Science of the Total Environment 783 (2021) 146905

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Review

Biomonitoring of occupational exposure to bisphenol A, bisphenol S and bisphenol F: A systematic review

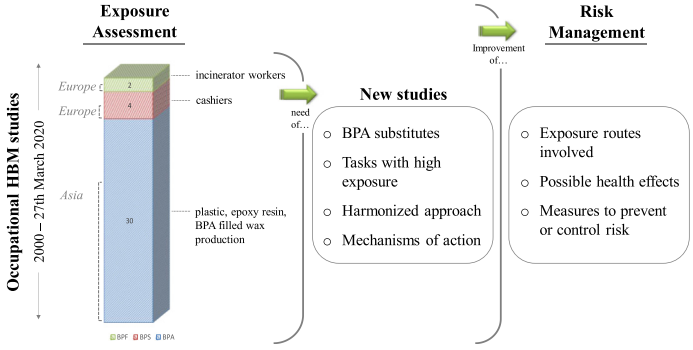
Radia Bousoumah [a,*], Veruscka Leso [b], Ivo Iavicoli [b], Pasi Huuskonen [c], Susana Viegas [d,e,f], Simo P. Porras [c], Tiina Santonen [c], Nadine Frery [g], Alain Robert [a], Sophie Ndaw [a]

[a] French Research and Safety Institute for the Prevention of Occupational Accidents and Diseases (INRS), 1 rue du Morvan, 54519 Vandœuvre-Lès-Nancy, France
[b] Department of Public Health (DPH), University of Naples Federico II, Via S. Pansini 5, 80131 Naples, Italy
[c] Finnish Institute of Occupational Health (FIOH), P.O. Box 40, FI-00032 Työterveyslaitos, Finland
[d] NOVA National School of Public Health, Public Health Research Centre, Universidade NOVA de Lisboa, 1600–560 Lisbon, Portugal
[e] Comprehensive Health Research Center (CHRC), 1169–056 Lisbon, Portugal
[f] H&TRC—Health & Technology Research Center, ESTeSL—Escola Superior de Tecnologia da Saúde, Instituto Politécnico de Lisboa, 1500–310 Lisboa, Portugal
[g] Public Health France (SpFrance), 12 rue du Val d'Osne, 94415 Saint Maurice Cedex, France

HIGHLIGHTS

- Review of human biomonitoring studies on occupational exposure to BPA, BPS and BPF.
- Further research on occupational exposure to bisphenols by biomonitoring tools needed.
- Harmonized approach for sample collection and analysis required.
- Future research work needs to consider the co-exposure to several bisphenols.
- Workplace contribution to the overall exposure to bisphenols should also be provided.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 27 October 2020
Received in revised form 29 March 2021
Accepted 29 March 2021
Available online 5 April 2021

Editor: Ewa Korzeniewska

Keywords:
Bisphenols
Occupational health
Exposure assessment
Biomonitoring
Endocrine disrupters

ABSTRACT

Bisphenol A (BPA) and its substitutes bisphenol S (BPS) and bisphenol F (BPF) are endocrine disrupting chemicals widely used in the production of polycarbonate plastics, epoxy resins and thermal papers. The aim of the review was to identify occupational studies using human biomonitoring (HBM) as a tool for bisphenol exposure assessment and to characterize research gaps on the topic as part of the HBM4EU project. Hence, a systematic literature search using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology was conducted for articles published between 2000 and 27th March 2020 across three databases (PubMed, Scopus and Web of Science). Thirty studies on the occupational HBM of BPA met the inclusion criteria. Regarding BPS and BPF, only 4 and 2 publications were retrieved, respectively. Fifty-seven percent (57%) of the studies selected for BPA were conducted in Asia whereas half of BPS and BPF studies were undertaken in Europe. Studies on BPA in plastic and epoxy resin sectors were infrequent in Europe while Asian data showed higher exposure when the substance is employed as raw material. The main data on BPS were among cashiers while BPF data were available from incinerator workers. Several research gaps have been identified: (i) shortage of HBM studies on occupational exposure, especially to BPS and BPF; (ii) different methodological designs making suitable comparisons between studies difficult; and (iii) only few studies conducted on the industrial applications of bisphenols outside Asia.

* Corresponding author.
E-mail address: radia.bousoumah@inrs.fr (R. Bousoumah).

https://doi.org/10.1016/j.scitotenv.2021.146905

This review highlights the lack of recent occupational HBM studies on bisphenols and the need for a harmonized approach to acquire reliable data. Considering the increasing replacement of BPA by BPS and BPF, it is of relevance to evaluate the exposure to these substances and the impact of the available risk management measures on workers exposure and possible health risk.

Contents

1. Introduction . . . 2
2. Methods . . . 2
3. Results . . . 3
3.1. Overview on available biomarkers . . . 3
3.2. Human biomonitoring data . . . 4
3.2.1. Countries . . . 4
3.2.2. Strengths and limitations of reviewed studies . . . 4
3.2.3. Association between occupational bisphenol exposure and health effects . . . 7
4. Discussion . . . 8
4.1. The current data on the exposure to bisphenols and data needs . . . 8
4.2. Methodological aspects related to occupational HBM studies on bisphenols . . . 8
4.3. Bisphenol exposure and effect markers . . . 9
4.4. Importance of good contextual data in the interpretation of bisphenol HBM results . . . 9
5. Conclusion . . . 9
Declaration of competing interest . . . 10
Acknowledgements . . . 10
Appendix A. Supplementary data . . . 10
References . . . 10

1. Introduction

Bisphenol A (BPA or 4,4′-(propane-2,2-diyl)diphenol) is a synthetic chemical that has been used for more than 50 years in a variety of industrial applications dedicated to the production of polycarbonate plastics, epoxy resins, other polymers and thermal papers; it is among the highest volume of chemicals produced worldwide (global consumption: 7.7 million metric tonnes in 2015, projection to 10.6 million tonnes in 2022 according to Lehmler et al., 2018). In 2018, ECHA developed a market survey to know the volume of bisphenol S (BPS) used as developer in thermal paper manufactured in the EU since EU paper manufacturers have started to substitute BPA with BPS. It was possible to conclude that the volume doubled between 2016 and 2017 (200 t to 397 t) (ECHA, 2018). Regarding BPF, information about the amount consumed is still missing.

Human exposure to BPA is widespread in the general population and it has been identified as potentially linked to a variety of adverse outcomes on the reproductive system, metabolic processes (obesity, metabolic dysfunctions and diabetes), the immune system and cognitive and behavioural development (Gore et al., 2015). BPA has been shown to exert estrogenic activity, but it may also interact with other hormone receptors, like androgen, glucocorticoid, and thyroid receptors (Cimmino et al., 2020). However, the toxicological effects of BPA are still controversial, despite the wealth of studies conducted to date. BPA is currently classified as reproductive toxicant category 1B under the EU CLP Regulation (Regulation 2016/1179) and is restricted in numerous consumer products for babies and children. BPA has been added to the REACH annex XVII restricted substances list on 2016 (Regulation 2016/2235). This new entry restricted BPA's use in thermal paper and stated that the concentration of BPA should not be above 0.02% by weight after 2 January 2020. In 2017, the European Chemical Agency (ECHA) added BPA to the Candidate List of substances of very high concern (SVHCs). In United States, in July 2012 and 2013, FDA has amended, respectively, its regulations to no longer provide for the use of BPA-based polycarbonate resins in baby bottles and sippy cups and for the use of BPA-based epoxy resins as coatings in packaging for infant formula. Unfortunately, these regulations have resulted in an increasing replacement of BPA with other bisphenols that might possess similar toxicological properties. These include bisphenol S (BPS; 4,4′-sulfonylbisphenol) or bisphenol F (BPF; 4,4′-dihydroxydiphenyl-methane) which have been considered as good substitutes for BPA in industrial applications. Significantly less information about potential adverse health outcomes is, however, available for BPF and BPS. Like BPA, BPF and BPS are suspected to be endocrine-disrupting chemicals and display hormonal activity, with similar average estrogenic and androgenic potencies across different in vitro assays (Rochester and Bolden, 2015). It has also been suggested that BPS affects signalling pathways involved in lipid metabolism and adipogenesis (Boucher et al., 2016).

Since bisphenols are widely used in different applications in industry, occupational exposure (i.e. exposure that may occur at workplace) and the health risk to workers are a real concern. Additionally, the level of exposure to bisphenols may be higher for workers who handle it than in general population. Total urinary levels, typically determined after deconjugation with β-glucuronidase, are considered a robust biomarker for exposure to bisphenols so that human biomonitoring (HBM) has been used to characterize exposure in workers. A systematic review was carried out under HBM4EU to identify biomonitoring studies reporting occupational exposure to BPA, BPS and BPF published between 2000 and 27th March 2020. HBM4EU (2017–2021) is a joint effort of 30 countries, the European Environment Agency and the European Commission, dedicated to coordinating and advancing human biomonitoring in Europe. The aim of this review is to provide an overview of available HBM data on occupational exposure to BPA, BPS and BPF focusing on: i) the current level of these bisphenols in workers; ii) the countries involved in HBM studies and the occupational settings investigated so far; iii) the health effects reported in workers; and iv) potential research gaps in the occupational biomonitoring of bisphenols.

2. Methods

A systematic literature search was conducted to select available information according to the PRISMA (Preferred Reporting Items for

Systematic Reviews and Meta-Analyses) methodology. For this purpose, three databases, namely PubMed, Scopus and Clarivate Web of Science, were used to select papers according to search terms related to the occupational exposure to bisphenols. One search strategy was developed and adapted for each database. Searches were carried out in English and included the period ranging from 1 January 2000 to 27 March 2020. The search terms used for each database for bisphenol A, bisphenol S and bisphenol F were ("occupational" OR "worker*") AND ("biomonitoring" OR "biomarker*" OR "urine" OR "blood" OR "serum").

Items obtained from the databases led to 205 PubMed papers, 144 Scopus papers and 97 Web of Science papers for BPA. The search strategy for BPS resulted in 13 PubMed papers, 11 Scopus papers and 8 Web of Science papers. Regarding BPF, 10 PubMed papers, 7 Scopus papers and 3 Web of Science papers were recovered.

After removing duplicates, the papers (titles and abstracts) were screened independently by two co-authors according to the predefined inclusion/exclusion criteria (Table S1). Hence, papers were categorised as follows: "papers excluded", "papers kept for discussion" and "papers selected". Publications in a language other than English, reporting in vitro or animal studies or out of topic were excluded from further analysis. Papers kept for discussion comprised different categories (review, reports and conference proceedings, occupational exposure studies without HBM or simulated, HBM with effect biomarkers or relation to health and HBM in general population). Papers reporting occupational HBM data on bisphenols of interest, biomarkers and analytical methods were selected.

To establish a final set of papers, the two reviewers compared their findings to identify consistencies and discrepancies. Any differences pointed out were resolved mutually. One relevant paper on BPA was missed (Wang et al., 2012). Thus, 37, 5 and 3 papers were identified respectively for BPA, BPS and BPF. The different phases of the selection of papers are described through the diagrams (Figs. S1, S2 and S3).

The quality of each study selected (i.e. 37 [BPA], 5 [BPS] and 3 [BPF]) was assessed according to a modified version of the LaKind scoring criteria (Table 1) (LaKind et al., 2014). These criteria were used to highlight the overall quality of the occupational biomonitoring (BM) studies on bisphenols. This scoring considers the quality of the study design, the analytical techniques, sample handling and quality assurance. Each paper was independently scored by a reviewer from 1 (Tier 1) to 3 (Tier 3) for each of the eight categories, giving total possible scores ranging from 9 (highest quality) to 27 (lowest quality). Overall, the scores were typically around 15, giving an objective measure of the quality of the chosen studies regarded as good.

3. Results

3.1. Overview on available biomarkers

Most of the papers retrieved for this review (79%) reported the use of urine as a biological matrix to assess BPA occupational exposure while serum and blood were investigated to a lesser extent. In one study, peritoneal fluid was used to study the association between endometriosis and BPA exposure. The measurement of total (conjugated and unconjugated) BPA was prevalent. Thayer et al. (2015) reported that upon oral ingestion the major fraction of BPA (almost 100%) is excreted in urine as conjugated forms, namely BPA glucuronide (BPAG) and BPA sulphate (BPAS). Within 24 h approximately 93% of absorbed dose can be recovered in urine. Only a minor fraction (less than 1%) of total BPA is excreted as unconjugated (commonly referred to as "free") (Thayer et al., 2015). Unlike free BPA, the conjugated forms are considered biologically inactive as they do not bind the estrogen receptor (Vom Saal and Hughes, 2005). Liu and Martin (2017) have shown that dermal absorption of BPA may lead to prolonged exposure to free BPA when compared to oral administration.

The measurement of both unconjugated BPA and total BPA (i.e. after deconjugation) is the conventional approach of BPA exposure assessment, which allows one to infer the conjugated levels. However, measuring the unconjugated form still poses a challenge. Given the low concentrations of unconjugated BPA in urine, reliable analytical methods that provide very low detection limits are mandatory. Besides, since BPA is ubiquitous in the environment, it is crucial to suppress or minimize background contribution during sample collection, storage,

Table 1
Adaptation of modified LaKind scoring criteria to BM studies of bisphenols. Papers were scored from 1 (Tier 1) to 3 (Tier 3) for each of the assessment components. The lower the LaKind score the better the overall quality (possible range 9–27).

Assessment component	TIER 1 (most relevant)	TIER 2 (relevant)	TIER 3 (not so relevant)
Study participants (target population, subgroups, inclusion/sampling strategy, sample size)	>20 occupationally exposed individuals.	5–20 occupationally exposed individuals.	<5 occupationally exposed individuals.
Chemicals under investigation	BPA, BPF and BPS	Other bisphenols.	
Exposure biomarker and matrix	Biomarker in a specified matrix has accurate and precise quantitative relationship with external exposure, internal dose or target dose.	Evidence exists for a relationship between biomarker in a specified matrix and external exposure, internal dose, or target dose.	Biomarker in a specified matrix is a poor surrogate (low accuracy and precision) for exposure/dose.
Biomarker specificity	Biomarker is at least the parent chemical or a specific metabolite (e.g.: BPAG).	Biomarker is derived from multiple parent chemicals with similar adverse endpoints.	Biomarker is derived from multiple parent chemicals with varying types of adverse endpoints.
Technique	Analytical methods that provide unambiguous identification and quantitation of the biomarker at the required sensitivity (e.g. GC–HRMS, GC–MS/MS, LC–MS/MS). Determination of background contamination.	Analytical methods that provide unambiguous identification and quantitation of the biomarker (e.g. HPLC-UV).	Analytical methods that only allow detection but not quantitation.
Method characteristics – *any specific weaknesses in study design leading to a TIER 3 score to be noted*	Acceptable (state-of-the-art) limit of detection/quantitation (LOD/LOQ) for all metabolites.	Acceptable (state-of-the-art) limit of detection/quantitation (LOD/LOQ) for some metabolites.	LOD/LOQ above current state-of-the-art for all metabolites.
	Samples with a known history and documented stability data.	Stability not specifically assessed, but samples were stored appropriately and analysed promptly.	Specific reason to query stability, e.g. samples with unknown history or known issues.
Quality assurance	Study has used external QA where appropriate.	Some QA used (note details).	No QA.
Matrix adjustment and sampling strategy	Study includes results for adjusted and non-adjusted concentrations if adjustment is needed. 24 h total urine collection or spot samples in different moments. e.g. pre and post shift.	Study includes results for adjusted and non-adjusted concentrations if adjustment is needed. And single spot urine sample per individual.	No established method for adjustment. Sampling time unclear.

extraction and analysis to avoid any exogenous contamination (Markham et al., 2010). Furthermore, the main BPA conjugated form (BPA-monoglucuronide or BPAG) has been shown to be unstable under certain conditions (Ye et al., 2007). Hydrolysis of BPAG to BPA during sample conservation and processing can be minimized by keeping the urine sample at room temperature for the shortest possible time after collection (Ye et al., 2007; Ndaw et al., 2016).

To avoid misinterpretation due to external contamination, the measurement of conjugates is recommended (Andra et al., 2016). Among the papers accessed, only Gerona et al. (2016) analysed BPAG, BPAS and unconjugated BPA besides total BPA separately. Monitoring of BPA conjugates could also enable researchers to determine the impact of route of exposure on the levels of free BPA since conjugation of BPA is likely to be faster after oral as opposed to dermal exposure (Andra et al., 2016).

Much like its BPA analogue, BPS undergoes a conjugation following ingestion. Its glucuronide and sulphate conjugates are measured as exposure biomarkers after deconjugation to find total BPS (unconjugated + conjugated forms, 1.72 ± 1.3% and 54 ± 10%, respectively) (Oh et al., 2018; Khmiri et al., 2020). According to Khmiri et al. (2020), the levels of the unconjugated form of BPS (i.e. active BPS) in blood are higher than those of BPA, due to its higher oral bioavailability. The little data on the human biomonitoring of BPF are derived from the measurement of total bisphenol F (González et al., 2019) and no data are available regarding the proportions of metabolites formed.

In most of the reviewed studies urinary concentrations were adjusted to creatinine excretion in order to take urinary dilution into account (Hanaoka et al., 2002; Cha et al., 2008; He et al., 2009; Li et al., 2010a, 2010b; Braun et al., 2011; Li et al., 2011; Wang et al., 2012; Miao et al., 2014; Liu et al., 2015; Miao et al., 2015; Gerona et al., 2016; Ndaw et al., 2016; Thayer et al., 2016; Waldman et al., 2016; Heinälä et al., 2017; Hines et al., 2017; Tian et al., 2018). Specific gravity was also used to adjust for urine dilution (Heinälä et al., 2017; Lee et al., 2018; Li et al., 2019) while no adjustment has been made in some others studies (Lyapina et al., 2016; Kouidhi et al., 2017; Simonelli et al., 2017).

3.2. Human biomonitoring data

Several topics have been addressed in this review on HBM studies on the occupational exposure to bisphenols: i) countries involved in HBM studies; ii) strengths and limitations of the reviewed HBM studies according to the continents in which they were performed; and iii) studies on the association between bisphenol levels and health effects in occupationally exposed subjects.

3.2.1. Countries

Regarding occupational exposures to BPA, from the 30 HBM studies considered in this review, 17 (57%) were performed in Asia. Among those, 12 papers were from China (He et al., 2009; Li et al., 2010a, 2010b, 2011; Wang et al., 2012; Zhou et al., 2013; Miao et al., 2014, 2015; Liu et al., 2015; Zhuang et al., 2015; Tian et al., 2018; Li et al., 2019), 2 from Korea (Cha et al., 2008; Lee et al., 2018), and one from each of Japan (Hanaoka et al., 2002), Malaysia (Kouidhi et al., 2017) and Iran (Vahedi et al., 2016). Seven studies (23%) were carried out in North America, all in the USA (Braun et al., 2011; Shaw et al., 2013; Waldman et al., 2016; Gerona et al., 2016; Thayer et al., 2016; Hines et al., 2017, 2018). Only one African study was retrieved from Egypt (Metwally et al., 2019). Five investigations (17%) were performed in Europe, one each from Bulgaria (Lyapina et al., 2016), Finland (Heinälä et al., 2017), France (Ndaw et al., 2016), Italy (Simonelli et al., 2017) and Spain (González et al., 2019).

In the case of BPS, only 4 studies fulfilling the inclusion criteria were retrieved. One of these studies was performed in China (Li et al., 2019), the other one in USA (Thayer et al., 2016) and two of them in Europe: one in France and one in Spain (Ndaw et al., 2018; González et al., 2019). The Chinese and Spanish studies presented data for all 3 analogues, BPA, BPS and BPF (Fig. 1).

3.2.2. Strengths and limitations of reviewed studies

3.2.2.1. Asian studies. Seventeen Asian studies on BPA occupational biomonitoring have been retrieved for review (Table S2a). Regarding the sample size, all but 2 studies (Cha et al., 2008; Wang et al., 2012) enrolled more than 40 exposed workers; this figure exceeded 100 in 9 studies (He et al., 2009; Li et al., 2010a, 2010b, 2011; Zhou et al., 2013; Liu et al., 2015; Miao et al., 2015; Zhuang et al., 2015; Li et al., 2019). Most of the studies included a control group in their methodological design, except in 3 studies (He et al., 2009; Wang et al., 2012; Lee et al., 2018). In some investigations, controls were described to be employed in factories different from that of exposed workers (Zhou et al., 2013; Liu et al., 2015; Miao et al., 2015; Zhuang et al., 2015; Kouidhi et al., 2017; Tian et al., 2018), although in others, the control group was employed in the same factory, even if in other departments to the

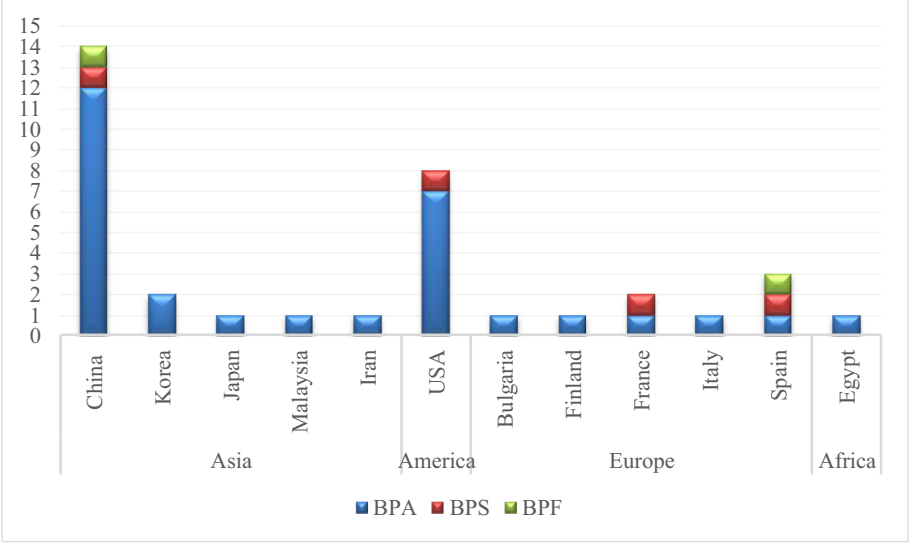


Fig. 1. Papers retrieved by countries and continents.

non-control cases (Hanaoka et al., 2002; Vahedi et al., 2016), or was indicated as unexposed without further details (Cha et al., 2008; Li et al., 2010a, 2010b, 2011). No comparison between male and female results could be extrapolated as only four investigations enrolled female subjects (Lee et al., 2018; Miao et al., 2015; Vahedi et al., 2016; Li et al., 2019). In general, analytical measurements were performed by high-performance liquid chromatography (HPLC) for urine analysis coupled with an electrochemical (Hanaoka et al., 2002) or fluorescence detector (He et al., 2009; Zhou et al., 2013; Liu et al., 2015; Miao et al., 2015; Tian et al., 2018) or mass spectrometry (Wang et al., 2012; Lee et al., 2018; Li et al., 2019). Few studies employed the gas chromatography coupled with mass spectrometry (GC–MS) for urinary BPA (Kouidhi et al., 2017) and serum samples (Zhuang et al., 2015). The limit of detection (LOD) was given in all studies except in Cha et al. (2008), Li et al. (2010a) and Wang et al. (2012). It should be noted, however, that more relevant quality parameters would be the limit of quantitation (LOQ). In the study of Wang et al. (2012) the minimum urinary BPA concentration was as high as 5.56 μg/l, meaning that all data were above LOD/Q.

Occupational exposure to BPA was studied in the manufacture of BPA, manufacture and use of epoxy resins (Hanaoka et al., 2002; He et al., 2009; Li et al., 2010a, 2010b, 2011; Wang et al., 2012; Miao et al., 2014, 2015; Liu et al., 2015; Zhuang et al., 2015; Tian et al., 2018), polycarbonate plastic moulding (Kouidhi et al., 2017), shipyard workers (Cha et al., 2008), market sellers (Vahedi et al., 2016), cashiers (Lee et al., 2018; Li et al., 2019) and a petrochemical company (Zhou et al., 2013). In their study, Li et al. (2019) also looked at healthcare workers, teachers, office workers and salespersons.

The post-shift urinary median BPA concentration in the manufacture of BPA and epoxy resins was 111 μg/g creatinine ($n = 198$, P75 (75th percentile) 934 μg/g creatinine) (He et al., 2009). The pre-shift value was 84.6 μg/g creatinine ($n = 186$, P75 618 μg/g creatinine), which suggests substantial exposure in a previous work shift. In subsequent Chinese studies on the manufacture of BPA and epoxy resins, the authors reported a post-shift median of 53.7 μg/g creatinine ($n = 173$, P75 558.9 μg/g creatinine) (Li et al., 2010b), a pre-shift median of 57.9 μg/g creatinine ($n = 123$, P75 467 μg/g creatinine) (Li et al., 2010a) and an averaged pre-shift and post-shift median of 685.9 μg/g creatinine ($n = 165$, P75 3671.8 μg/g creatinine) (Liu et al., 2015). In all cases, when there was a control group, the difference between workers' data and the control data was significant. No P95 (95th percentile) or maximum value was reported. However, it is not fully clear whether the cohort is the same in all above-mentioned BPA and epoxy resin studies, and only a different number of urinary samples were presented in each case. Studies by Miao et al. (2011a, 2011b, 2014, 2015) and Tian et al. (2018) seem at least to use the urinary data from their previous works (Li et al., 2010a, 2010b, 2011).

Wang et al. (2012) reported a urinary median BPA concentration of 21.42 μg/g creatinine for all workers in an epoxy resin factory ($n = 28$, GM (geometric mean) 31.96 μg/g creatinine, P75 111.86 μg/g creatinine, range 4.61–1253.69 μg/g creatinine). BPA feeding operators had significantly higher urinary BPA concentrations (GM 192.45 μg/g creatinine) than crushing and packing workers (GM 17.08 μg/g creatinine) and office workers (GM 11.60 μg/g creatinine). The median serum BPA concentration of epoxy resin factory workers was 18.75 μg/l ($n = 281$, range not detected – 98.50 μg/l) (Zhuang et al., 2015). The respective control data point was 3.37 μg/l ($n = 278$, range not detected – 28.40 μg/l).

Hanaoka et al. (2002) studied epoxy resin workers in a plastic plant in which bisphenol A diglycidyl ether (BADGE) with mixed organic solvents was sprayed. The authors assumed that BADGE may generate BPA endogenously. The median urinary BPA concentration of the 42 workers was 1.06 μmol/mol creatinine (2.14 μg/g creatinine), which was significantly higher than the respective median of the control group 0.52 μmol/mol creatinine ($n = 42$, 1.05 μg/g creatinine). To the authors' knowledge, no P95 data of the general population is available in Japan while it is around 5–10 μg/g creatinine in many other countries. Accordingly, workers' median concentration is clearly below that.

The median post-shift urinary BPA concentrations of polycarbonate plastic factory workers in Malaysia was 3.81 μg/l ($n = 70$, P75 4.99 μg/l) (Kouidhi et al., 2017). The respective median of the control group was 0.73 μg/l (n = 70, P75 1.57 μg/l). The urine concentrations of the factory workers were significantly higher than those obtained in the control group. However, the concentrations are relatively low when compared to BPA and the data concerning epoxy resin workers. The data are also below the reference values (RVs) for urinary BPA, based on P95 of the non-exposed population, available in some countries (SCOEL, 2014) (Malaysian P95 data is not available though).

Cha et al. (2008) studied exposure among epoxy resin painters in a shipyard in Korea. The GM urinary BPA concentration of the painters was 2.61 μg/g creatinine ($n = 25$). The respective GM of the control group was 1.38 μg/g creatinine. No other data were given. Although there was a significant difference between the results, these concentrations are well below, e.g., BPA and epoxy resin workers' data, and below P95 of the Korean adult population (9.44 μg/g creatinine) (Kim et al., 2011).

Li et al. (2019) examined urinary BPA concentrations according to occupation among 941 pregnant women. Higher urinary BPA levels (data not given) were found in participants who worked in health care sectors (e.g., nurses and physical therapists).

The BPA exposure of female market sellers was studied by Vahedi et al. (2016). The Serum AM (arithmetic mean) of exposed workers (0.48 μg/l, $n = 62$) was significantly higher than that of the control group (0.16 μg/l, n = 62).

Zhou et al. (2013) studied the association between serum BPA and sex hormone levels in male workers at a petrochemical company in China. A significant difference in BPA concentrations was found between the exposed and the unexposed workers (median 3.19 vs 0.27 μg/l). But the authors reported that no serum BPA data were available for the general population, which would make it easier to interpret the significance of the serum BPA results.

Asian data show clearly that the highest BPA exposure occurs in the manufacture of BPA and epoxy resins, especially when pure BPA is handled. However, apart from the above-mentioned considerations regarding the employment of the substance as a raw and pure material, the diversity of forms of industrial processes—i.e. manual or automatic; the existence, type and efficiency of the protective measures adopted —might influence BPA BM results.

The efficacy/usefulness of personal protective equipment was underlined by Lee et al. (2018) in one Asian study retrieved for review that focused on cashiers. The authors demonstrated that the urinary BPA concentration increased between pre- and post-shift samples (median 0.45 vs 0.95 μg/l), only in cashiers handling receipts without gloves. Through the adoption of such protective measures as wearing gloves, post-shift urinary BPA levels in cashiers did not show differences compared to the pre-shift ones.

Only Li et al. (2019) addressed BPS and BPF exposure in Asia among pregnant participants. Elevated urinary BPS concentrations were found among cashiers, office workers, teachers, and salespersons (data not given). Due to the moderate reliability of urinary BPF concentration during pregnancy, no conclusion could be driven regarding the exposure to this compound.

3.2.2.2. American studies. Bisphenol A occupational biomonitoring has been addressed in 7 American studies, all performed in the USA (Table S2b). In 3 studies the number of investigated workers was lower than 100 (Shaw et al., 2013; Hines et al., 2017, 2018). Braun et al. (2011) used unemployed people as a reference population, Gerona et al. (2016) used those whose job did not involve handling paper receipts as a reference, and Hines et al. (2017) compared workers' results to the US general population data (≥20-year-old adults) collected during the same years in which the sample collection of the

workers took place. The occupational sectors under investigation included the production of BPA and BPA-based products (Hines et al., 2017, 2018), jobs involved work that required the handling of paper receipts (Gerona et al., 2016), cashiers (Thayer et al., 2016) and firefighters (Shaw et al., 2013; Waldman et al., 2016). Since Hines et al. (2017, 2018), Waldman et al. (2016) and Shaw et al. (2013) focused on industrial exposures in the manufacture of BPA or BPA products or firefighter exposure, almost all of the workers studied were male. Braun et al. (2011) and Gerona et al. (2016) focused specifically on pregnant employees occupationally exposed through handling paper receipts containing BPA. Thayer et al. (2016) examined cashiers.

Analytical measurements were performed by enzyme hydrolysis followed by high-performance liquid chromatography tandem mass spectrometry (HPLC-MS/MS) for both serum and urine samples, while only one study adopted LC-MS/MS to directly measure unconjugated BPA, BPA glucuronide and BPA sulphate (Gerona et al., 2016). LODs were provided by all the retrieved studies, while LOQ was only provided by Gerona et al. (2016).

Bisphenol A was found only as a minor contaminant in the serum of exposed firefighters (Shaw et al., 2013), and the urinary BPA concentrations of firefighters were not significantly different to those of the US general population data extrapolated from the 2009–10 National Health and Nutrition Examination Survey (NHANES) cycle for males, 25 years and older (Waldman et al., 2016). According to these studies, firefighters were not occupationally exposed to BPA or the exposure was so low that it could not be differentiated from the background exposure. Handling paper receipts was positively, although not significantly, associated with urinary BPA concentrations (Braun et al., 2011; Gerona et al., 2016). Urinary GM values ± GSD (geometric mean standard deviation) were in the same order of magnitude among all the 3 studies investigating pregnant women handling thermal papers: (1) 2.8 ± 1.1 μg/g creatinine total BPA (Braun et al., 2011); (2) 1.89 ± 3.63 and 2.76 ± 3.53 μg/g creatinine as total pre and post-shift values in cashiers (Thayer et al., 2016), respectively; and (3) 9.13 μg/g creatinine as tBPA in conjugated form (BPA in glucuronide form + BPA in sulphate form) (Gerona et al., 2016). Thayer et al. (2016) demonstrated that post-shift urine levels in cashiers handling BPA-receipt paper were significantly higher than concentrations in non-cashiers, but no significant differences could be detected between pre-shift and post-shift urine samples in exposed workers. According to these 3 American studies, the occupational exposure via paper handling is visible but at a lower level than in the production of BPA. Additionally, a single spot urine sample cannot take into account the daily intra-individual variability. Comparable considerations can be made for the studies in which a spot collection of urine samples was performed (Braun et al., 2011; Gerona et al., 2016). Braun et al. (2011) collected 3 spot urine samples around 16 and 26 weeks of gestation and within 24 h of delivery, while in Gerona et al. (2016) pregnant women provided a non-fasting spot urine sample on the day prior to the medical procedures. Another issue is the delay in peak concentration after skin exposure, as for cashiers. The highest urinary BPA of cashiers is not necessarily in the post-shift sample collected right after the shift, but in the evening sample, even in the next morning sample. This could explain that there is sometimes no difference in the BPA levels of cashiers' pre-shift and post-shift samples.

Hines et al. (2017) studied BPA exposure in the manufacture of phenolic resins, BPA and polycarbonate resins, BPA-filled wax and BPA. Seven urine samples were collected in 2 consecutive days (n = 72–77). Before the sampling campaign workers were off work for at least 24 h. The GMs of urinary total BPA in day 1 pre-shift samples in different industries were in the range of 6.56–111 μg/g creatinine. All pre-shift GMs were significantly higher than the GM of the US adult population in 2013–2014 (1.27 μg/g creatinine), and all GMs were higher than the P95 of the US adult population (5.09 μg/g creatinine, n = 1813) (NHANES, 2019). This indicates that in many cases traces of the previous BPA exposure were still observable after more than 24 h off work in the pre-shift sample collection in day 1. In all industries the urinary GM of workers increased during day 1 and, in all but one case, reached the maximum in post-shift samples collected 4 to 6 h after the end of the shift. The urinary GMs of the day 2 pre-shift samples were again lower but at least about three times higher than those of the day 1 pre-shift samples. Thereafter the GMs increased reaching the maximum in the day 2 end-shift samples: GM range 60.3–584 μg/g creatinine, which was 1.2 to 1.6 times higher than the respective day 1 end-shift data. The day 2 end-shift GMs were 12 to 115 times higher than the P95 of 5.09 μg/g creatinine of the US adult population. The highest GMs were obtained in the manufacture of BPA-filled wax (Hines et al., 2017). Here the GMs were in the range of 111–584 μg/g creatinine and the maximum concentrations were in the range of 1580–5400 μg/g creatinine (n = 14). The highest individual urinary BPA concentration 18,900 μg/g creatinine was detected in the manufacture of BPA. The free BPA concentrations reported by Hines et al. (2017) were 0.005–10.8% of the total BPA. The workers studied by Hines et al. (2017) were substantially exposed to BPA—the level of exposure was, on average, similar to that in some Asian studies (see above).

Importantly, when full-shift breathing zone air and pre-shift and end-shift hand wipe samples were collected for each participant, a significant correlation was detected between total BPA levels in urine at the mid and end-shift and BPA concentrations in air as well as in hand-wipe samples (Hines et al., 2018). Although both inhalation and dermal contact likely contributed to exposure, these analyses suggested that inhalation, on average, appeared to be a more dominant exposure route than dermal contact for this group of manufacturing workers.

Concerning the exposure caused by handling receipts containing BPS, difference between cashiers and unexposed controls was non-significant, while a significant difference in the urinary levels of BPS was seen between pre-shift and post-shift in cashiers (Thayer et al., 2016).

3.2.2.3. European studies. In Europe, 5 studies are available on the HBM of BPA. These were carried out in Bulgaria (Lyapina et al., 2016), France (Ndaw et al., 2016), Finland (Heinälä et al., 2017), Italy (Simonelli et al., 2017) and Spain (González et al., 2019) (Table S2c). Only 2 investigations included a control group of unexposed workers, one recruited from the same companies where exposed workers were employed (Ndaw et al., 2016), and another from working-aged non-occupationally exposed volunteers (Heinälä et al., 2017). In the latter study, the control group samples were collected two years earlier than the workers' samples. Analytical methods employed were gas chromatography coupled with mass spectrometry (González et al., 2019; Heinälä et al., 2017), tandem mass spectrometry (Simonelli et al., 2017) and liquid chromatography coupled with tandem mass spectrometry (Ndaw et al., 2016). LODs or LOQs were provided in all the reviewed studies.

Occupational BPA exposure was studied in cashier work (Ndaw et al., 2016), in production of paints, composites, thermal papers and tractors (Heinälä et al., 2017), dental medicine (Lyapina et al., 2016) and workers from a waste incinerator plant (González et al., 2019).

Handling receipts may boost cashiers' exposure to BPA. Ndaw et al. (2016) showed an increase in total BPA urinary concentration compared to unexposed controls. In fact, the median concentration of total BPA was 8.92 μg/l, which is approximately 2 to 3 times higher than that obtained from the non-occupationally exposed group: 3.54 μg/l. The workers' median was slightly higher than the P95 of the adult population in France: 8.10 μg/l (Balicco et al., 2019).

Since free BPA is the active form of the substance, its concentration could be considered to be a relevant indicator of potential BPA effects. Therefore, this study specifically addressed this biological indicator in cashiers, although it found no significant differences between exposed and unexposed individuals. Additionally, when the urinary total BPA elimination profile for cashiers was investigated, slight variations of BPA concentrations throughout the day could be detected, suggesting a continuous exposure during and after the work shift. This may support

the finding that the internal dose of BPA may be influenced by an equilibrium phenomenon, meaning that BPA may be stored in the skin providing exposed subjects with a constant reservoir for absorption. This may be further confirmed by the absence of a significant association between total BPA urinary concentration and the number of receipts handled during the working shift.

Heinälä et al. (2017) studied BPA exposure in the production of liquid and powder paints, composite products and the manufacture of thermal papers containing BPA. They also studied exposure in the test-driving of tractors. Apparent occupational exposure took place in the manufacturing of liquid paint hardener, where urine samples collected after the work shift showed BPA levels reaching up to 100–170 μg/l. The highest exposure was measured in people handling pure BPA. The highest BPA concentrations of the coating machine workers in a thermal paper factory were in the range of 1000–1500 μg/l. Here the workers were in contact with liquid coating material containing pure BPA. Since air concentrations were low, the exposure was supposed to be dermal. High urinary BPA levels were also measured among coating machine operators after a 4-day holiday. The authors speculated that this might be due to slow skin uptake and/or delayed excretion of high BPA levels. The highest urinary BPA concentrations in the liquid paint factory and the thermal paper factory were up to 1–2 times higher than the background level of the non-occupationally exposed control group (P95 8 μg/l, $n = 121$). No clear occupational exposure was stated in other jobs.

The exposure to dental materials—composed of composite resins where BPA might be present as an impurity derived from the synthesis process—during practical education in dentistry, was reported to be not essential (Lyapina et al., 2016).

González et al. (2019) studied BPA-exposed workers in a waste incineration plant. Their results suggest that these workers could be more exposed to BPA than those in administrative and laboratory roles. However, both urinary and total blood concentrations were low.

Regarding a possible gender-related variability in BM results, no statistically significant differences could be detected between male and female employees of a waste incinerator plant in measurements of total blood free BPA, urinary free BPA or urinary total BPA concentrations, whereas significantly higher total BPA concentrations were detected in the total blood of male workers compared to female workers (González et al., 2019). No significant gender-related variability in urinary total BPA was reported in students of dental medicine (Lyapina et al., 2016) or in cashiers (Ndaw et al., 2016).

Exposure to BPS was studied in cashiers (Ndaw et al., 2018) and in incinerator workers who were also examined for BPF (González et al., 2019). In cashiers (Ndaw et al., 2018), urine samples showed total BPS concentrations significantly higher than those collected in unexposed controls (median values of 2.07 vs. 0.52 μg/g creatinine, respectively), but lower than the P95 of the adult population in France of 8.49 μg/g creatinine (Balicco et al., 2019). Although BPS levels were not correlated with the number of receipts, an increase in BPS was significant between pre and post-shift samples in exposed workers. When incinerator workers were examined for BPS and BPF levels, the two analogues could not be detected in serum or urinary samples (González et al., 2019).

3.2.2.4. African studies. Only one African study was available for review (Metwally et al., 2019) (Table S2d). The study was performed in an Egyptian plastic processing industrial setting. The manufacturing process was semiautomatic. More than half of the studied workers (56.7%) were machine operators controlling the machinery and retrieving the products, 12.2% were maintenance workers changing the mould and maintaining the machinery and the same percentage of workers was in the finishing work (painting and packaging), while 18.9% dealt with chemicals. No control group was included in the study. Median serum BPA was 15.6 μg/l. Neither the nature of the work nor the duration of employment was witnessed as having any influence on BPA concentration in serum.

In order to compare biomonitoring data available across studies above mentioned, Tables S3a, S3b and S3c present urinary data according to occupation for BPA, BPS and BPF, respectively.

3.2.3. Association between occupational bisphenol exposure and health effects

The endocrine-disrupting properties of BPA have been demonstrated in vitro and in vivo experimental studies, in which BPA has exhibited both estrogenic and anti-androgenic effects (Li et al., 2011). However, no conclusive evidence is currently available to confirm the BPA endocrine-disrupting effects in humans.

3.2.3.1. Effects on sex hormone levels. A negative correlation between urine BPA and serum follicle-stimulating hormone (FSH) levels was found among 42 men employed as BADGE sprayers, while no significant impact was detected on testosterone (T) and luteinizing hormone (LH) levels (Hanaoka et al., 2002). Confounding effect of other exposures cannot be excluded and BPA levels in the epoxy resin sprayers were still close to control levels (about 2.1 μg/g creatinine in exposed workers as opposed to 1.05 μg/g creatinine in controls). In a subsequent study, T serum levels were significantly lower, while FSH and LH levels were significantly higher in 25 epoxy resin painters in the shipyard compared to unexposed controls (Cha et al., 2008). Urinary BPA levels in these workers were in the same order of magnitude as in the Hanaoka et al. (2002) study. When male sex hormones were assessed in petrochemical workers, the levels of androstenedione (AD) and free T, and free androgen index (FAI) were significantly lower compared to unexposed controls, while the level of sex hormone-binding globulin (SHBG) was significantly higher (Zhou et al., 2013). Median BPA levels in these workers ($n = 137$) were significantly higher than those in the concurrent controls (3.19 μg/l vs 0.27 μg/l).

Although BPA-exposed workers in factories manufacturing epoxy resin ($n = 281$) showed significantly higher median levels of serum BPA compared to controls (18.75 μg/l vs 3.37 μg/l), no significant differences were detected between the two groups in levels of T, inhibin B (INB), AD, and SHBG (Zhuang et al., 2015). However, BPA serum concentrations were positively associated with SHBG and inversely correlated with the AD levels in serum. Another study, in the same epoxy resin manufacturing field, reported a statistically significant association between increasing urine BPA levels and increased levels of prolactin (PRL), SHBG and estradiol (E2) and reduced levels of FSH, AD and FAI, while no relationship was determined with total T, INB or free T levels (Liu et al., 2015). The median urinary BPA levels in these workers ($n = 165$) were more than 100 times higher than in the controls (see Table S2a).

There is only one available study evaluating a correlation between BPA exposure and reproductive hormone levels among women (Miao et al., 2015). The authors found a significant correlation between urinary BPA and serum PRL and progesterone (PROG) concentrations in female manufacturers of epoxy resins ($n = 106$). A borderline significant association was obtained between urine BPA and E2 in exposed workers.

3.2.3.2. Other endocrine effects. Three studies assessed the relationship between BPA occupational exposure and thyroid functionality (Wang et al., 2012; Vahedi et al., 2016; Metwally et al., 2019). Among 28 epoxy resin workers, Wang et al. (2012) found that 8 of them (28.5%) had free triiodothyronine (FT3) levels exceeding the upper normal limit. With increasing urinary BPA levels, serum FT3 significantly rose, while TSH levels dropped in the meantime. Subclinical hypothyroidism was described in 32 out of 90 workers involved in industrial plastic processing (35.6%) (Metwally et al., 2019). The impact of other substances or mixtures of substances than BPA on the thyroid functionality cannot to be excluded in plastic industry.

A Korean study addressed the possible relationship between BPA occupational exposure in cashiers and metabolic syndrome-related biomarkers (Lee et al., 2018). Post-shift urinary BPA levels among cashiers not wearing protective gloves ($n = 54$) were 2 times higher than those of cashiers wearing gloves. This finding was significantly associated with higher fasting insulin levels and insulin resistance.

3.2.3.3. Sexual dysfunction and semen quality. An Asian study (Li et al., 2010a, 2010b) provided evidence that occupational BPA exposure in epoxy resin manufacturing field may be associated with male sexual dysfunction. Compared to unexposed workers, a higher occupational BPA exposure was associated with a higher reporting of male sexual dysfunction: sexual desire, erectile function, orgasmic function and overall satisfaction with sex life (odds ratios varying between 3.9 and 7.1). This association was also present after controlling possible confounding physiological and behavioural factors. Moreover, a dose and time-dependent relationship could be demonstrated, thus providing further support to these findings.

As far as semen quality is concerned, a significant linear relationship was demonstrated between increasing urinary BPA concentration and declining semen quality: low sperm concentration, sperm vitality and motility (Li et al., 2011). But no linear correlation was established between semen volume and sperm morphology. Men with detectable urine BPA had an increased risk of having low sperm quality parameters (adjusted odds ratios between 2.3 and 4.1 for sperm vitality, motility and count). Miao et al. (2014) saw a significantly lower spermatic LINE-1 (long interspersed nucleotide element-1) methylation in epoxy resin workers exposed to BPA compared to that of the controls. The highest tercile of urine BPA was also associated with the lowest methylation rate in sperm LINE-1. However, the possible mediating role of LINE-1 methylation regarding poor semen quality could not be demonstrated. In a more recent study performed in the same occupational exposure field, Tian et al. (2018) demonstrated that workers exposed to BPA had greater levels of LINE-1 hydroxymethylation in individual human sperm compared to unexposed controls. When the dose-response relationship was examined, the medians of 5-hydroxymethylcytosine generally increased with increasing urinary BPA levels, although in a non-linear fashion. Overall, these preliminary data should be further investigated to better explain the impact of possible epigenetic effects of BPA on male reproductive function.

4. Discussion

The fundamental role of HBM in occupational health programmes is to complement information obtained by workplace environmental monitoring through the assessment of the exposure by all routes: inhalation, dermal and/or ingestion due to hand-mouth contact (Manno et al., 2010; NRC, 2006; Viegas et al., 2020). This is of most relevant in occupational settings in which workers are in contact with substances, such as bisphenols, that do not have a significant vapour pressure but have the capacity to be absorbed through the skin. HBM is also relevant in case of occupational exposure to chemicals with significant levels of environmental or consumer exposure, e.g. via food, since, through a specific approach (Ladeira and Viegas, 2016; Ndaw et al., 2016), it enables researchers to recognize what the workplace environment might be adding to the exposure already occurring as a result of food intake. Moreover, HBM can be used to assess exposure trends, like for bisphenols, due to the BPA substitution with BPS and BPF pushed by regulation (Sogorb et al., 2019; ECHA, 2020). All of these aspects support the need for developing new HBM studies dedicated to assess exposure to bisphenols with a particular focus on occupational settings in which the substitution of BPA by BPS and BPF is expected in a near future, such as in their application in thermal paper. More thorough investigation in this field might lend support to future policy actions concerning the adoption of additional regulatory risk management strategies for bisphenols and the assessment of the efficacy of the ones that are already in place.

4.1. The current data on the exposure to bisphenols and data needs

Some critical issues could be identified in the analysis of currently available HBM studies on occupational exposure to bisphenols that need to be considered for a suitable interpretation of the results and for planning future investigations on the topic. One obvious data gap is the small number of HBM occupational exposure data especially on BPS and BPF worldwide (Tables S3b and S3c). This seems even more important considering the need for "safer" alternatives to BPA that has stimulated the employment of some other bisphenol analogues whose toxicological profile is not complete and may be comparable to that of BPA. Therefore, other HBM studies should be focused on exposure and effect biomarkers for different bisphenols, primarily BPS and BPF.

Even for BPA, the available studies do not cover all the settings in which bisphenols are used and represent the potential for occupational exposure (Tables S2a, S2b, S2c and S2d). In this perspective, a major gap in the European literature concerning BPA concerns the lack of data on settings in which plastic, epoxy resin and BPA-filled wax are manufactured and used (i.e. highest exposure industries) (Table S2c). Asian studies, by contrast, have been primarily focused on these settings (Table S2a). These disparities prevent drawing suitable comparisons between regions, particularly with regard to the effectiveness of different risk management measures adopted to control exposure. Moreover, it should be noted that the classification of the occupations was not made by an industrial hygienist in most of the studies; therefore a possible misclassification of this variable cannot be excluded. In this regard, possible conditions of co-exposures to a wide and highly variable range of toxic chemicals, whose impact on specific effect marker and adverse health effect findings still needs to be clarified.

The extent and pathways of exposure occurring in specific occupational settings should be investigated further. It is important to study the exposure to BPA replacements, such as BPS, in cashier stations (ECHA, 2020). In addition, it is also important to cover the tasks that involve handling pure bisphenols or manufacturing bisphenols or products containing pure bisphenols. As shown in a number of BPA studies, in these industries the exposure can be several orders of magnitude higher than the observed in the general population (Table S3a). The handling of hazardous materials as a potential source of exposure to bisphenols should also be taken into consideration.

4.2. Methodological aspects related to occupational HBM studies on bisphenols

With regard to methodological design, not all of the current investigations included a control group of unexposed workers. This would be worthwhile since we are dealing with chemicals with significant environmental/consumer exposure and it is important in being able to evaluate the contribution of the workplace environment in the total exposure. In some cases, the possible bisphenol exposure of the control groups engaged in the same plant of exposed cases cannot be excluded, as it cannot be completely excluded in different job categories from which controls were recruited due to indirect exposure. Thus, it is advisable to have a separate control group of non-occupationally exposed workers from the same area (or at least from the same country). Another option would be the use of general population data from adults by matching the sample collection location and date as closely as possible to those of occupationally exposed workers.

A single spot urinary or blood sample, as was used in most of the current studies (Tables S3a, S3b and S3c), may result in a misclassification of bisphenol exposure due to the still limited knowledge regarding bisphenol's toxicokinetics via different exposure routes and the consequent difficulties in defining the ideal sampling time (Thayer et al., 2016). As an example, several studies have shown that one or two days

off work before collecting the pre-shift sample may not be a sufficient time for bisphenol to return to baseline level (Thayer et al., 2016; Heinälä et al., 2017; Hines et al., 2017). Therefore, occupational bisphenol biomonitoring studies should preferably include more than one post-shift urine sample, especially if skin exposure is expected. It may be important to overcome uncertainties regarding the toxicokinetics of bisphenols analogues by defining suitable HBM strategies: *i*) to standardize the schedule of sample collection; *ii*) to collect multiple samples over the course of ≥1 day (since peak exposure appears later after the shift); *iii*) to define the time interval between sample collection and the last occupational exposure; and *iv*) to determine the most suitable analytical methodologies for detecting different biological indicators. Since BPA is ubiquitous in the environment, suppressing or minimizing background contribution while collecting, storing, extracting and analysing sample became crucial means of avoiding any exogenous contamination (Markham et al., 2010; Ndaw et al., 2016). In this perspective, relevant lifestyle factors (e.g. smoking) should be considered as possible confounding factors of HBM results even when a control group is considered.

With regard to the type of biological indicator measured in collected samples, total BPA concentration was the most relevant parameter for obtaining information on the extent of the exposure (Ndaw et al., 2016). Although the unconjugated form is considered to be the biologically active form of BPA, its measurement is, however, limited due to its low concentration in biological matrices and the need to develop reliable analytical methods with low LOQs.

Another important aspect is the normalization of bisphenol urinary concentrations for urine dilution. The most common approach to compensate for this involves measurement of the creatinine concentration in the sample and expression of the concentration of the analyte as a ratio of the creatinine concentration. However, creatinine levels have been shown to vary by factors such as age, sex, ethnicity or diet. Alternatives such adjustment to specific gravity was reported to be less dependent on these factors (Carrieri et al., 2000; Middleton et al., 2019).

Gender-related differences in occupationally exposed workers could only be observed due to the different types of occupational settings that male and female workers were engaged in. Since pregnant women (and their foetuses) are a specific risk group for the endocrine effects of bisphenols, it is of special interest to study the exposure of those occupational groups having numerous female workers. The most prominent of groups is cashiers, who have been shown to be exposed to bisphenols through the handling of thermal paper receipts. Although the exposure of this group is far lower than those observed in industry (Tables S3a and S3b), a risk to the foetuses cannot to be excluded.

4.3. Bisphenol exposure and effect markers

Endocrine-disrupting properties of BPA have also motivated the study of the impact of occupational exposure on male and female sex hormone concentrations, thyroid hormone and insulin levels as well as on sexual dysfunction and semen quality. Occupational studies addressing the associations between BPA exposure and effect biomarkers or health effects in Asian occupational settings have all been conducted in the contexts of epoxy resin and plastic manufacturing (Table S2a). Although conflicting, and not always significant, some alterations in male sex hormone levels, i.e. lower concentrations of serum T (Cha et al., 2008; Zhou et al., 2013), and increased values of SHBG (Zhuang et al., 2015; Zhou et al., 2013) were observed in occupationally exposed workers compared to the controls. Li et al. (2010a, 2010b, 2011) have also suggested an increased risk of sexual dysfunction and a significant reduction in semen quality in exposed workers. Overall, these studies, together with preliminary data on the effects on thyroid hormones and insulin levels and insulin resistance, recommend that additional research is needed on the possible causal interferences exerted by BPA exposure. Understanding the mechanisms of the adverse effects of bisphenols is important in defining new effect biomarkers for future investigations.

4.4. Importance of good contextual data in the interpretation of bisphenol HBM results

The present review also underlines how important it is to collect contextual information concerning the nature and duration of the work, as well as the job practices and raw materials used as potential influencing factors on occupational exposure and HBM results. The type of industry and specific tasks developed (Hines et al., 2017), the availability of automatic or semiautomatic processes, the manual handling of raw materials, the lack of ventilation systems in workplaces and the infrequent employment of gloves and dust masks might function as determinants for BPA exposure in specific job categories (Wang et al., 2012). As regards occupational sectors, the highest BPA exposure occurs in the manufacture of BPA and epoxy resins (Table S3a). Moreover, with regard to differences in exposure as a result of job tasks, operators engaged in the position of feeding free BPA to the containers in an epoxy resin plant had significantly more than 10 times higher BPA urine concentrations compared to those tasked with crushing and packing, as well as office colleagues (Wang et al., 2012). The feeding position, where raw BPA was manually handled by workers, was reported as not being ventilated, while the other manufacturing lines were semiautomatic (Wang et al., 2012). Combining HBM data with relevant contextual information allows us to understand the principal exposure routes and workplace conditions that influence contamination and, consequently, identify the type of interventions required. As for the duration of work, conflicting data on serum BPA concentrations have been reported (Metwally et al., 2019; Zhuang et al., 2015), implying deeper research on this topic, also considering the possibility for bisphenol accumulation in the human body. Good practices at work, intended as occupational hygiene practices and the use of personal protective equipment, should be more deeply investigated to better interpret HBM results. As an example, hand to mouth contact, eating during work and washing hands may all influence bisphenol exposure (Hines et al., 2017). All the above-mentioned aspects should be taken into consideration in order to achieve specifically tailored risk assessment procedures and priorities in developing management strategies focused on subgroups with different levels of exposure and risk (Hines et al., 2017).

Finally, most of the reviewed studies did not provide environmental or personal exposure data in relation to the HBM data. Additionally, further possible confounding general living and lifestyle factors that may affect BPA HBM levels have not always been controlled to assess the reliability of the association found (workplace responsible for the exposure). Future research plans should be focused on overcoming the lack of information concerning the relationship between individual external-internal dose and HBM results in terms of exposure and effect biomarkers, particularly in conditions of long-term, chronic, high level exposure to BPA.

5. Conclusion

Based on this review, it is clear that there is only a limited number of HBM studies on occupational exposure to bisphenols worldwide, especially with regard to BPS and BPF. Moreover, in terms of geographical distribution, Asia stands out with more studies conducted. Additionally, available studies on BPA do not cover all the uses and settings where bisphenols are used with a lack of European data on plastic, epoxy resin and BPA-filled wax production which are uses considered to result in the highest exposures as shown by Asian studies. Taking into account the current policies leading to the substitution of BPA by analogue substances, there is a need for research on the occupational exposure to these compounds, including BPS and BPF. This would include studying cashier work in which BPS may have replaced BPA. Future occupational HBM studies should also include consideration of tasks that involve handling pure bisphenols or manufacturing bisphenols or products that contain pure bisphenols, since exposure can be several orders of

magnitude higher in such cases when compared with the general population.

New biomonitoring studies should also focus on evaluating the impact of protective measures on the exposure of and possible health risks to workers. A harmonized approach to sample collection and analysis for the biomonitoring of bisphenols is needed in order to obtain comparable data between countries. This includes defining the most appropriate sampling time and considering the most relevant exposure routes in the workplace. Combining HBM data with the description of work tasks, operational conditions and workplace characteristics would lend support to the need: i) to prioritize risk management measures and actions for policy making; ii) to evaluate the effectiveness of the policy measures already adopted; iii) to promote more comprehensive policy options to control exposure levels; and, consequently, iv) to avoid the possible impact on workers' health.

Finally, future investigations on mechanisms of the adverse effects of bisphenols will enable research to identify new and more reliable effect biomarkers.

Considering the major role of HBM in occupational health surveillance, exposure and risk assessment and risk management, its use should be more generalized; this extends to the occupational exposure assessment of bisphenols. Within the framework of HBM4EU project (www.hbm4eu.eu), consistent efforts have been made to develop biological guidance values in order to facilitate the interpretation of such results. However, for the proper interpretation of the occupational HBM data, more information is still needed on the toxicokinetics and levels of free bisphenol in serum in occupational scenarios involving different routes of exposure.

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.

Acknowledgements

The HBM4EU project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 733032 and received co-funding from the authors' home institutions.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.146905.

References

Andra, S.S., Austin, C., Yang, J., Patel, D., Arora, M., 2016. Recent advances in simultaneous analysis of bisphenol A and its conjugates in human matrices: exposure biomarker perspectives. Sci. Total Environ. 572, 770–781. https://doi.org/10.1016/j.scitotenv.2016.07.062.

Balicco, A., Bidondo, M.L., Fillol, C., Gane, J. et al., 2019. Imprégnation de la population française par les bisphénols A, S et F. Programme national de biosurveillance, Esteban 2014-2016. Santé publique France Saint-Maurice (available at www.santepubliquefrance.fr).

Boucher, J.G., Ahmed, S., Atlas, E., 2016. Bisphenol S induces adipogenesis in primary human preadipocytes from female donors. Endocrinology 157, 1397–1407. https://doi.org/10.1210/en.2015-1872.

Braun, J.M., Kalkbrenner, A.E., Calafat, A.M., Bernert, J.T., Ye, X., Silva, M.J., Barr, D.B., Sathyanarayana, S., Lanphear, B.P., 2011. Variability and predictors of urinary bisphenol A concentrations during pregnancy. Environ. Health Perspect. 119 (1), 131–137. https://doi.org/10.1289/ehp.1002366.

Carrieri, M., Trevisan, A., Bartolucci, G., 2000. Adjustment to concentration-dilution of spot urine samples: correlation between specific gravity and creatinine. Int. Arch. Occup. Environ. Health 74, 63–67. https://doi.org/10.1007/s004200000190.

Cha, B.S., Koh, S.B., Park, J.H., Eom, A., Lee, K.M., Choi, H.S., 2008. Influence of occupational exposure to bisphenol A on the sex hormones of male epoxy resin painters. Mol. Cell. Toxicol. 4 (3), 230–234.

Cimmino, I., Fiory, F., Perruolo, G., Miele, C., Beguinot, F., Formisano, P., Oriente, F., 2020. Potential mechanisms of bisphenol A (BPA) contributing to human disease. Int. J. Mol. Sci. 21 (16), 5761. https://doi.org/10.3390/ijms21165761.

ECHA, 2018. Market Survey: Use of bisphenol A and its alternatives in thermal paper in the EU from 2014 to 2017. https://echa.europa.eu/pt/news-and-events/news-alerts/all-news/-/asset_publisher/yhAseXkvBI2u/content/bpa-being-replaced-by-bps-in-thermal-paper-echa-survey-finds?_cldee=Y2F0aGVyaW5lLmdhbnpsZWJlbkBlZWEuZXVyb3BhLmV1&recipientid=lead-9dc45e64dc3be81180fd005056952b31-e33c42737608483a916fc8370db125a6&esid=8476ef3d-695e-e811-80fe-005056952b31&urlid=0.

ECHA, 2020. The use of bisphenol A and its alternatives in thermal paper in the EU during 2014–2022. https://echa.europa.eu/documents/10162/23294236/bpa_thermal_paper_report_2020_en.pdf/59eca269-c788-7942-5c17-3bd822d9cba0.

Gerona, R.R., Pan, J., Zota, A.R., Schwartz, J.M., Friesen, M., Taylor, J.A., Hunt, P.A., Woodruff, T.J., 2016. Direct measurement of bisphenol A (BPA), BPA glucuronide and BPA sulfate in a diverse and low-income population of pregnant women reveals high exposure, with potential implications for previous exposure estimates: a cross-sectional study. Environ. Health 15, 50. https://doi.org/10.1186/s12940-016-0131-2.

González, N., Cunha, S.C., Monteiro, C., Fernandes, J.O., Marquès, M., Domingo, J.L., Nadal, M., 2019. Quantification of eight bisphenol analogues in blood and urine samples of workers in a hazardous waste incinerator. Environ. Res. 176, 108576. https://doi.org/10.1016/j.envres.2019.108576.

Gore, A.C., Chappell, V.A., Fenton, S.E., Flaws, J.A., Nadal, A., Prins, G.S., Topari, J., Zoeller, R.T., 2015. EDC-2: the endocrine society's second scientific statement on endocrine-disrupting chemicals. Endocr. Rev. 36 (6), E1–E150. https://doi.org/10.1210/er.2015-1010.

Hanaoka, T., Kawamura, N., Hara, K., Tsugane, S., 2002. Urinary bisphenol A and plasma hormone concentrations in male workers exposed to bisphenol A diglycidyl ether and mixed organic solvents. Occup. Environ. Med. 59 (9), 625–628. https://doi.org/10.1136/oem.59.9.625.

He, Y., Miao, M., Wu, C., Yuan, W., Gao, E., Zhou, Z., Li, D.K., 2009. Occupational exposure levels of bisphenol A among Chinese workers. J. Occup. Health 51 (5), 432–436. https://doi.org/10.1539/joh.o9006.

Heinälä, M., Ylinen, K., Tuomi, T., Santonen, T., Porras, S.P., 2017. Assessment of occupational exposure to bisphenol A in five different production companies in Finland. Ann. Work Expo. Health 61 (1), 44–55. https://doi.org/10.1093/annweh/wxw006.

Hines, C.J., Jackson, M.V., Deddens, J.A., Clark, J.C., Ye, X., Christianson, A.L., Meadows, J.W., Calafat, A.M., 2017. Urinary Bisphenol a (BPA) concentrations among workers in industries that manufacture and use BPA in the USA. Ann. Work Expo. Health 61 (2), 164–182. https://doi.org/10.1093/annweh/wxw021.

Hines, C.J., Christianson, A.L., Jackson, M.V., Ye, X., Pretty, J.R., Arnold, J.E., Calafat, A.M., 2018. An evaluation of the relationship among urine, air, and hand measures of exposure to bisphenol A (BPA) in US manufacturing workers. Ann. Work Expo. Health 62 (7), 840–851. https://doi.org/10.1093/annweh/wxy042.

Khmiri, I., Côté, J., Mantha, M., Khemiri, R., Lacroix, M., Gely, C., Toutain, P.-L., Picard-Hagen, N., Gayrard, V., Bouchard, M., 2020. Toxicokinetics of bisphenol-S and its glucuronide in plasma and urine following oral and dermal exposure in volunteers for the interpretation of biomonitoring data. Environ. Int. 138, 105644. https://doi.org/10.1016/j.envint.2020.105644.

Kim, K., Park, H., Yang, W., Lee, J.H., 2011. Urinary concentrations of bisphenol A and triclosan and associations with demographic factors in the Korean population. Environ. Res. 111 (8), 1280–1285. https://doi.org/10.1016/j.envres.2011.09.003.

Kouidhi, W., Thannimalay, L., Soon, C.S., Ali Mohd, M., 2017. Occupational exposure to bisphenol A (BPA) in a plastic injection molding factory in Malaysia. Int. J. Occup. Med. Environ. Health 30 (5), 743–750. https://doi.org/10.13075/ijomeh.1896.00917.

Ladeira, C., Viegas, S., 2016. Human biomonitoring – an overview on biomarkers and their application in occupational and environmental health. Biomonitoring 3, 15–24. https://doi.org/10.1515/bimo-2016-0003.

LaKind, J.S., Sobus, J.R., Goodman, M., Barr, D.B., Furst, P., Albertini, R.J., Weisel, C.P., 2014. A proposal for assessing study quality: biomonitoring, environmental epidemiology, and short-lived chemicals (BEES-C) instrument. Environ. Int. 73, 195–207. https://doi.org/10.1016/j.envint.2014.07.011.

Lee, I., Kim, S., Kim, K.T., Kim, S., Park, S., Lee, H., Jeong, Y., Lim, J.E., Moon, H.B., Choi, K., 2018. Bisphenol A exposure through receipt handling and its association with insulin resistance among female cashiers. Environ. Int. 117, 268–275. https://doi.org/10.1016/j.envint.2018.05.013.

Lehmler, H.J., Liu, B., Gadogbe, M., Bao, W., 2018. Exposure to bisphenol A, bisphenol F, and bisphenol S in U.S. adults and children: the national health and nutrition examination survey 2013–2014. ACS Omega 3 (6), 6523–6532. https://doi.org/10.1021/acsomega.8b00824.

Li, D., Zhou, Z., Qing, D., He, Y., Wu, T., Miao, M., Wang, J., Weng, X., Ferber, J.R., Herrinton, L.J., Zhu, Q., Gao, E., Checkoway, H., Yuan, W., 2010a. Occupational exposure to bisphenol-A (BPA) and the risk of self-reported male sexual dysfunction. Hum. Reprod. 25 (2), 519–527. https://doi.org/10.1093/humrep/dep381.

Li, D.K., Zhou, Z., Miao, M., He, Y., Qing, D., Wu, T., Wang, J., Weng, X., Ferber, J., Herrinton, L.J., Zhu, Q., Gao, E., Yuan, W., 2010b. Relationship between urine bisphenol-A level and declining male sexual function. J. Androl. 31 (5), 500–506. https://doi.org/10.2164/jandrol.110.010413.

Li, D.K., Zhou, Z., Miao, M., He, Y., Wang, J., Ferber, J., Herrinton, L.J., Gao, E., Yuan, W., 2011. Urine bisphenol-A (BPA) level in relation to semen quality. Fertil. Steril. 95 (2), 625–630.e4. https://doi.org/10.1016/j.fertnstert.2010.09.026.

Li, J., Wu, C., Zhao, H., Zhou, Y., Cao, G., Yang, Z., Hong, Y., Xu, S., Xia, W., Cai, Z., 2019. Exposure assessment of bisphenols in Chinese women during pregnancy: a longitudinal study. Environ. Sci. Technol. 53, 7812–7820. https://doi.org/10.1021/acs.est.9b01281.

Liu, J., Martin, J.W., 2017. Prolonged exposure to bisphenol A from single dermal contact events. Environ. Sci. Technol. 51, 9940–9949. https://doi.org/10.1021/acs.est.7b03093.

Liu, X., Miao, M., Zhou, Z., Gao, E., Chen, J., Wang, J., Sun, F., Yuan, W., Li, D.K., 2015. Exposure to bisphenol-A and reproductive hormones among male adults. Environ. Toxicol. Pharmacol. 39 (2), 934–941. https://doi.org/10.1016/j.etap.2015.03.007.

Lyapina, M.G., Dencheva, M.S., Krasteva, A.Z., Nikolov, G.S., Cekova, M.P., Deliverska, M.S., Kisselova-Yaneva, A.I., 2016. Biomonitoring of urinary levels of bisphenol A. C. R. Acad. Bulg. Sci. 69 (6), 807–814.

Manno, M., Viau, C., Cocker, J., Colosio, C., Lowry, L., Mutti, A., Nordberg, M., Wang, S., in collaboration with, 2010. Biomonitoring for occupational health risk assessment (BOHRA). Toxicol. Lett. 192 (1), 3–16. https://doi.org/10.1016/j.toxlet.2009.05.001.

Markham, D.A., Waechter Jr., J.M., Wimber, M., Rao, N., Connolly, P., Chuang, J.C., Hentges, S., Shiotsuka, R.N., Dimond, S., Chappelle, A.H., 2010. Development of a method for the determination of bisphenol A at trace concentrations in human blood and urine and elucidation of factors influencing method accuracy and sensitivity. J. Anal. Toxicol. 34 (6), 293–303. https://doi.org/10.1093/jat/34.6.293.

Metwally, F.M., Hasheesh, A., Zaid, M.M., El Sharkawy, S.A.F., Abd Fattah, F.A.Z.M., Mazhar, M.S., 2019. Bisphenol A levels among workers in plastic processing industry and their relations to thyroid hormones. J. Appl. Pharm. Sci. 9 (11), 107–111. https://doi.org/10.7324/JAPS.2019.91114.

Miao, M., Yuan, W., Zhu, G., He, X., Li, D.K., 2011a. In utero exposure to bisphenol-A and its effect on birth weight of offspring. Reprod. Toxicol. 32 (1), 64–68. https://doi.org/10.1016/j.reprotox.2011.03.002.

Miao, M., Yuan, W., He, Y., et al., 2011b. In utero exposure to bisphenol-A and anogenital distance of male offspring. Birth Defects Res. Part A Clin. Mol. Teratol. 91 (10), 867–872. https://doi.org/10.1002/bdra.22845.

Miao, M., Zhou, X., Li, Y., Zhang, O., Zhou, Z., Li, T., Yuan, W., Li, R., Li, D.-K., 2014. LINE-1 hypomethylation in spermatozoa is associated with bisphenol A exposure. Andrology 2 (1), 138–144. https://doi.org/10.1111/j.2047-2927.2013.00166.x.

Miao, M., Yuan, W., Yang, F., Liang, H., Zhou, Z., Li, R., Gao, E., Li, D.K., 2015. Associations between bisphenol A exposure and reproductive hormones among female workers. Int. J. Environ. Res. Public Health 12 (10), 13240–13250. https://doi.org/10.3390/ijerph121013240.

Middleton, D.R.S., Watts, M.J., Polya, D.A., 2019. A comparative assessment of dilution correction methods for spot urinary analyte concentrations in a UK population exposed to arsenic in drinking water. Environ. Int. 130, 104721. https://doi.org/10.1016/j.envint.2019.03.069.

Ndaw, S., Remy, A., Jargot, D., Robert, A., 2016. Occupational exposure of cashiers to bisphenol A via thermal paper: urinary biomonitoring study. Int. Arch. Occup. Environ. Health 89 (6), 935–946. https://doi.org/10.1007/s00420-016-1132-8.

Ndaw, S., Remy, A., Denis, F., Marsan, P., Jargot, D., Robert, A., 2018. Occupational exposure of cashiers to bisphenol S via thermal paper. Toxicol. Lett. 298, 106–111. https://doi.org/10.1016/j.toxlet.2018.05.026.

NHANES, 2019. Fourth National Report on Human Exposure to Environmental Chemicals, Updated Tables, Volume One. Available at https://www.cdc.gov/exposurereport/pdf/FourthReport_UpdatedTables_Volume1_Jan2019-508.pdf (Accessed on 16 July 2020).

NRC, Human Biomonitoring for Environmental Chemicals, 2006. Washington, DC: The National Academies Press. Retrieved from https://www.nap.edu/catalog/11700/human-biomonitoring-for-environmental-chemicals.

Oh, J., Choi, J.W., Ahn, Y.-A., Kim, S., 2018. Pharmacokinetics of bisphenol S in humans after single oral administration. Environ. Int. 112, 127–133. https://doi.org/10.1016/j.envint.2017.11.020.

Rochester, J.R., Bolden, A.L., 2015. Bisphenol S and F: a systematic review and comparison of the hormonal activity of bisphenol A substitutes. Environ. Health Perspect. 123 (7), 643–650. https://doi.org/10.1289/ehp.1408989.

SCOEL, 2014. Recommendation from the Scientific Committee on Occupational Exposure Limits for Bisphenol-A. SCOEL/SUM/113.

Shaw, S.D., Berger, M.L., Harris, J.H., Yun, S.H., Wu, Q., Liao, C., Blum, A., Stefani, A., Kannan, K., 2013. Persistent organic pollutants including polychlorinated and polybrominated dibenzo-p-dioxins and dibenzofurans in firefighters from Northern California. Chemosphere 91 (10), 1386–1394. https://doi.org/10.1016/j.chemosphere.2012.12.070.

Simonelli, A., Guadagni, R., De Franciscis, P., Colacurci, N., Pieri, M., Basilicata, P., Pedata, P., Lamberti, M., Sannolo, N., Miraglia, N., 2017. Environmental and occupational exposure to bisphenol A and endometriosis: urinary and peritoneal fluid concentration levels. Int. Arch. Occup. Environ. Health 90 (1), 49–61. https://doi.org/10.1007/s00420-016-1171-1.

Sogorb, M.A., Estévez, J., Vilanova, E., 2019. Case study: is bisphenol S safer than bisphenol A in thermal papers? Arch. Toxicol. 93, 1835–1852. https://doi.org/10.1007/s00204-019-02474-x.

Thayer, K.A., Doerge, D.R., Hunt, D., Schurman, S.H., Twaddle, N.C., Churchwell, M.I., Garantziotis, S., Kissling, G.E., Easterling, M.R., Bucher, J.R., Birnbaum, L.S., 2015. Pharmacokinetics of bisphenol A in humans following a single oral administration. Environ. Int. 83, 107–115. https://doi.org/10.1016/j.envint.2015.06.008.

Thayer, K.A., Taylor, K.W., Garantziotis, S., Schurman, S.H., Kissling, G.E., Hunt, D., Herbert, B., Church, R., Jankowich, R., Churchwell, M.I., Scheri, R.C., Birnbaum, L.S., Bucher, J.R., 2016. Bisphenol A, bisphenol S, and 4-hydro xyphenyl 4-isopro oxyphenyl sulfone (BPSIP) in urine and blood of cashiers. Environ. Health Perspect. 124 (4), 437–444. https://doi.org/10.1289/ehp.1409427.

Tian, Y., Zhou, X., Miao, M., Li, D.K., Wang, Z., Li, R., Liang, H., Yuan, W., 2018. Association of bisphenol a exposure with LINE-1 hydroxymethylation in human semen. Int. J. Environ. Res. Public Health 15 (8), 1770. https://doi.org/10.3390/ijerph15081770.

Vahedi, M., Saeedi, A., Poorbaghi, S.L., Sepehrimanesh, M., Fattahi, M., 2016. Metabolic and endocrine effects of bisphenol A exposure in market seller women with polycystic ovary syndrome. Environ. Sci. Pollut. Res. 23, 23546–23550. https://doi.org/10.1007/s11356-016-7573-5.

Viegas, S., Jeddi, M.Z., Hopf, N.B., Bessems, J., Palmen, N., Galea, K.S., Jones, K., Kujath, P., Duca, R.-C., Verhagen, H., Santonen, T., Pasanen-Kase, R., 2020. Biomonitoring as an underused exposure assessment tool in occupational safety and health context—Challenges and way forward. Int. J. Environ. Res. Public Health 17 (16), 5884. https://doi.org/10.3390/ijerph17165884.

Vom Saal, F., Hughes, C., 2005. An extensive new literature concerning low-dose effects of bisphenol A shows the need for a new risk assessment. Environ. Health Perspect. 113 (8), 926–933. https://doi.org/10.1289/ehp.7713.

Waldman, J.M., Gavin, Q., Anderson, M., Hoover, S., Alvaran, J., Ip, H.S.S., Fenster, L., Wu, N.T., Krowech, G., Plummer, L., Israel, L., Das, R., She, J., 2016. Exposures to environmental phenols in Southern California firefighters and findings of elevated urinary benzophenone-3 levels. Environ. Int. 88, 281–287. https://doi.org/10.1016/j.envint.2015.11.014.

Wang, F., Hua, J., Chen, M., Xia, Y., Zhang, Q., Zhao, R., Zhou, W., Zhang, Z., Wang, B., 2012. High urinary bisphenol A concentrations in workers and possible laboratory abnormalities. Occup. Environ. Med. 69 (9), 679–684. https://doi.org/10.1136/oemed-2011-100529.

Ye, X., Bishop, A.M., Reidy, J.A., Needham, L.L., Calafat, A.M., 2007. Temporal stability of the conjugated species of bisphenol A, parabens, and other environmental phenols in human urine. J. Expo. Sci. Environ. Epidemiol. 17, 567–572. https://doi.org/10.1038/sj.jes.7500566.

Zhou, Q., Miao, M., Ran, M., Ding, L., Bai, L., Wu, T., Yuan, W., Gao, E., Wang, J., Li, G., Li, D.-K., 2013. Serum bisphenol-A concentration and sex hormone levels in men. Fertil. Steril. 100 (2), 478–482. https://doi.org/10.1016/j.fertnstert.2013.04.017.

Zhuang, W., Wu, K., Wang, Y., Zhu, H., Deng, Z., Peng, L., Zhu, G., 2015. Association of serum bisphenol-A concentration and male reproductive function among exposed workers. Arch. Environ. Contam. Toxicol. 68 (1), 38–45. https://doi.org/10.1007/s00244-014-0078.