SOCIETAL LCA

Social life cycle assessment of an innovative industrial wastewater treatment plant

Monica Serreli[1] · Luigia Petti[1] · Andrea Raggi[1] · Alberto Simboli[1] · Guglielmo Iuliano[2]

Abstract

Background The social impacts generated by industrial waste treatment processes have not been studied enough, as shown in the literature. Social life cycle assessment studies have mainly focused on the assessment of products and less on industrial waste, especially wastewater, although potentially relevant from an environmental point of view, and also from a social one for various stakeholders.

Purpose This case study concerns the social assessment of an innovative technology to treat the wastewater of a micro-electronics company. In order to produce electronic components and semiconductors, the company has to treat and dispose of relevant wastewater streams containing various toxic substances. The wastewater streams need to be treated in order to protect the eco-system, representing a high cost for the company and a potential impact on the environment.

For this reason, the company developed a LIFE project to demonstrate the viability to decrease the burdens on water bodies. The positive outcome of the test on the pilot plant paved the way for the construction of the full-scale plant that will treat all the wastewater generated by the company.

The objective of this paper is the socio-economic assessment of a full-scale plant designed to treat three different kinds of wastewater.

Methods The assessment of socio-economic potential impacts of a new technology has been carried out through the PSILCA (Product Social Impact Life Cycle Assessment) database implementation to evaluate 65 social indicators of a wastewater treatment plant.

Results The line with the highest impact is the one which treats tetramethylammonium hydroxide; this is because this wastewater flow is the most abundant (14 and 43 times greater than the other wastewaters, respectively).

The most affected stakeholder is the Local Community, followed by the Actors of the Value Chain; in fact, the results referred to the functional unit considered exceed 300,000 medium risk hours in both cases. For the Local Community this result arises from the indicator "Contribution to environmental load," which is understandable considering the object of the study since this indicator includes health effects. As far as the Value Chain Actors stakeholder is concerned, the two indicators most impacted are "Corruption" and "Social responsibility along the supply chain".

The analysis conducted has also shown that upstream has a fundamental relevance for the social risks detected.

Conclusions Considering the current lack of studies on both environmental and social impacts of wastewater treatment, and the fact that Social Life Cycle Assessment has not been widely used in this field, as emerged from literature review, this work is the first use of the PSILCA database to assess an industrial wastewater plant. The use of a social life cycle assessment database allows the value chain of a product system to be considered: the results show that most of the overall social risk derives from upstream sectors.

Keywords S-LCA · Social life cycle assessment · Wastewater treatment (WWT) · PSILCA · Electronics and semiconductor (E&S) sector · Tetramethylammonium hydroxide (TMAH)

✉ Luigia Petti
l.petti@unich.it

Extended author information available on the last page of the article

Nomenclature

AHP	Analytic hierarchy process
ANP	Analytic network process
BES	Bio-electrochemical systems
DoS	Dashboard of sustainability

E&S   Electronics and semiconductor
GDP   Gross domestic product
MRIO   Multi-regional input output
mrh   Medium risk hours
PSILCA   Product Social Impact Life Cycle Assessment
REACH   European Regulation on Registration, Evaluation, Authorisation and Restriction of Chemicals
SAM   Subcategory assessment method
SHDB   Social hotspot database
TMAH   Tetramethylammonium hydroxide
USD   US dollar
WWT   Wastewater treatment
WWTF   Wastewater treatment facilities
WWTP   Wastewater treatment plant

1 Introduction

Chemicals have become essential to several production and consumption processes; however, some of them can severely damage human health or the environment. In the second half of the last century, the global production of chemicals grew over 50-fold leading to a huge amount of newly registered global chemicals (EC 2019), thus mounting the chemical burden worldwide. In recent years, the EU has undertaken numerous actions to regulate and improve the production, use and disposal of toxic substances, as given in REACH (European Regulation on Registration, Evaluation, Authorisation and Restriction of Chemicals—EC 2006)—aiming at ameliorating human health and environment safeguard by means of identifying the inherent properties of chemicals—or the 7th Environment Action Programme (EC 2013) adopted to come up with an innovative strategy for a safe environment. These actions were characterized by a proactive approach, which helped to enhance innovation and competitiveness in the EU chemical sector.

Despite this, great advances can still be made to improve the sustainability of chemicals, which are widely used both in various industrial sectors, among which are the electronics and semiconductor (E&S) sector.

The use of highly pure chemicals is of great importance in the semiconductor industry; in fact, minor traces of impurities can critically affect the electrical properties of materials. In the production of printed circuit boards, the photosensitive resin applied to the substrate (wafer) is exposed to light using a mask on defined points and then developed in a chemical reaction. The developer contains a certain concentration of tetramethylammonium hydroxide (TMAH) and ensures that the areas exposed to light can be easily removed from the substrate. TMAH ($N(CH_3)_4{}^+OH^-$; CAS 75–59-2) is an alkaline ingredient (a colourless to light yellow solution that is miscible with

water and has similar density) in photoresist developer, in concentrations of 2.38–2.62% (by weight) in a great number of applications.

Given that large amounts of developer are used in E&S industries, a considerable amount of wastewater containing TMAH is generated every year by this sector. Based on empirical investigations carried out and taking into account the size of the European E&S sector, it can be estimated that more than 250,000 t of TMAH solution are used every year in Europe (more than 2 million tons/year worldwide) (Life Bitmaps 2020).

As concerns the ecotoxicity on the water environment, the OECD (2012) reported that TMAH degrades quickly in water and has a scarce bio-accumulation capacity. Nevertheless, fatal accidents were described due to the high toxicity of TMAH, which is lethal in both concentrated and diluted formulations (at 2.38% by weight) (Lin et al. 2010; Lee et al. 2016; Mori et al. 2015).

In spite of that, it must be noted that TMAH emission levels are currently not regulated, e.g. by any EU or Italian regulation (EC 2006).

Technical notes reveal that the NOEC (no observed effect concentration)—acceptability concentration of TMAH to prevent chronic toxic effects on invertebrates (*Ceriodaphnia dubia*, *Daphnia magna*)—should be equal to 0.02 mg/L (OECD 2012). Considering a safety factor of 10, as foreseen by the EU Water Framework Directive 2000/60/EC, the Italian *Istituto Superiore di Sanità* (ISS, Higher Institute of Health) came out with a recommendation to keep the discharge limits below 0.4 mg/L in the drainage system to ensure 0.2 mg/L thresholds in water bodies (ISS 2013).

Hence, a tremendous volume of wastewater carrying TMAH is released every day from the E&S industry and the current operational limit can be considered adequate for human safety but not for protecting the water ecosystem (Vegliò 2016). Additionally, the cost for the disposal or the chemical treatment of spent TMAH solution significantly affects the operational costs in the E&S industry. Thus, technically viable and economically sustainable solutions would be very welcome and advanced treatments of industrial wastewaters, spent TMAH and photoresist process solutions represent a key challenge for the E&S industry.

The purpose of this paper is to evaluate the socio-economic aspects of implementing the above wastewater treatment technologies at a full-scale by means of a social life cycle assessment (S-LCA).

The outline of this paper is as follows: the next section illustrates the background of the scientific literature concerning the social assessment of wastewater treatment technologies. The specific objectives of the study, the methodology used and the boundaries of the system analysed are

described in Sec. 3. The data collected are shown in Sec. 3.4, while the impacts detected and the results obtained are discussed in Sec. 4. Some conclusions are finally drawn in Sec. 5.

2 Literature background

In order to conduct a socio-economic analysis, it is useful to look over what the literature proposes in this field.

In the analysis of the literature background, S-LCA studies on industrial wastewater treatment (WWT) or, more generally, on WWTs, were considered by focusing on which social aspects of WWTs were assessed in the S-LCA case studies and on the methodology used. Also, the specific indicators utilised to assess the social aspects of a WWT in S-LCA studies were taken into consideration.

Any study on WWT that included the assessment of social aspects published in scientific journals between 2009 and 2020 has been taken into account. Instead, the following was not considered: grey literature, duplicate studies, conference papers and papers by the same authors on the same subject and works not written in English.

The timeframe (2009–2020) for the literature search was chosen to start from 2009, because it was when the S-LCA guidelines (UNEP/SETAC 2009) were first published; therefore, earlier studies, if any, are supposed to have not been carried out in compliance with the most widely recognised relevant guidelines. For this purpose, Scopus was consulted. The search topics were included in the Title-Abstract-Keyword field. The most relevant results are those obtained from the following keywords: "Social life cycle assessment" AND "wastewater treatment"; "social assessment" AND "wastewater treatment".

The papers identified were reviewed for the methodology applied and the stakeholders and the social indicators involved for each of the case studies (Table 1).

The low number of works found suggests that, despite that considerable progress has been made on WWT technologies, only few studies have evaluated the social consequences of the WWT processes.

García-Sánchez and Güereca (2019) conducted an S-LCA on the WWT of Mexico City and considered only the workers' stakeholder. They obtained the highest social performance average in the phase of the WWT, whilst the storage phase obtained the poorest rating. They concluded that water systems need an S-LCA methodology with specific indicators to help the decision-making process.

Padilla-Rivera et al. (2019) proposed a useful metric to decide which is the best WWT from an environmental, social and economic perspective. In selecting the appropriate indicators, they considered that, up to now, the emphasis on wastewater has been on the epidemiological features and

their consequences on health and on the social aspects of its use, mainly linked to irrigation. Another concern has been how wastewater practices have been dealt with by institutions. Therefore, they decided to consider the following stakeholders and indicators:

- Community and society: public participation, local employment, safe and healthy living conditions
- Workers: working hours, fair salary, training, health and safety
- Consumers: feedback mechanism
- Supply chain: promoting social responsibility (Padilla-Rivera et al. 2019, p. 23)

Sadhukhan et al. (2019), in their case study carried out by means of the Social Hotspots Database (SHDB), recommended the practice of macroalgae growing as a more sustainable option for wastewater treatment. Shemfe et al. (2018) used the same database in the analysis of the sustainability of bio-electrochemical systems (BES), which was classified as a technical solution for a few urgent worldwide problems, such as environmental pollution, scarcity of resources and scarcity of freshwater. Finally, this study assessed positively the results obtained from the analysis carried out on BES with the SHDB.

Amaral et al. (2019) evaluated the treatment and disposal of biological sludge and biogas in a wastewater Brazilian plant (WWTP) by means of Dashboard of Sustainability (DoS) (Traverso et al. 2012) which makes for the conversion of data into a sole sustainability indicator and the weighting of every indicator for the same scale.

Kamali et al. (2019) assessed the sustainability of the treatment of industrial effluents by means of engineered nanomaterials. In this case, the social indicators used are odour, noise, visual impacts and public acceptance.

In the paper by Opher et al. (2018), the benefits and social impacts of four alternative re-use of non-potable domestic urban water are compared: (1) central WWT, no urban re-use, the recovered water is discharged into nature; (2) central WWT and urban re-use of the tertiary effluent of the WWTP; (3) semi-distributed grey water treatment and its re-use; and (4) distributed grey water treatment and its re-use within each apartment building.

The selected subcategories and indicators useful for evaluating them are listed below.

- Public: water saving/equity
- Local community: community engagement/local employment/urban landscape
- Consumers' health: concerns (level of contact with the reclaimed water, source of the reclaimed water, trust in supplier), household expenses, convenience

Table 1 Literature review results

Authors	Methodology applied	Stakeholder involved	Indicators
García-Sánchez and Güereca (2019)	S-LCA (method developed by Franze and Ciroth 2011)	Workers	Working hours Fair wage Health and safety conditions (exposure to risks in the facility, basic requirements for installation security, personal safety equipment work accidents, emergency plans, health) Social security (social benefits) Professional development (training)
Padilla-Rivera et al. (2019)	S-LCA Subcategory Assessment Method (SAM) The methodology evaluates indicators that were developed using different sources of data: questionnaires, household interviews and observations, based on a previous identification of the relevant stakeholders involved in wastewater treatment facilities (WWTF) Transforming qualitative information into quantitative data (1 to 4, with 1 being the worst and 4 the best assessment)	Community and society Workers Consumers Supply chain	(Public participation, local employment, safe and healthy living conditions) (Working hours, fair salary, training, health and safety) (Feedback mechanism) (Promoting social responsibility)
Sadhukhan et al. (2019)	S-LCA Social Hotspots Database (SHDB)	No	Labour rights and decent work Health and safety Human rights Governance Community infrastructure
Amaral et al. (2019)	S-LCA Subcategory Assessment Method (SAM) An adaptation of the methodologies described by Ramirez et al. (2014), Zortea et al. (2017) and Padilla-Rivera et al. (2016) was used for the assessment of social impacts	Workers Consumers Local community and society	Wages paid to workers, noise level, odour emission (H_2S and NH_3) Values of pathogens present in sludge, noise level, odour emission Biological risks Ability to generate employment Use of hazardous chemicals Biological risks (bacteria, fungi, viruses) N and P content in the sludge Capacity to generate employment
Kamali et al. (2019)	Fuzzy-Delphi method	50 experts from 19 countries	Odour, noise, visual impacts, public acceptance
Shemfe et al. (2018)	S-LCA SHDB	Workers Workers and society Society and local community Society and value chain actors Society and local community	Labour rights and decent work (child labour, forced labour, excessive working time, poverty, wage assessment, migrant labour, wage assessment, collective bargaining, inadequate social benefits) Health and safety (injuries and fatalities, toxics and hazards) Human rights (indigenous rights, gender equity, high conflict) Governance (legal system, corruption) Community infrastructure (drinking water, improved sanitation, hospital beds)

Table 1 (continued)

Authors	Methodology applied	Stakeholder involved	Indicators
Opher et al. (2018)	S-LCA AHP (analytical hierarchy process)	Public, Local community, Consumers	(Water saving/equity) (Community engagement/local employment/urban landscape) Health concerns (level of contact with the reclaimed water, source of the reclaimed water, trust in supplier); household expenses; convenience (supply reliability, consumption habits)
Ren and Liang (2017)	Multi-criteria group decision-making	Researchers, Administrators, Local residents	Social-political (public acceptability, added jobs, governmental support)
Bui et al. (2016)	Multicriteria assessment	All relevant stakeholders (public, scientists, practitioners, politicians)	Public acceptance of the different methods
Padilla-Rivera et al. (2016)	S-LCA (Franze and Ciroth 2011)	Community and society, Workers, Consumers, Supply chain	(Public participation, social acceptance, community engagement, sustainable behaviour, local employment; safe, healthy and secure living conditions, public commitments to sustainable issues, contribution to economic development) (Freedom of association and collective bargaining, child labour, working hours, fair salary, equal opportunities/discrimination, training, health and safety, availability of wastewater management documentation, management performance, monitoring program) (Effluent quality, demand satisfaction, health and safety, feedback mechanism, consumer satisfaction) (Fair competition, supplier relationship, promoting social responsibility)
Molinos-Senante et al. (2015)	Analytic network process (ANP) Multi-criteria decision-making	Experts from the academic, research and industrial fields	Odours, noise, visual impact, public acceptance, complexity of construction, operation
Molinos-Senante et al. (2014)	Composite indicator	Standard stakeholders (decision makers, experts, planners and analysts involved in preparing and managing the process)	Odours, noise, visual impact, public acceptance, complexity of construction, operation
Gómez-López et al. (2009)	Multicriteria decision making	Experts and decision makers	Enterprise image

As for the case study, the re-use of distributed urban water resources had a positive impact, due to the promotion of public commitment for natural water resources conservation and the promotion of community commitment.

Ren and Liang (2017) proposed a method to help decision-makers in choosing the most sustainable WWT among different processes; the social criteria used are related to the public acceptability of the plants, to the jobs created by the plants and to the policy supports, i.e. fiscal and policy/regulation enhancement.

Byrne et al. (2017) reviewed the S-LCA studies on urban water infrastructure. Despite, they collected 22 studies on various urban water systems worldwide, only two of them (Kobayashi et al. 2015; Sharma et al. 2009) had assessed the social themes, by using neither S-LCA nor the stakeholder Workers. The other 20 case studies had focused solely on the assessment of environmental impacts and, in three cases, of the economic ones.

Bui et al. (2016) used multi-criterion analysis to assess micropollutants treatments by means of full-scale and pilot-scale studies; the social indicator used was public acceptance of different treatment methods.

Padilla-Rivera et al. (2016) measured social performance by using a 25-indicator framework to assess and compare two different WWTs in Mexico at both urban and rural locations.

Molinos-Senante et al. (2014; 2015) proposed to use an analytic network process or to elaborate a composite indicator useful to favour the evaluation of various types of WWT. In reference to this, they considered the following indicators: odours, noise, visual impact, public.

Gómez-López et al. (2009) aimed at choosing the best methods of disinfection of treated wastewater prior to its re-use, as well as considering enterprise image as a social indicator.

Lessons learned from the analysis of the 14 papers using S-LCA or having assessed social aspects in WWT are the following:

- The analysis of the literature has not shown any element useful to draw methodological conclusions, the S-LCA studies are very few and no industrial WWT assessment has been found among these.
- Technical and financial aspects have the precedence in wastewater treatment facilities (WWTF), whereas social aspects have not been completely assessed. Therefore, no method for their evaluation has been yet acknowledged.
- At present, most of the research focuses on finding the most economically and environmentally sustainable method for wastewater treatment. Furthermore, the social aspects have been considered almost exclusively in studies dealing with the treatment of wastewater from civil plants, although it is evident that the greatest problems for humans arise from wastewater coming from industries and agriculture (UN Water 2020).
- Most of the analysed studies are very recent (from 2015 to 2019). From 2009 to 2015, only two case studies were found. In this period, the analysis of the sustainability of WWT systems mainly considered environmental and economic aspects and the social features concerned only the public acceptance of the external physical aspects of WWT.

Fig. 1 Current WWT
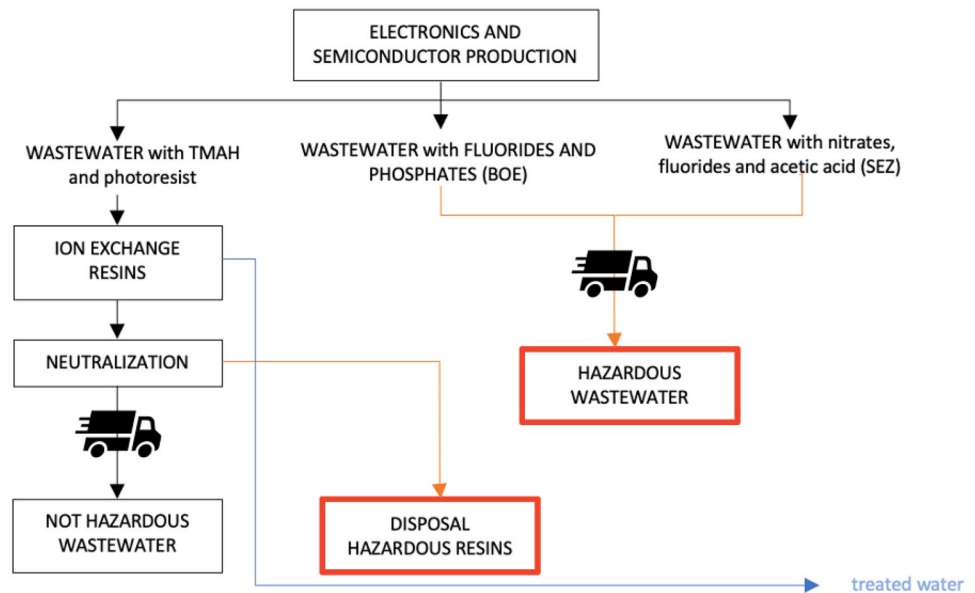
3 Methods

Approaches for the evaluation of social impacts are still under development. S-LCA is a method proposed to measure the social and socio-economic impacts of products and/or processes from cradle to grave (i.e. from raw material extraction to their end of life) (UNEP/SETAC 2009).

The case study carried out regards an E&S company situated in the Abruzzo region, Italy. Prior to the project, the company neutralized the TMAH used in semiconductor manufacturing using H_2SO_4 and NaOH. By so doing, the TMAH was concentrated, resulting in a lower volume. This solution was then kept and sent to an external plant authorized to treat such waste (Fig. 1). The WW from the other two lines, line 2 (named BOE) and line 3 (named SEZ), was not treated on site, but sent to external companies for disposal. The Regional Agency for the Environment Protection of Abruzzo region, based on the ISS technical note (ISS 2013), issued to the company under study a recommendation to investigate viable solutions for reducing the TMAH concentration in its plant (Regional Agency for the Environment Protection of Abruzzo Region 2013).

The company decided to build a pilot plant to test a new treatment technology for the three WW lines internally, instead of disposing of WW externally, thus hoping to gain significant savings in the operating costs related to waste treatment and to improve the environmental impacts generated by these three lines.

This article deals with an experimental project on the biodegradation of TMAH (line 1) in a proper bioreactor (De Michelis et al. 2019). The aim of the project was to implement a TMAH biological treatment plant on a pilot scale, which went into operation in 2018. Subsequently, the project demonstrated that the biodegradation of TMAH into non-toxic substances and ammonia can take place on an industrial scale using aerobic biological treatment, with an efficiency greater than 99% (Innocenzi et al. 2019). The new technology plant provided treatment of line 1 by neutralisation with sulphuric acid, followed by biological treatment (De Michelis et al. 2019) (Fig. 2).

The second WW lines carried fluorides and phosphates (BOE—line 2), while the third was abundant in nitrates, fluorides, phosphoric acid and acetic acid (SEZ—line 3). These lines were chemically treated with lime together with aluminium sulphates ($Al_2(SO)_4*18H_2O$) added as a coagulant. Lime allowed the solutions to be neutralized by precipitating the impurities: indeed, lime was able to successfully eliminate pollutants from residual solutions. Thereafter, filtration enabled the separation of solid and liquid phases.

The liquid streams, produced at the end of the three lines, are treated in a biological reactor, water, can then be recycled and/or discharged into surface waters (Innocenzi et al. 2019).

Regarding the solid waste produced by lines 2 and 3, the classification as non-hazardous was confirmed by the pilot plant tests (De Michelis et al. 2019).
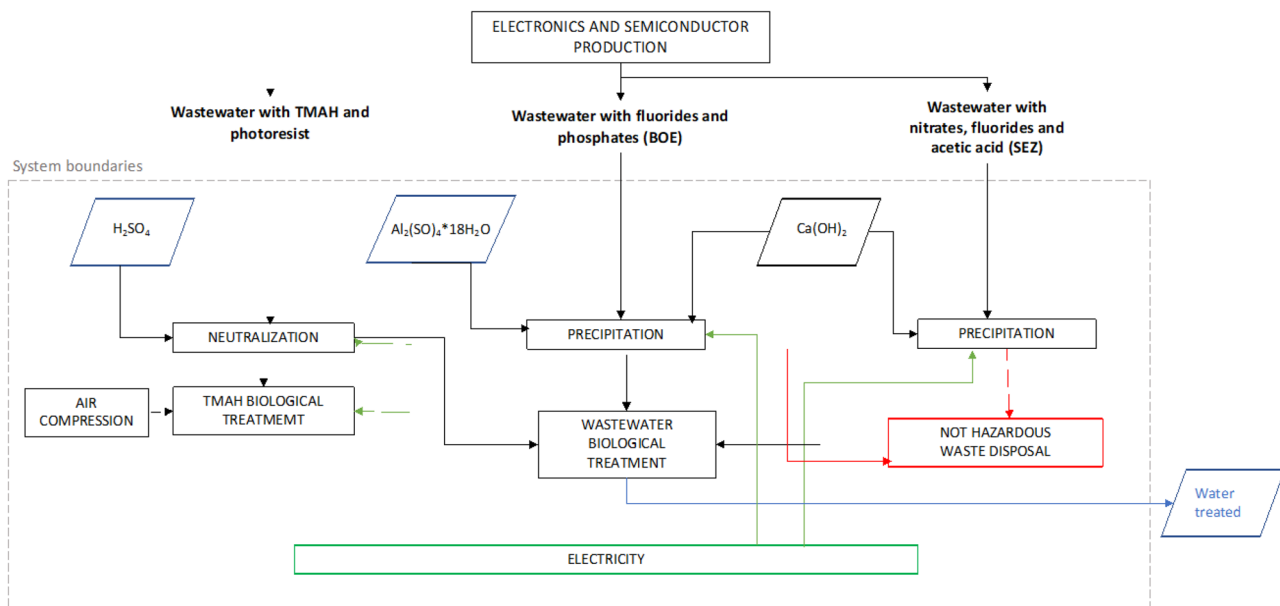

Fig. 2 System boundaries for LCA and S-LCA of the full-scale plant

The pilot plant worked as a test for the future construction of a full-scale plant. The analysis carried out considered the volumes that the full-scale plant will have to handle, because the company was interested in assessing the social risks related to it.

3.1 Goal of the study

The aim of this study is to assess the socio-economic aspects of a new wastewater treatment technology used to control the pollution arising from the production of semiconductors carried out in the company's facilities located in Abruzzo, Italy. The current technology only partially treats WW streams, whilst the new technology, which was tested on a pilot plant, treats all three types of WW. The analysis considered the flows of a full-scale plant, which are planned to be built after a positive evaluation of the project.

3.2 Tools

This study was carried out using Product Social Impact Life Cycle Assessment—PSILCA v2.0 (Eisfeldt and Ciroth 2017), a comprehensive database developed by Green-Delta GmbH in Berlin, available within the open-source LCA software "openLCA" (www.openlca.org). PSILCA uses a multi-regional input/output database called Eora (Eora 2015) to provide information for 189 countries and almost 15,000 different sectors, divided into industries and commodities. Like many input/output tables, Eora considers cash flows between processes. Input/output tables are an accounting representation of the exchange flows occurring in a given economic system, over a given period of time. The inputs of each sector are expressed in terms of USD needed to produce US$1 of output.

Social indicators are structured according to the Guidelines for Social Life Cycle Assessment of Products (UNEP/SETAC 2009).

PSILCA uses worker-hours as its activity variable to quantify the impacts of a process along its life cycle, although the addition of further variables is currently being analysed.

The PSILCA database proposes 65 qualitative and quantitative indicators, measured in various units, such as single values or percentages. They are structured in clusters describing 19 social and socio-economic subcategories related to UNEP/SETAC (2009). Indicator values defined as "intensive" and independent of the system size (e.g. size of the sector or economy density) are given in the PSILCA database, so as to render the indicator results comparable across countries and different sectors.

The indicators are quantified in medium risk hours (mrh), i.e. hours with an average risk of an occurring given social issue.

The subcategories focus on five stakeholder categories: workers, local community, society, consumers and value chain actors.

3.3 Scope of the study

3.3.1 Functional unit

The plant treats three different kinds of wastewater, with different treatments. The social assessment is consistent with the environmental life cycle assessment (LCA) conducted on the pilot plant, the full scale and the current management (Life Bitmaps 2020).

The functional unit used for the analysis is the same as that chosen for the LCA, i.e. the current annual generated amounts for each kind of wastewater considered, as specified below:

1. 6300 t of wastewater with TMAH and photoresist (line 1);
2. 435 t of wastewater with NH_4F (BOE) (line 2);
3. 145 t of wastewater with nitrates, fluorides, phosphoric acid and acetic acid (SEZ) (line 3).

3.3.2 System boundaries

The system boundaries were also defined consistently with the environmental LCA study (Fig. 2).

In the current management option, the wastewater with TMAH and photoresist is treated internally (ion exchange and neutralisation) and then managed by external companies, while the other two types of wastewaters are not currently treated within Company facilities but are sent to external companies for treatment as hazardous wastewater.

As regards the plant with innovative processes, the system boundaries include, for line 1, sulphuric acid and biological treatments. While for the other two lines, precipitation and filtration were included. Finally, a treatment in a biological reactor for all the three lines is considered.

In principle, for a comparison between the full-scale system with new technology and the current system to be meaningful, the overall social impacts generated by both systems should be assessed. As regards that aim, in the *current system*, the processes carried out by the companies currently treating the waste disposal (for line 2 BOE and line 3 SEZ) should also be included in the system boundaries. However, for consistency reasons, the system boundaries of this study are the same as those of the environmental LCA study and, therefore, as regards the *current system*, they include only transportation to the external companies that treat wastewater.

Table 2 Input data, origin and Eora sector category for the three lines of wastewater treated within the full-scale innovative processes

Material	Input (tons per year)	Originating from	Eora sector
Wastewater with TMAH and photoresist			
Wastewater	6300 t	Italy	Waste Flow
Sulphuric acid (98%)	23.62 t	Italy	Chemicals, chemical products and man-made fibres
Water	55.12 t	Italy	Collection, purification and distribution of water
Electricity	630,000 kWh	Italy	Electrical energy, gas, steam and hot water
Wastewater with fluorides and phosphates NH_4F (BOE)			
Wastewater	435 t	Italy	Waste Flow
Lime	102.6 t	Italy	Chemicals, chemical products and man-made fibres
Water	410.25 t	Italy	Collection, purification and distribution of water
$Al_2(SO_4)_3 *18H_2O$	17.4 t	Italy	Chemicals, chemical products and man-made fibres
Electricity	7500 kWh	Italy	Electrical energy, gas, steam and hot water
Wastewater with nitrates, fluorides and acetic acid (SEZ)			
Wastewater	145 t	Italy	Waste Flow
Lime	33.95 t	Italy	Chemicals, chemical products and man-made fibres
Water	135.7 t	Italy	Collection, purification and distribution of water
$Al_2(SO_4)_3 *18H_2O$	5.8 t	Italy	Chemicals, chemical products and man-made fibres
Electricity	2500 kWh	Italy	Electrical energy, gas, steam and hot water

3.3.3 Assumptions

The material inputs shown in Table 2 were entered in PSILCA as economic value and were provided by the company.

The economic value of all the inputs has been converted from euro to USD using a deflator into USD 2011, as the current version of PSILCA is based on USD 2011 ($1.2939 to the euro).

3.4 Inventory analysis

3.4.1 Full-scale plant, data collection

The data required by the PSILCA database to model the product systems are: input materials, their origin, the Eora MRIO database category, the total cost of each input material and the working hours needed for the 3 WWT.

The product systems modelled on PSILCA are the three wastewater lines of the new full-scale plant.

Table 2 summarizes the input data, their country of origin and the Eora sector category for the full-scale plant. All data and estimates were provided by the company. An average Italian power mix is chosen as energy source to feed all the main process blocks, the PSILCA database uses energy mix data from Istat (the Italian Statistical Office) referring to 2011 (Istat 2014).

3.5 Impact assessment

The risk level of indicators is assessed for the product system and entered in the output table. Indicators are then "characterized" by the activity variable. The characterisation factors used are expressed on an ordinal scale and divided into 6 levels as follows: no risk = 0, very low risk = 0.01, low risk = 0.1, medium risk = 1, high risk = 10, very high risk = 100 and a missing value (no data) equals to very low risk. The activity variable used by PSILCA is worker hours, i.e. the time spent by each worker to manufacture a certain quantity of product in a process/sector. "Worker hours" allow us to quantify the social risks to which each worker is affected in a product system.

To build the DB for each process the amount of worker hours has been computed in relation to US$1 of output (Eisfeldt and Ciroth 2017).

$$\text{Worked hours} = \frac{\text{unit labour cost}\left(\frac{USD}{USD}\right)}{\text{mean hourly labour cost}\left(\frac{USD}{h}\right)} \quad (1)$$

The *unit labour cost* is the compensation of employees for US$1 output within a sector, and it is expressed in USD. The *mean hourly labour cost* is the average hourly wages, and it is expressed in USD for 1 h. The equation result is expressed in hours of work per 1 USD of output.

Table 3 Stakeholders, subcategories and indicators in the PSILCA database

Stakeholder	Subcategory	Indicator	Risk level
Workers	Child labour	Children in employment, male	
		Children in employment, female	
		Children in employment, total	No risk
	Forced labour	Goods produced by forced labour	
		Frequency of forced labour	Very low risk
		Trafficking in persons	
	Fair salary	Living wage, per month	Very low risk
		Minimum wage, per month	Very low risk
		Sector average wage, per month	Very low risk
	Working time	Weekly hours of work per employee	Medium risk
	Discrimnation	Women in the sectoral labour force	Medium risk
		Men in the sectoral labour force	Very low risk
		Gender wage gap	Medium risk
	Health and safety	Rate of non-fatal accidents at workplace	Very low risk
		Rate of fatal accidents at workplace	Very low risk
		DALYs due to indoor and outdoor air and water pollution	Low risk
		Presence of sufficient safety measures	Medium risk
		Workers affected by natural disasters	Low risk
	Social benefits, legal issues	Social security expenditures out of the total GDP	Very low risk
		Evidence of violations of laws and employment regulations	Very low risk
	Freedom of association	Trade union density	Low risk
		Right of association	
		Right of collective bargaining	
		Right to strike	No risk
Value chain actors	Fair competition	Presence of anti-competitive behaviour or violation of anti-trust and monopoly legislation	Low risk
	Corruption	Public sector corruption	Low risk
		Active involvement of the enterprises in corruption and bribery	Low risk
	Promoting social responsibility	Social responsibility along the supply chain	
Society	Contribution to economic development	Contribution of the sector to economic development	Low Opportunity
		Public expenditure on education	
		Adult illiteracy rate (15 + years), male	
		Adult illiteracy rate (15 + years), female	
		Adult illiteracy rate (15 + years), total	
		Youth illiteracy rate, male	
		Youth illiteracy rate, female	
		Youth illiteracy rate, total	
	Health and safety	Health expenditure, total	Medium risk
		Health expenditure, public	Low risk
		Health expenditure, out-of-pocket	Medium risk
		Health expenditure, external resources	Very low risk
		Life expectancy at birth	No risk
Local community	Access to material resources	Level of industrial water use (related to total withdrawal)	Very low risk
		Level of industrial water use (related to actual renewable resources)	Very low risk
		Extraction of biomass (related to area)	
		Extraction of biomass (related to population)	
		Extraction of fossil fuels	

Table 3 (continued)

Stakeholder	Subcategory	Indicator	Risk level
		Extraction of industrial and construction minerals	
		Extraction of ores	
		Certified environmental management systems (CEMs)	Low risk
	Respect of indigenous rights	Presence of indigenous population	
		Human rights issues faced by indigenous peoples	
	Safe and healthy living conditions	Pollution level of the country	Medium risk
		Drinking water coverage	Very low risk
		Sanitation coverage	No risk
	Local employment	Unemployment rate in the country	Medium risk
	Migration	International migrant workers in the sector	
		International migrant stock	
		Net migration rate	Low risk
Consumers	Transparency	Presence of business practices deceptive or unfair to consumers	Low risk

Table 3 shows the stakeholders, subcategories and all indicators in PSILCA (the 36 indicators used to assess the three lines of wastewater in the new plant are highlighted in light blue) as well as the risk level of each indicator.

The assignment of risk levels to the indicators was carried out by consulting various databases (Istat, Ministero del Lavoro e delle Politiche Sociali, Wage indicator org, ILOSTAT, OECD, WHO) and specific literature, referring to Italy or to Europe, to better reflect the specific goal and scope of the study.

For the remaining indicators, the risk levels were entered as "no data" and analysed by the database with a value equal to very low risk.

The impact assessment method used by PSILCA (Social Impacts Weighting Method) assigns characterisation factors to the various impact categories per sector, previously assessed according to risk level. The working hours of each process are used as an *activity variable* in order to quantify the social risk, i.e. how much each process affects workers. The software uses the characterisation factors of each input (specific to sector and country) and the working hours of every process to determine the social risk (expressed in medium risk hours for each indicator). For example, if in the process the child labour indicator has a very low risk characterisation factor corresponding to 0.01 and the working hours of that process correspond to 1, 0.01 will be multiplied by 1.

The relative social impacts within the life cycle are calculated by aggregating the various indicators scaled on the price of the inputs, on the basis of the hours worked and on the characterisation factors.

4 Results and discussion

The results were first aggregated by subcategories (Figs. 3, 4 and 5) but are also available by indicator as required by the guidelines (UNEP/SETAC 2009) to ensure the transparency of the case study.

Line 1 has the highest risks, which is certainly due to the fact that the amount of WW with TMAH is the highest, 14 times higher than line 2 and even 43 times higher than line 3 (Fig. 5).

The subcategory most generally affected is "Safe and healthy living conditions" (except for line 1, where this subcategory is surpassed by "Corruption"). This is relevant as it is based on data from three indicators concerning the country's pollution level, the accessibility and availability of clean water and the country's health coverage (Fig. 6).

For all three lines, another high-risk subcategory is "Access to material resources". This subcategory, like the previous one, belongs to the Local Community stakeholder, and evaluates its access to material resources or limitation caused by commercial or industrial activities (Fig. 7).

Industries should, in fact, guarantee and develop infrastructures useful for community access to local material resources (i.e. water, land, mineral and biological resources). To describe this subcategory, the level of industrial water use, the extraction of other material resources, the presence of certified environmental management systems and the potential for material resource conflicts are assessed (Figs. 8 and 9).
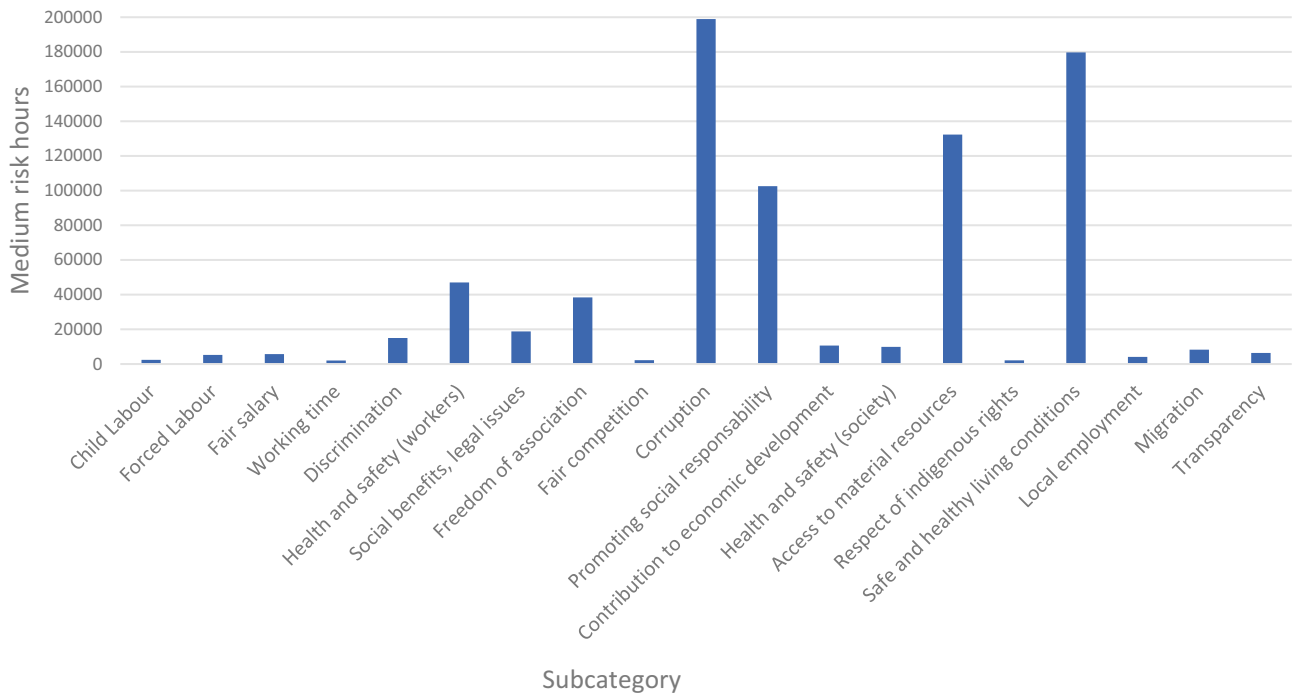
Fig. 3 Results by subcategory for the line 1 TMAH

The analysis of results from an indicator perspective (Figs. 10, 11, and 12 in Appendix) for all three lines examined, showing the highest impact is "Public sector corruption", whose indicator is expressed by the Corruption Perception Index (Transparency International 2012). Corruption typically affects public institutions or governments and can have major effects on everyday life. In this case study, corruption is linked to the electrical and chemical sectors, despite the fact that the risk assessment assigned to the company analysed is "low risk" (Table 3).

The other impact categories affected are (Eisfeldt and Ciroth 2017):
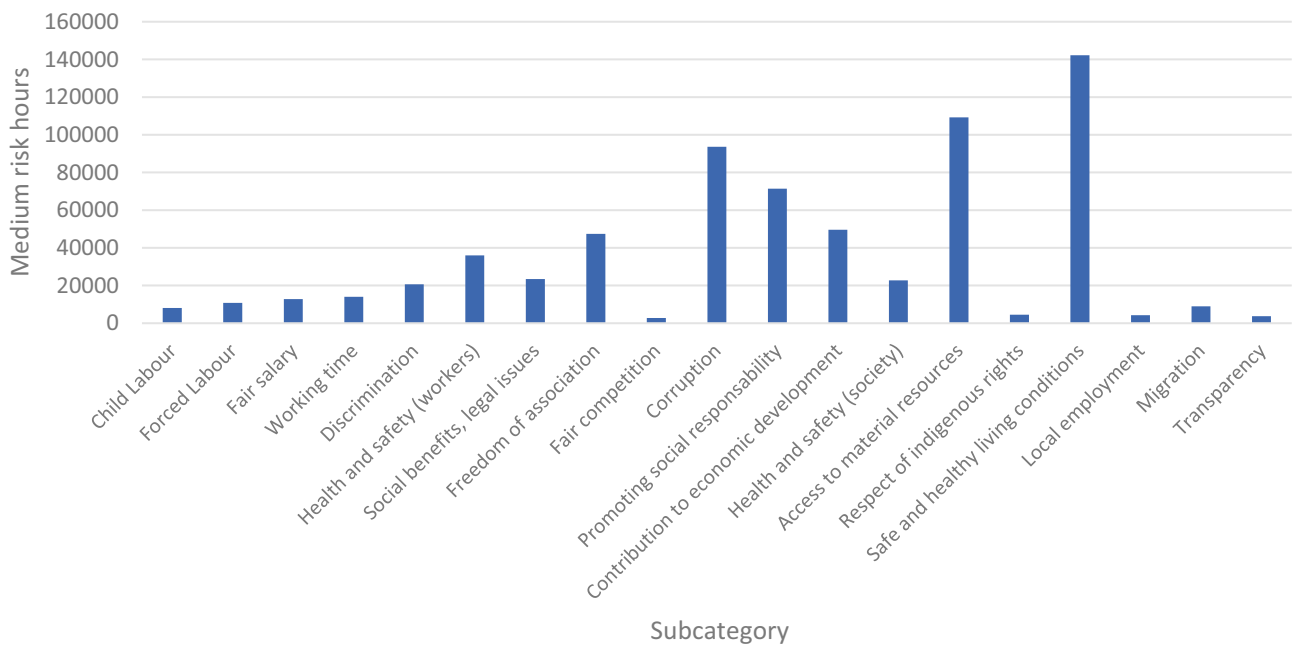
Fig. 4 Results by subcategory for the line 2 BOE
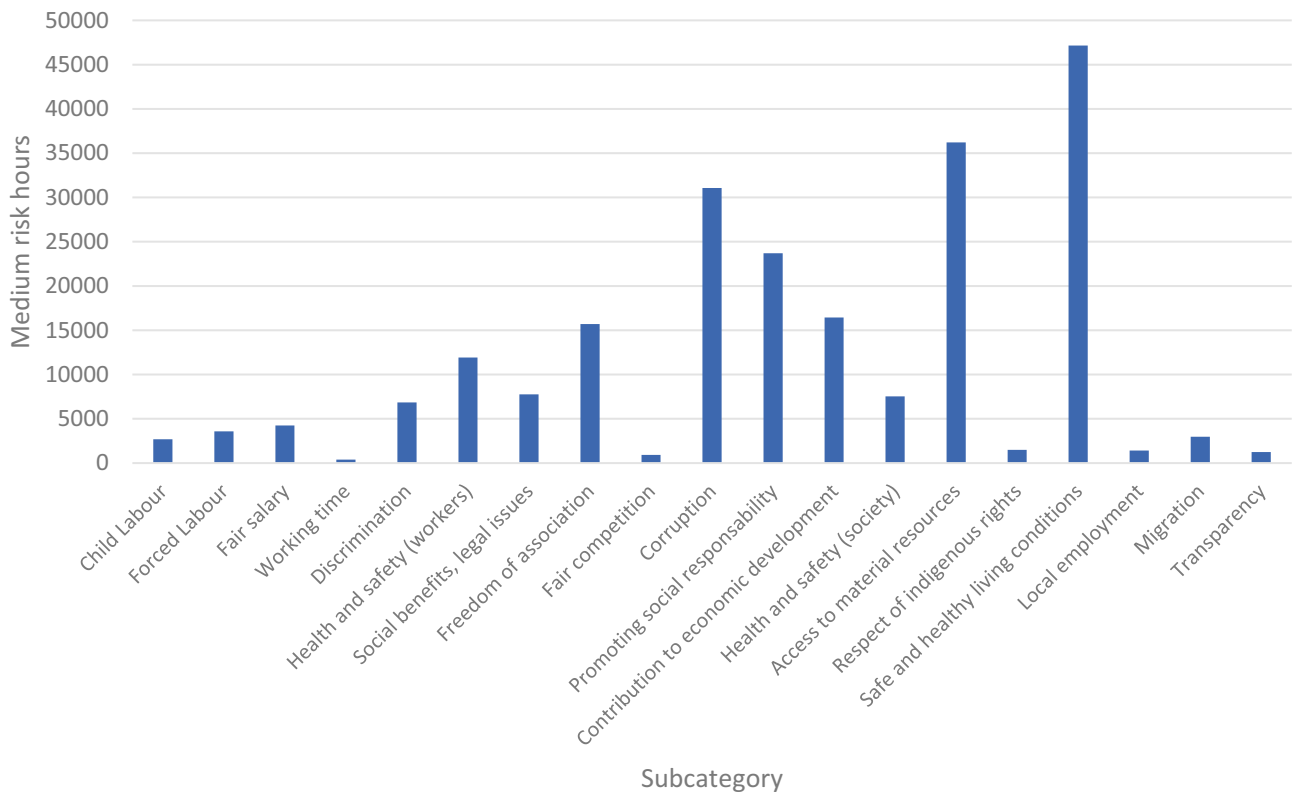
Fig. 5 Results by subcategory for the line 3 SEZ

- "Social responsibility along the supply chain"; the pertinent indicator considers how much companies in specific sectors take into consideration and ensure social responsibility.

- "Contribution to environmental load"; taking into account various airborne emissions (Table 3), this indicator expresses the contribution of a given sector to global warming, environmental pollution and, ultimately, health
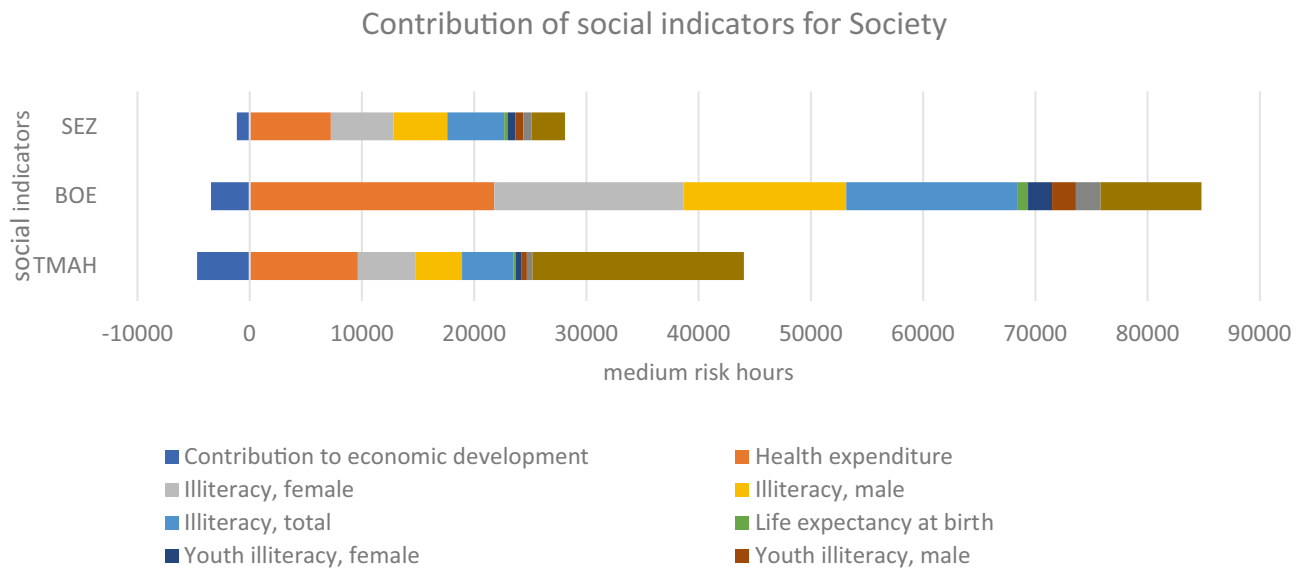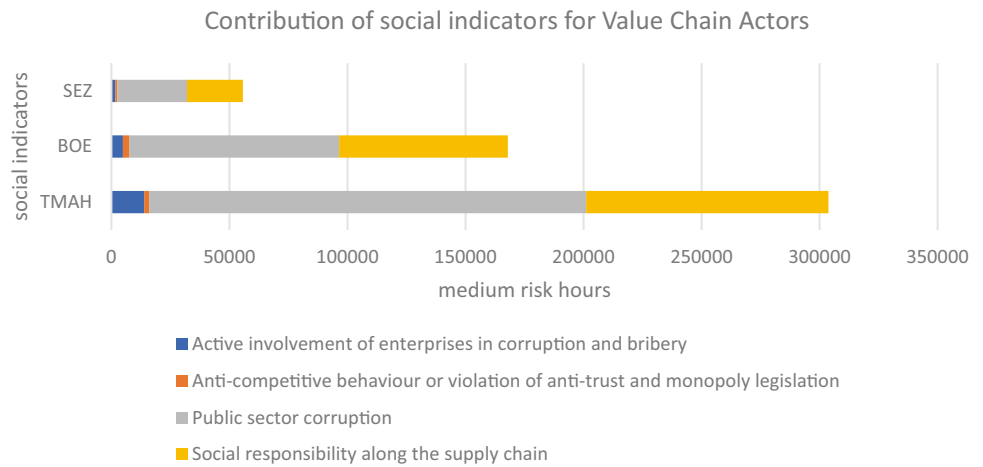

Fig. 6 Relative contribution to social indicators in the stakeholders society, considered for line 1 TMAH, line 2 BOE and line 3 SEZ processes (functional unit: annual generation of wastewater, 6300 t TMAH, 435 t BOE, 145 t SEZ)
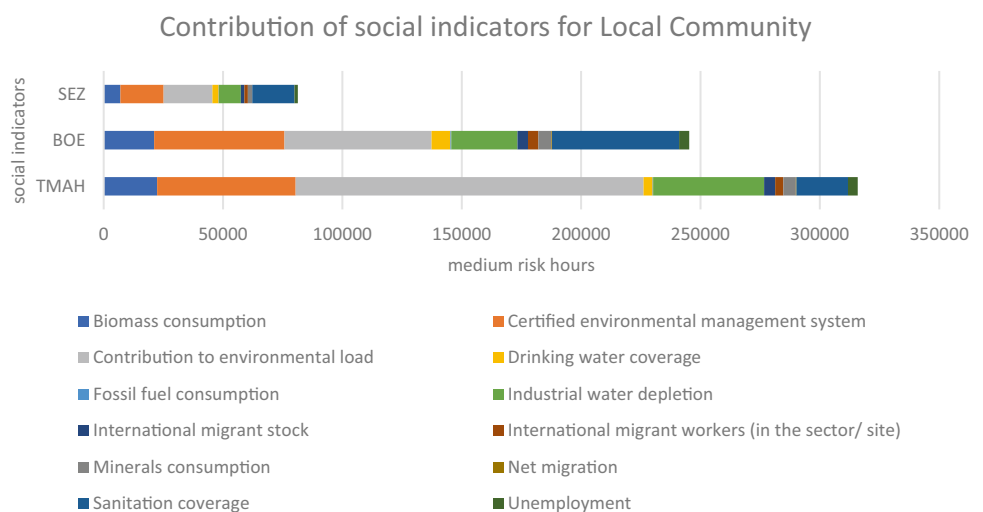
Fig. 7 Relative contribution to social indicators in the stakeholders Value Chain Actors, considered for line 1 TMAH, line 2 BOE and line 3 SEZ processes (functional unit: annual generation of wastewater, 6300 t TMAH, 435 t BOE, 145 t SEZ)

Contribution of social indicators for Value Chain Actors

- Active involvement of enterprises in corruption and bribery
- Anti-competitive behaviour or violation of anti-trust and monopoly legislation
- Public sector corruption
- Social responsibility along the supply chain

risks. In this case study, reference is made to the supply chain of the sectors concerned.

- "Certified environmental management systems"; for a given sector this indicator takes into consideration the ratio between the number of certified Environmental Management Systems (EMS) and the number of employees in that sector.
- "Industrial water depletion"; this indicator assesses the degree of industrial water consumption by relating the amount of water withdrawn for industrial purposes to the overall water withdrawal for other uses (agricultural, industrial and municipal) as well as to the total renewable water resources.
- "Sanitation coverage"; this indicator assesses a population's access to improved sanitation facilities, and thus the associated exposure to infectious disease risks, assuming that poor access to such facilities is associated with lower levels of wastewater treatment. The indicator also offers information on overall water quality.

- "Trade union density"; this indicator expresses the spread and freedom of trade union culture in a given sector; thus, in the final analysis, the right of workers to organize freely in trade unions in that sector.

The positive impact of the indicator "Contribution of the sector to economic development" is very significant. This indicator evaluates the contribution of a given sector to the economic development of a whole country and is determined as that sector's contribution to the country's Gross Domestic Product GDP, and it is the only positive indicator considered (Eisfeldt and Ciroth 2017). This indicator represents all types of sector contributions to economic development, e.g. investment in business/infrastructure, job creation, specific education and training. For this reason, it is expressed in levels of opportunity: low levels of opportunity assume that the sector, compared to others, does not make significant contributions to economic development, while high levels represent a positive impact. This result stems from the

Fig. 8 Relative contribution to social indicators in the stakeholders Local Community considered for line 1 TMAH, line 2 BOE and line 3 SEZ processes (functional unit: annual generation of wastewater, 6300 t TMAH, 435 t BOE, 145 t SEZ)

Contribution of social indicators for Local Community

- Biomass consumption
- Certified environmental management system
- Contribution to environmental load
- Drinking water coverage
- Fossil fuel consumption
- Industrial water depletion
- International migrant stock
- International migrant workers (in the sector/ site)
- Minerals consumption
- Net migration
- Sanitation coverage
- Unemployment

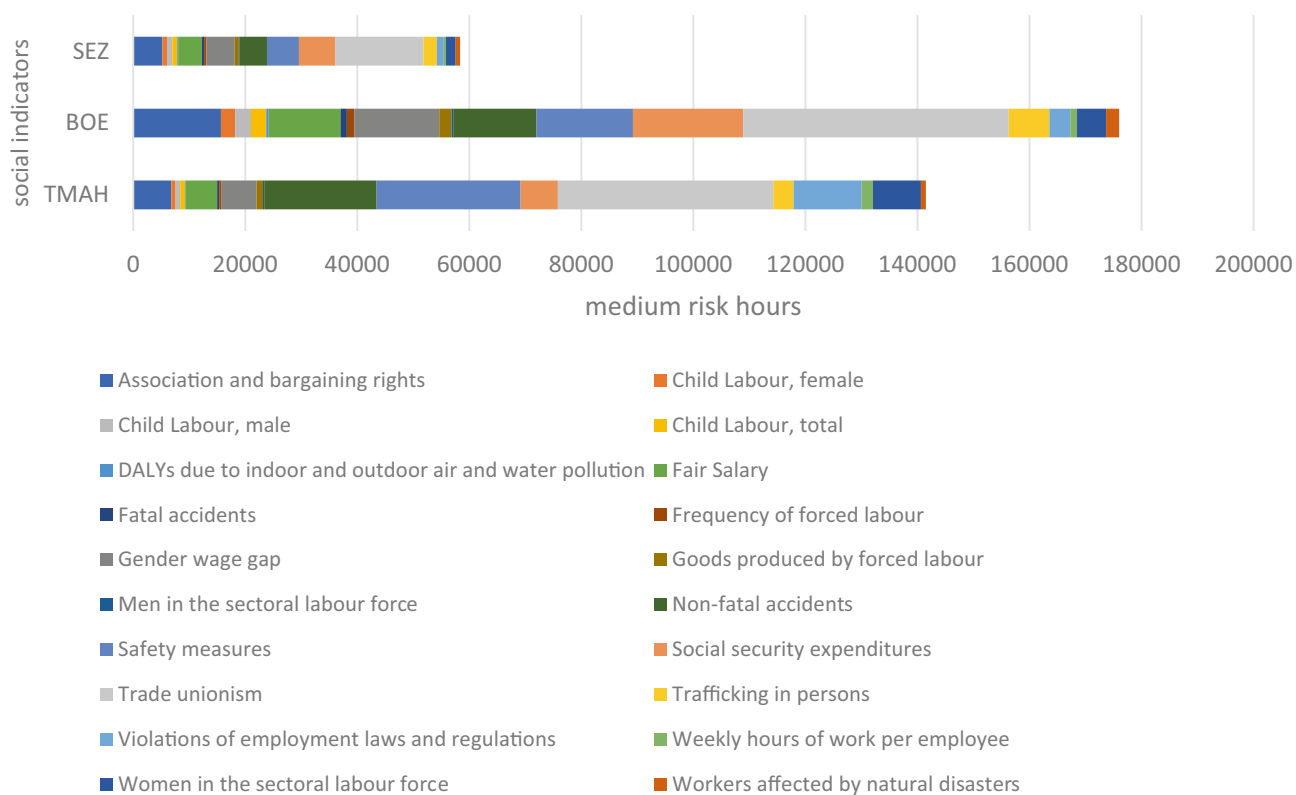## Contribution of social indicators for Workers

Fig. 9 Relative contribution to social indicators in the stakeholder workers considered for line 1 TMAH, line 2 BOE and line 3 SEZ processes (functional unit: annual generation of wastewater, 6300 t TMAH, 435 t BOE, 145 t SEZ)

contribution of the sectors from which our inputs come, in this case from the "Chemicals, chemical products and man-made fibres" sector, which in Italy is growing both in terms of imports and exports.

PSILCA analysis for stakeholders shows the Local Community to be the most affected group (Fig. 6).

The impacts on "Local Communities" are mainly generated by: "Contribution to environmental load", "Certified environmental management system" and the "Use of industrial water". These indicators have negative impacts on the environment, even though they are here considered for their associated health risks.

Value chain actors (Fig. 7) such as Local Community (Fig. 6) show results exceeding 300,000 mrh for line 1. In this case, the indicators that most contribute to the result are "Corruption" and "Social responsibility along the supply chain".

Social consequences for employees (Fig. 8) across all three lines include a high vulnerability related to "Gender inequality", "Safety measures" and "Amount of working hours".

Line 2 BOE indicators contribute most to the impacts on stakeholders Society (Fig. 9) and Workers.

The Sankey diagram shows (Fig. 13 in Appendix) that the direct contribution from the TMAH line to the impact category "contribution to environmental load" is very low (0.041%), compared to the indirect (97.37% upstream sectors) one. Indeed, the risk is spread throughout the supply chain, according to the results of our analysis from the 3 WWT lines with innovative technology; this implies that the overall risk is mainly related to sectors upstream the TMAH, BOE and SEZ processes.
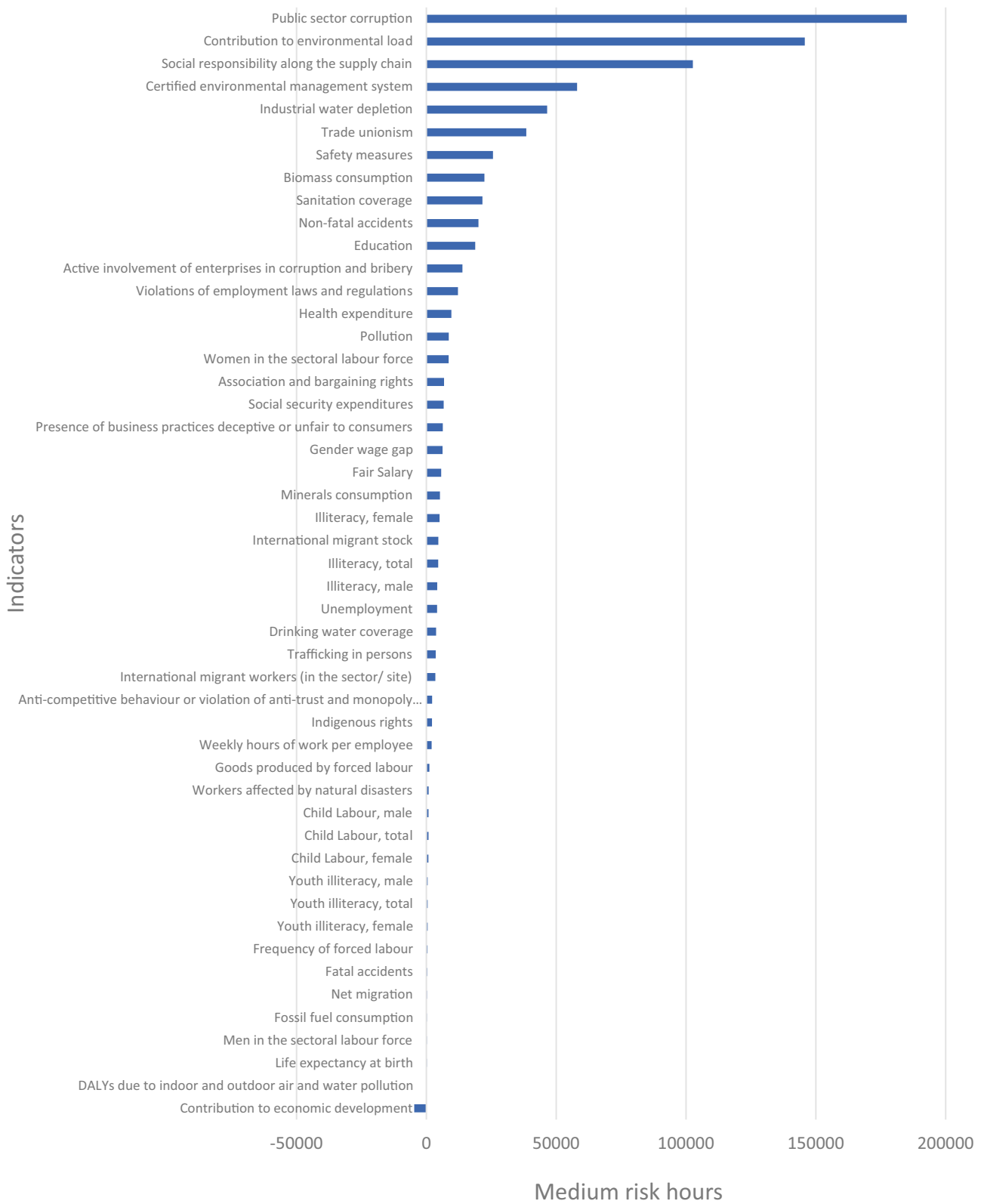
Line 1 TMAH results

Fig. 10 Results by social indicators of the TMAH lines of the plant, in mrh for the FU (functional unit: annual production of wastewater 6300 t TMAH)
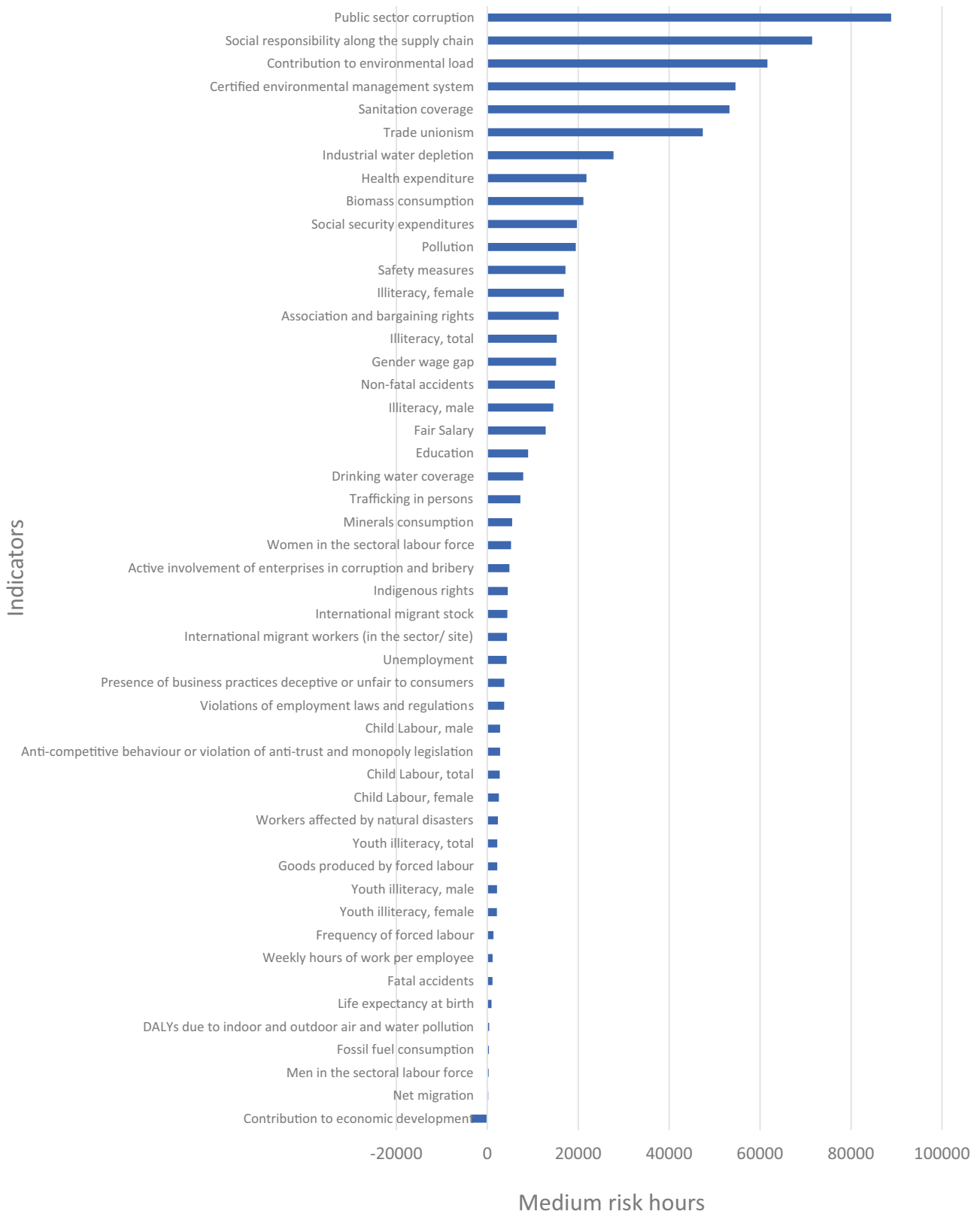
Line 2 BOE results

Fig. 11 Results by social indicators of the BOE lines of the plant, in mrh for the FU (functional unit: annual production of wastewater, 435 t BOE)
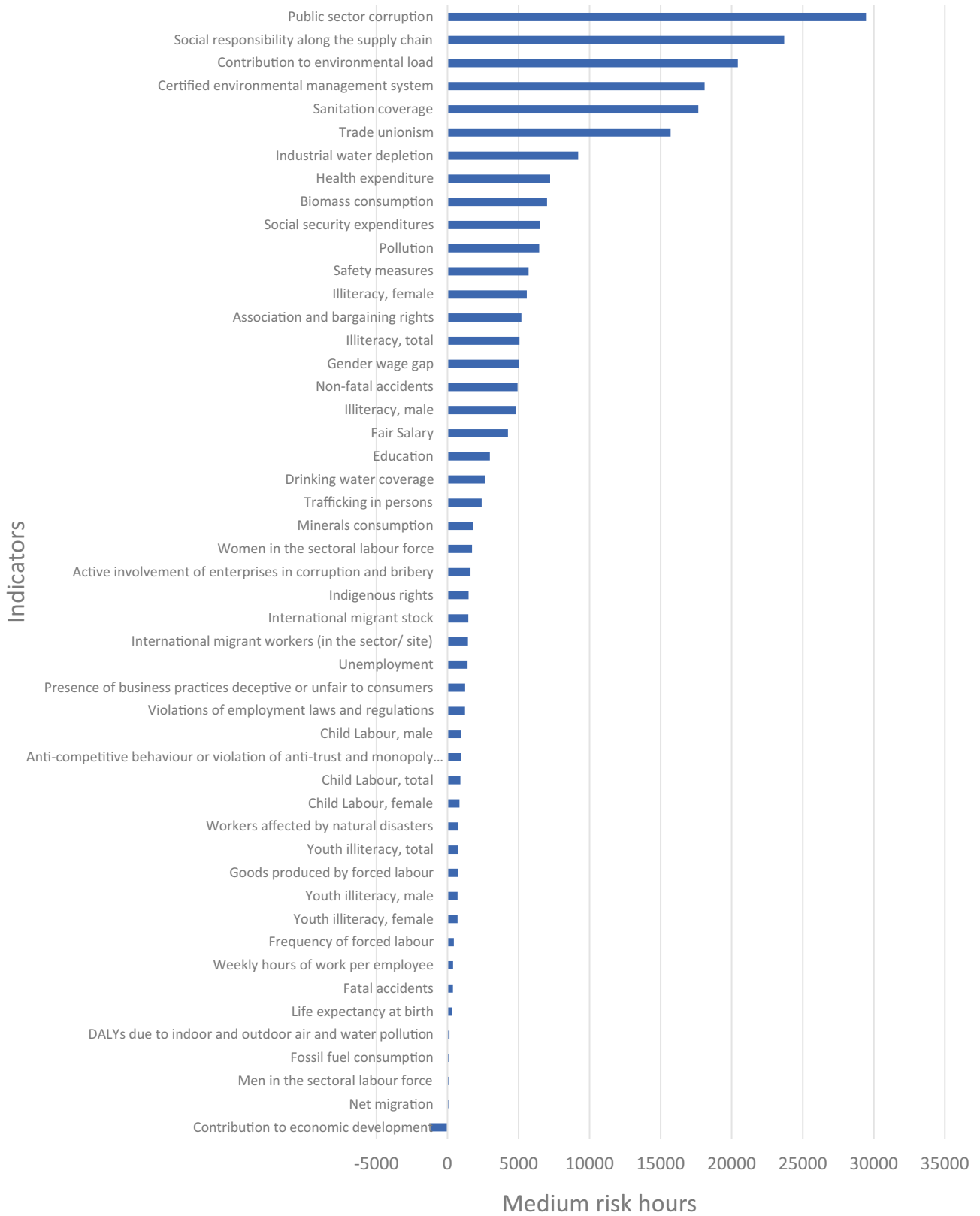
Line 3 SEZ results

Fig. 12 Results by social indicators of the SEZ lines of the plant, in mrh for the FU (functional unit: annual production of wastewater 145 t SEZ)

5 Conclusions

This paper presented an S-LCA of a new plant for the wastewater treatment of an E&S manufacturing company in Italy, using the PSILCA database.

The specific objective of the semi-industrial plant developed was to enable the treatment of spent TMAH, ammonium fluoride solution, nitrates, fluorides, phosphoric acid and acetic acid. This new pilot plant contributed to identify priority hazardous substances, such as TMAH, considering the precautionary principle, relying on the determination of any potentially adverse effects of the product and on a scientific assessment of the risk. Furthermore, the full-scale plant will be able to process the concentrated TMAH wastewater which is currently disposed of as waste. The positive results of this project would make it possible first of all to obtain a decrease in the concentration of TMAH at the discharge of industrial waters, thus substantially reducing the economic, environmental and social impact of the disposal of this substance.

In some sectors, such as the electronics and semiconductor one, it is necessary to start evaluating, also from a social point of view, civil and industrial plants that may have important environmental impacts. Bearing in mind that there is, in general, a lack of studies considering environmental and social impacts in an integrated way, and that S-LCA has not been widely used in the WWT field, as demonstrated by the literature analysis, this work is the first that uses PSILCA database to evaluate an industrial wastewater plant.

A consideration regarding the PSILCA database concerns the difficulty in explaining the unit of measurement of the results (mrh), particularly for those subcategories not linked to working conditions, e.g. access to material resources. Furthermore, the type of results that the databases return seems to be meaningful when a comparison with a similar product is allowed, as there is no absolute reference scale capable of defining the intensity of a given impact. In this case, it will be possible to assess which of the two products carries more social risk. The lack of reference scales to assess social risks is due to the reason that the social aspects are context-related and linked to cultural values.

The difficulty in presenting, commenting and understanding the results is an issue that the S-LCA will have to improve, especially for companies that want to use the results to develop policies or to communicate them to a wider audience.

Furthermore, PSILCA only assesses social risks, i.e. indicators which, if they have a significant result (expressed in mrh), are social issues, but it does not allow a precise evaluation of the possible positive effects of the company's performance. Moreover, Impact Assessment used in the database gives the same weight to all indicators and sub-categories, which leads to flattening the analysis. Recently, the weighing of indicators has become a fundamental step in S-LCA in order to give each indicator its relative importance (or contribution) to the performance of a specific impact subcategory.

Finally, it is worthy to underline the difficulty in modelling a waste in a database that currently works for the evaluation of products. Indeed, the results are expressed in terms of overall risk, measured as mrh per unit of output value, which makes little sense when it comes to waste, because this is usually a cost for companies and has no economic value.

Concerning the main limitation of the study, the comparison between the current management and the new plant would certainly have allowed us to appreciate the difference between the social impacts. To do this, external companies had to be included in the system boundaries.

The most meaningful social impacts concern aspects related to the supply chain. However, it is necessary to highlight the presence of a positive impact related to sectors that contribute to the economic development of the country.

S-LCA takes into account all stages upstream of the supply chain. Social risks being mostly found in sectors that are suppliers of the WWT innovative technology considered demonstrates the high analytical capacity of life cycle analysis, highlighting which countries, sectors and locations contribute most to the risk. The high incidence of indirect impacts substantiates the meaning of adopting a life-cycle approach in the assessment and management of social risks within global supply chains.

As a concluding remark, it can be observed that social aspects are often the most neglected in sustainability assessments, while a growing demand for company behaviour is spreading. This work provides a relevant contribution to the development of social assessments from a practical point of view, as it is an implementation of the S-LCA in an operational reality of an innovative industrial context.

Data availability Data supporting the results of this study will be made available upon reasonable request and within the limits of the informed consent provided by the corresponding author (LP) and the company promoting the study.

Appendix

Fig. 13 Sankey diagram for the TMAH line, overall structure and zoom. The figure shows the contribution of the different Country Specific Sector to the overall risk in the social impact category "contribution to environmental load"

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Authors and Affiliations

Monica Serreli[1] · Luigia Petti[1] · Andrea Raggi[1] · Alberto Simboli[1] · Guglielmo Iuliano[2]

[1] Department of Economic Studies, "G. D'Annunzio" University, Viale Pindaro, 42, 65127 Pescara, Italy

[2] LFoundry S.R.L, Via Pacinotti 7, 67051 Avezzano, L'Aquila, Italy