. Inherent occupational health assessment index for research and development stage of process design. Process Saf. Environ. Prot. 147, 103–114. https://doi.org/10.1016/j.psep.2020.09.015.

Zhang, J., Chang, V.W.C., Giannis, A., Wang, J.Y., 2013. Removal of cytostatic drugs from aquatic environment: a review. Sci. Total Environ. 445-446, 281–298. https://doi.org/10.1016/j.scitotenv.2012.12.061.