SDU
University of Southern Denmark

Predictors of serum- per- and polyfluoroalkyl substance (PFAS) concentrations among infants in Guinea-Bissau, West Africa

Sørensen, Marzanna Marianna; Fisker, Ane Bærent; Dalgård, Christine; Jensen, Kristoffer Jarlov; Nielsen, Flemming; Benn, Christine Stabell; Grandjean, Philippe; Timmermann, Amalie

Published in:
Environmental Research

DOI:
10.1016/j.envres.2023.115784

Publication date:
2023

Document version:
Final published version

Document license:
CC BY

Citation for pulished version (APA):
Sørensen, M. M., Fisker, A. B., Dalgård, C., Jensen, K. J., Nielsen, F., Benn, C. S., Grandjean, P., & Timmermann, A. (2023). Predictors of serum- per- and polyfluoroalkyl substance (PFAS) concentrations among infants in Guinea-Bissau, West Africa. *Environmental Research*, *228*, Article 115784. https://doi.org/10.1016/j.envres.2023.115784

Go to publication entry in University of Southern Denmark's Research Portal

Terms of use
This work is brought to you by the University of Southern Denmark.
Unless otherwise specified it has been shared according to the terms for self-archiving.
If no other license is stated, these terms apply:

- You may download this work for personal use only.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying this open access version

If you believe that this document breaches copyright please contact us providing details and we will investigate your claim.
Please direct all enquiries to puresupport@bib.sdu.dk

Download date: 11. Jan. 2025

Environmental Research 228 (2023) 115784

Contents lists available at ScienceDirect

Environmental Research

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

Predictors of serum- per- and polyfluoroalkyl substance (PFAS) concentrations among infants in Guinea-Bissau, West Africa

Marzanna Marianna Sørensen [a], Ane Bærent Fisker [b,c], Christine Dalgård [a], Kristoffer Jarlov Jensen [d], Flemming Nielsen [a], Christine Stabell Benn [c,e], Philippe Grandjean [a,f], Amalie Timmermann [g,*]

[a] Research Unit of Clinical Pharmacology, Pharmacy and Environmental Medicine, University of Southern Denmark, Odense, Denmark
[b] Bandim Health Project, INDEPTH Network, Bissau, Guinea-Bissau
[c] OPEN, Department of Clinical Research, University of Southern Denmark/Odense University Hospital, Odense, Denmark
[d] Copenhagen Phase IV Unit, Center for Clinical Research and Prevention, Bispebjerg and Frederiksberg Hospital, Copenhagen, Denmark
[e] Danish Institute for Advanced Study, University of Southern Denmark, Odense, Denmark
[f] Department of Environmental Health, Harvard T.H. Chan School of Public Health, Boston, MA, United States
[g] National Institute of Public Health, University of Southern Denmark, Copenhagen, Denmark

ARTICLE INFO

Handling Editor: Jose L Domingo

Keywords:
Infants
Residence location
Per- and polyfluoroalkyl substances
Predictors

ABSTRACT

Background: Knowledge about PFAS exposure in Africa is limited. We have previously detected six types of PFAS in the serum of infants from Guinea-Bissau, West Africa. The aim of this study was to identify predictors of the infant serum-PFAS concentrations.

Methods: This cross-sectional study was based on a subset of data from a randomized controlled trial of early measles vaccination performed in 2012–2015 in three rural regions of Guinea-Bissau. Blood samples were obtained from 237 children aged 4-to-7 months, and six types of PFAS were quantified in serum. Location of residence was recorded, and information about predictors related to socioeconomic status as well as maternal and child characteristics were obtained through structured interviews with the mothers through routine surveillance.

Associations between potential predictors and infant serum-PFAS concentrations were examined in linear regression models while adjusting for potential confounding and mediating factors as identified in a directed acyclic graph.

Results: Infants from the Cacheu region had the lowest concentrations of perfluorooctanoic acid (PFOA), while infants from the Oio region had the lowest concentrations of all other PFAS. Compared to infants from Oio, infant serum-perfluorooctane sulfonic acid (PFOS) concentrations were 94.1% (95% CI: 52.4, 147.1%) and 81.9% (95% CI: 45.7, 127.1%) higher in Cacheu and Biombo, respectively. Higher maternal age and lower parity were associated with slightly higher child-serum perfluorohexane sulfonic acid (PFHxS) concentrations, while infants with higher socioeconomic status and infants breastfed without supplementary solid foods at inclusion had higher average concentrations of most PFAS, although the confidence intervals were wide and overlapped zero.

Discussion: Location of residence was the most important determinant of serum-PFAS concentrations among Guinea-Bissau infants, indicating a potential role of diet as affected by the global spread of PFAS, but future studies should explore reasons for the regional differences in PFAS exposure.

1. Introduction

Pollution with per- and polyfluoroalkyl substances (PFAS) has become a global health threat (Pelch et al., 2019). This group of man-made chemicals, frequently referred to as 'forever chemicals', are persistent and bioaccumulative (ATSDR, 2021). They have been produced since the 1940s and are used in various consumer products including impregnated carpets, furniture, water-repellent clothing, coated food packaging materials, non-stick cookware, and firefighting foam (EFSA CONTAM Panel et al., 2020). Today they are ubiquitous in

* Corresponding author. National Institute of Public Health, University of Southern Denmark Studiestræde 6, 1455 København K, Denmark.
E-mail address: atimmermann@health.sdu.dk (A. Timmermann).

https://doi.org/10.1016/j.envres.2023.115784
Received 23 January 2023; Received in revised form 7 March 2023; Accepted 26 March 2023
Available online 1 April 2023
0013-9351/© 2023 The Authors. Published by Elsevier Inc. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

the environment and found in rivers, soil, air, drinking and rainwater, food, and house dust (Cousins et al., 2022; Pelch et al., 2019). PFAS exposure have been associated with numerous adverse health effects including higher total cholesterol, effects on the immune system, cancers, thyroid hormone disorders, and changed lipid- and insulin regulation (ATSDR, 2021; EFSA CONTAM Panel et al., 2020; Fenton et al., 2021; Liew et al., 2018).

In North America, Europe, and Asia, humans are exposed to PFAS through contaminated drinking water and food, direct skin contact, and inhalation of indoor air and dust (Domingo and Nadal, 2019; Poothong et al., 2020; Sunderland et al., 2019). Children are exposed from the same sources as adults (Winkens et al., 2017), but they are additionally exposed prenatally via transplacental transfer and after birth via breastfeeding (Gyllenhammar et al., 2018; Kingsley et al., 2018; Mamsen et al., 2019; Manzano-Salgado et al., 2016).

PFAS exposure have been widely examined among populations in Europe (EFSA CONTAM Panel et al., 2020), North- and South America (ATSDR, 2021; Kurwadkar et al., 2022), the Middle East, and Asia (IPEN, 2019), but knowledge about PFAS exposure and exposure routes in Africa is still limited (Ssebugere et al., 2020). PFAS have been found in sewage, drinking water, fish and invertebrates, soil, crops, and food packaging materials in some African countries (Ssebugere et al., 2020). Furthermore, they have been detected in maternal serum, umbilical cord blood (Hanssen et al., 2010), and breast milk (Macheka et al., 2022) from South African women, in breast milk samples from women across Africa (KoneTraore et al., 2021), and in blood samples obtained from Tanzanian women after they gave birth (Muller et al., 2019). We have previously detected six types of PFAS in serum from infants in Guinea-Bissau (Timmermann et al., 2020), but the sources of PFAS in this area are largely unknown. Knowledge about predictors of exposure is needed to potentially prevent further PFAS exposure and to identify potential confounders when studying adverse health effects of PFAS exposure. The aim of this study was thus to identify predictors of infant serum-PFAS concentrations using data from Guinea-Bissau infants.

2. Materials and methods

2.1. Study population

This study was based on data from a trial conducted by the Bandim Health Project, which runs a health and demographic surveillance system in Guinea-Bissau (Thysen et al., 2019). In 2012–2015, children aged 4-7-months from three rural areas of Guinea-Bissau (Oio, Biombo and Cacheu, Fig. 1) were included in a randomized controlled trial of early measles vaccination (Fisker et al., 2018). At inclusion, finger-prick blood samples were collected from a subgroup of infants living in villages within a 2-h drive from Bissau, the capital of Guinea-Bissau, and sufficient serum from 237 children allowed assessment of six types of PFAS.

2.2. PFAS assessment

As previously described (Timmermann et al., 2020), PFAS were measured at University of Southern Denmark using online solid-phase extraction followed by liquid chromatography and triple quadrupole mass spectrometry. The six types of PFAS measured were perfluorohexane sulfonic acid (PFHxS), perfluorooctane sulfonic acid (PFOS), perfluorooctanoic acid (PFOA), perfluorononanoic acid (PFNA), perfluorodecanoic acid (PFDA), and perfluoroundecanoic acid (PFUnDA). The limit of detection (LOD) was 0.03 ng/mL for all types of PFAS. One child had serum-PFUnDA concentrations below the LOD, and the serum-PFUnDA concentration for this child was replaced by 0.015 ng/mL (LOD/2). All other types of PFAS were detected in all serum samples (Timmermann et al., 2020). One extreme PFNA value (16.2 ng/mL) was determined, and residual serum was insufficient for

Fig. 1. Guinea-Bissau regions Map
Modified from free vector maps (Free Vector Maps, 2022)

duplicate analysis. This extreme value was excluded from the statistical analysis to avoid excessive influence.

2.3. Potential predictors

Based on existing knowledge (ATSDR, 2021; EFSA CONTAM Panel et al., 2020) and data availability, we examined three groups of potential predictors: Location of residence, maternal/child characteristics, and socioeconomic status (SES). Residence location was defined based on region, i.e., Oio, Biombo, or Cacheu, and maternal and child characteristics included child sex, weight, age, maternal age, parity indicated by the number of children previously born by the mother, and breastfeeding without introduction of solids. We considered maternal education, owning a mobile phone or radio, having a generator in the house, having a bathroom, roof type (hard or straw) on the home, as well as number of people sleeping in the same room and same bed as the child as SES indicators. At enrolment all children were weighed and information about number of children sleeping in the same room and bed as the child was obtained. Information about all other factors were collected through the Bandim Health Project health and demographic surveillance system (Thysen et al., 2019).

2.4. Statistical analyses

Associations between potential predictors and serum-PFAS concentrations were examined in linear regression models. Because PFAS distributions were skewed, the data were log-10 transformed, and results were subsequently converted to express percentage differences in PFAS concentrations relative to changes in the predictors. For each PFAS and each predictor, we conducted both crude analyses and analyses adjusted for potential confounders and mediators as identified in a Directed Acyclic Graph (Fig. 2). Mediators were included to estimate the direct effect of each predictor on the PFAS concentration. Analyses of SES indicators were performed both with and without mutually adjustment for all SES indicators, whereas when adjusting for SES in other analyses we included only maternal education. Information on maternal education was missing for 10% of the participants. In order not to reduce the sample size, we divided education into three categories including also those with missing information, i.e., no education/1–11 years of education/unknown. The rest of the variables had relatively few missing values, and we thus performed complete case analysis. All analyses were adjusted for possible dependence between twins (6 pairs) and children from the same villages (37 villages) using the Stata package reghdfe (Correia, 2017), which allows for two-way clustering. Homoscedasticity and normal distribution of the residuals were examined by visual inspection of residual-versus-fitted values plots (RVF plots) and quantile-quantile plots (QQ plots), respectively. Linearity of continuous variables was examined by visual inspection of the RVF plots. In all analyses, the assumption about normal distribution of the residuals, homoscedasticity and linearity was met. Variance inflation factor (VIF) was used to investigate multicollinearity between the covariates in adjusted analyses, and all mean VIFs were lower than 5. All statistical analyses were performed using Stata BE 17.

2.5. Ethical considerations

The original study was approved by the ethical review committee in Guinea-Bissau (Comité Nacional de Etica na Saúde) and in Denmark (Danish Central Ethical Committee [consultative approval]). Re-use of the blood samples for PFAS analyses were approved by the ethical committee of the Capital region of Denmark (Journal number H-21066975). This study was conducted without access to any personal identifiers.

3. Results

Among the 237 infants included in the study the median serum-PFAS concentration ranged from 0.10 ng/mL for PFHxS to 0.77 ng/mL for PFOS (Table 1). The sex distribution was relatively even with 48% girls. Sixty-one (26%) of the children came from the Oio region, 141 (59%)

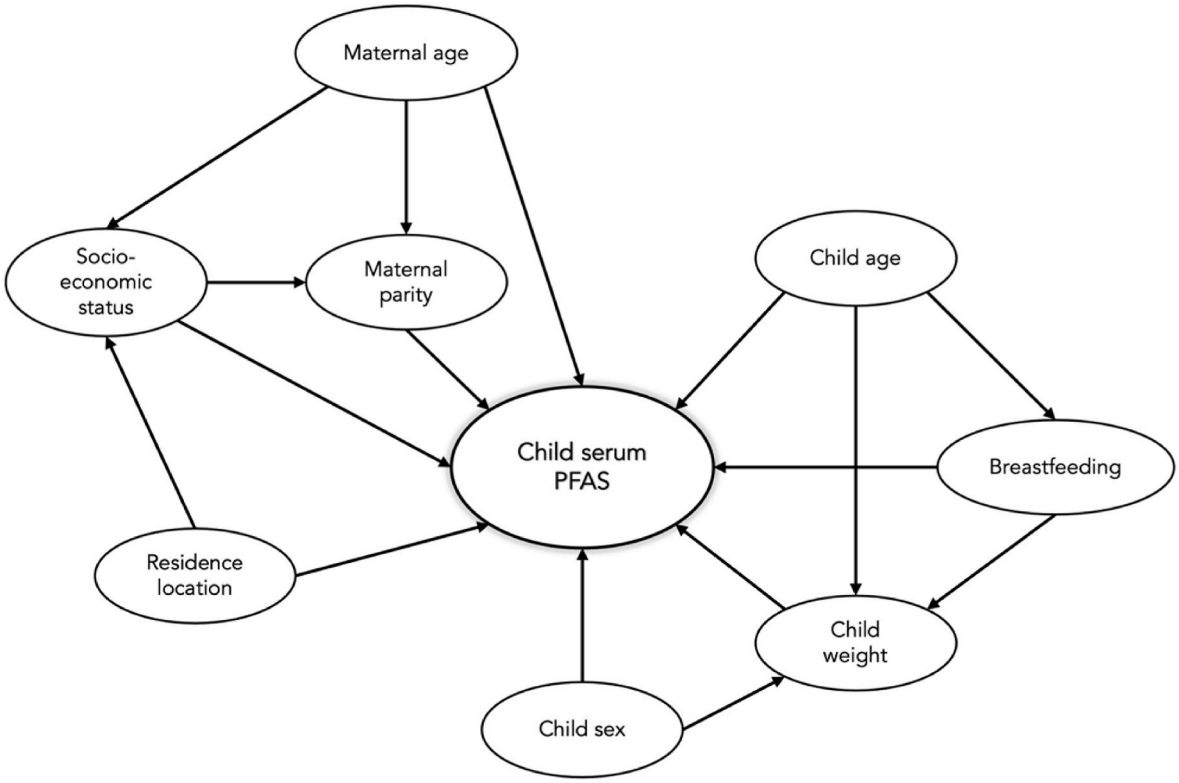

Fig. 2. Directed acyclic graph (DAG) illustrating the hypothesized associations between potential predictors and child serum-PFAS concentrations.

Table 1
Distribution of serum-PFAS concentrations in 237 infants from Guinea-Bissau.

PFAS	*n*	Median ng/mL serum (25th, 75th percentile)
PFHxS	237	0.10 (0.09, 0.14)
PFOS	237	0.77 (0.53, 1.02)
PFOA	237	0.68 (0.53, 0.92)
PFNA	236	0.21 (0.13, 0.31)
PFDA	237	0.19 (0.15, 0.25)
PFUnDA	237	0.12 (0.10, 0.16)

from Biombo, and 35 (15%) from Cacheu (Table 2). At the time of inclusion in the study, all but one child was still being breastfed (results not shown), and 102 children (44%) were being breastfed without supplementary solids foods (Table 2). The maternal age ranged from 13 to 47 years, with 44 (19%) of the mothers being 13–19 years old and 32 (14%) being 36–47 years old at the time of birth. Only 34 (14%) were first time mothers, while 60 women (26%) had given birth to between five and eleven children. One-hundred-and-two women (43%) had no education (Table 2).

3.1. Maternal and child characteristics

Serum-PFAS concentrations were generally slightly lower among boys than girls, but confidence intervals were wide, and none of the sex differences were significant (Table 3). Maternal age was also not significantly associated with child serum-PFAS concentrations, but after adjustment for maternal parity and education, each one-year higher maternal age was associated with 1.6% (95% CI: −0.1, 3.4%) higher infant serum-PFHxS concentrations and a similar though weaker association was seen for PFOA. In crude analyses, maternal parity was not significantly associated with child serum-PFAS concentrations, but child serum-PFHxS concentrations were 6.0% (95% CI: 0, 11.7%) lower for each of the mothers' prior born children, when adjusting for maternal age and education. Higher parity was likewise associated with slightly lower child serum-PFOA concentrations but higher PFNA and PFDA concentrations, though these associations were not statistically significant. After adjustment for child age and weight, breastfeeding without solid foods by the time of inclusion at 4–7 months of age was associated with 13.7% (95% CI: −1.2, 30.7%) higher serum-PFDA concentrations, and similar trends were seen for PFOA, and PFUnDA (Table 3). Higher infant age and lower infant weight at inclusion was associated with slightly higher serum-concentrations of most PFAS, but the associations were not significant (Table 3).

3.2. Socioeconomic status

After adjustment for maternal age, parity and location of residence, low socio economic status tended to be associated with lower child-serum-PFAS concentrations. Thus, each extra person sleeping in the same bedroom as the child, was associated with 3.9% (95% CI: 0.5, 7.2) lower serum-PFOS concentrations, and similar though non-significant associations were seen for the other types of PFAS. Likewise, each extra person sleeping in the same bed as the child, was associated with 9.6% (95% CI: 2.8, 16.0) lower serum-PFOA concentrations, and similar but non-significant associations were seen for most types of PFAS (Table 4). Having a bathroom in the compound, was non-significantly associated with higher concentrations of all types of PFAS. However, children living in a house with a hard roof had 24.6% (95% CI: 13.3, 34.5) lower serum-PFNA concentrations compared to children living in a

Table 2
Participant characteristics among 237 Guinea-Bissau infants and their mothers.

Maternal/child characteristics	n (%)	Socio-economic status (SES)	n (%)	Residence location	n (%)
Children's sex		**Maternal education**		**Regions**	
girls	114 (48)	none	102 (43)	Oio	61 (26)
boys	123 (52)	1-11 grade	111 (47)	Biombo	141 (59)
		unknown	24 (10)	Cacheu	35 (15)
Maternal age					
13–19	44 (19)	**Roof Types**			
20–25	62 (26)	straw roof	95 (41)		
26–35	98 (41)	hard roof	138 (59)		
36–47	32 (14)	*missing*	*4*		
missing	*1*				
		Bathroom in compound			
Maternal parity		no	137 (59)		
0	34 (14)	yes	94 (41)		
1–2	80 (34)	*missing*	*6*		
3–4	61 (26)				
5–11	60 (26)	**Owns a mobile phone**			
missing	*2*	no	106 (46)		
		yes	125 (54)		
Breastfeeding without supplementary solids foods		*missing*	*6*		
no	135 (56)				
yes	102 (44)	**Radio in house**			
		no	43 (19)		
Child age at inclusion		yes	188 (81)		
4–5.5 months	108 (46)	*missing*	*6*		
>5.5–7 months	129 (54)				
		Generator/Solar panel in house			
Child weight at inclusion		no	192 (83)		
<7 kg	131 (55)	yes	40 (17)		
≥7 kg	106 (45)	*missing*	*5*		
		Number of persons sleeping in the bed of the child			
		2 persons	56 (24)		
		3 persons	130 (55)		
		4-5 persons	51 (21)		
		Number of persons sleeping in the bedroom of the child			
		2-3 persons	118 (50)		
		4-5 persons	78 (33)		
		6-9 persons	41 (17)		

Table 3
Associations between maternal/child characteristics and child serum-PFAS concentrations in linear regression models.

Maternal/child characteristics		Precent difference in child serum-PFAS concentration (95% CI)					
		PFHxS	PFOS	PFOA	PFNA	PFDA	PFUnDA
Child sex							
boys	crude (n 237[a])	−7.2 (−15.9, 2.4)	−6.0 (−17.2, 6.8)	−7.7 (−18.1, 4.0)	−4.3 (−18.0, 11.8)	−0.0 (−11.3, 12.7)	−10.0 (−20.3, 1.7)
	adjusted[b] (n 237[a])	−5.5 (−13.4, 3.1)	−6.7 (−17.5, 5.4)	−6.5 (−17.3, 5.6)	−3.1 (−18.2, 14.8)	0.4 (−10.3, 12.4)	−9.0 (−20.0, 3.4)
Maternal age							
per year	crude (n 236[a])	0.1 (−0.9, 1.1)	0.3 (−0.9, 1.5)	−0.1 (−0.9, 0.7)	0.2 (−1.0, 1.5)	0.5 (−0.4, 1.4)	0.5 (−0.4, 1.4)
	adjusted[c] (n 234[a])	1.6 (−0.1, 3.4)	0.7 (−1.2, 2.5)	1.0 (−0.4, 2.4)	−0.9 (−3.3, 1.6)	−0.1 (−1.4, 1.3)	−0.0 (−1.4, 1.4)
Maternal parity							
per child	crude (n 235[a])	−1.7 (−3.9, 0.5)	0.2 (−3.1, 3.6)	−0.9 (−3.2, 1.4)	1.3 (−2.1, 4.8)	1.8 (−0.5, 4.2)	1.5 (−0.7, 3.8)
	adjusted[d] (n 234[a])	−6.0 (−11.7, −0.0)	−0.9 (−5.8, 4.3)	−1.5 (−5.8, 2.9)	2.2 (−3.6, 8.3)	2.5 (−1.2, 6.4)	0.9 (−3.4, 5.3)
Breastfeeding without supplementary solids							
yes	crude (n 237[a])	1.4 (−9.5, 13.6)	3.3 (−9.1, 17.5)	6.6 (−7.5, 22.8)	−2.5 (−20.0, 18.8)	11.3 (−2.1, 26.5)	4.2 (−6.7, 16.3)
	adjusted[e] (n 237[a])	1.5 (−9.6, 13.9)	1.1 (−11.2, 15.0)	6.7 (−9.9, 26.4)	−1.7 (−19.8, 20.5)	13.7 (−1.2, 30.7)	6.1 (−6.9, 20.8)
Child age at inclusion							
per month	crude (n 237[a])	0.4 (−8.0, 9.6)	−4.5 (−12.7, 4.6)	−1.0 (−9.4, 8.2)	2.4 (−8.1, 14.2)	0.8 (−7.0, 9.4)	2.4 (−5.2, 10.6)
	adjusted[f] (n 237[a])	1.3 (−7.2, 10.5)	−4.3 (−12.7, 4.9)	1.0 (−9.2, 12.4)	2.3 (−7.9, 13.6)	4.2 (−4.2, 13.3)	4.3 (−4.5, 14.0)
Child weight at inclusion							
per kilo	crude (n 237[a])	−4.4 (−10.9, 2.6)	0.9 (−6.8, 9.2)	−3.5 (−8.2, 1.5)	−2.9 (−12.4, 7.7)	−0.9 (−6.7, 5.4)	−3.4 (−8.9, 2.5)
	adjusted[g] (n 237[a])	−3.7 (−10.3, 3.3)	2.1 (−5.7, 10.4)	−2.6 (−7.8, 2.9)	−2.6 (−13.0, 9.0)	−0.8 (−6.3, 5.0)	−2.3 (−8.3, 4.1)

CI: confidence interval.
[a] n is one lower for all PFNA analyses.
[b] Adjusted for child weight.
[c] Adjusted for maternal parity and maternal education.
[d] Adjusted for maternal age and maternal education.
[e] Adjusted for child age and weight at inclusion.
[f] Adjusted for breastfeeding without solids and child weight at inclusion.
[g] Adjusted for child sex, breastfeeding without solids, and child age at inclusion.

house with straw roof, with similar non-significant associations seen for most types of PFAS (Table 4).

3.3. Location of residence

PFAS concentrations in infant serum differed markedly between the three Guinea-Bissau regions included in the study (Biombo, Cacheu and Oio), with infants from Oio having the lowest median serum concentrations of all types of PFAS, though median serum-PFOA concentrations were comparable between Oio and Cacheu (Fig. 3). Children from Biombo had significantly higher serum-concentrations of all types of PFAS compared to children from Oio, while children from Cacheu had significantly higher serum-PFOS, PFDA, PFOS, and PFUnDA concentrations than children from Oio (Table 5). The most pronounced differences were seen for serum-PFOS concentrations, which were 94.1% (95% CI: 52.4, 147.1%) and 81.9% (95% CI: 45.7, 127.1%) higher among children from Cacheu and Biombo, respectively (Table 5).

4. Discussion

Serum PFAS-concentrations in the present study were generally lower than among children in high-income countries (ATSDR, 2021; EFSA CONTAM Panel et al., 2020), but serum-PFDA concentrations were similr to those seen among Danish 18-month-olds (Højsager et al., 2022), and serum concentrations of both PFDA and PFUnDA were higher than among North American 3-5-year-olds (Ye et al., 2018). We found location of residence to be an important predictor of serum-PFAS concentrations among infants in Guinea-Bissau, West Africa, while maternal parity, age, breastfeeding without solid foods, and socio economic status played minor roles.

4.1. Residence location

Infants from the regions of Biombo and Cacheu had significantly higher serum-concentration of most types of PFAS compared to Oio infants. Such regional differences have also been seen between South African communities, with the highest concentrations found in urban and semi-urban areas (Hanssen et al., 2010). In our study, most children lived in areas that would be considered rural as compared to the urban areas of South Africa, but there might still be differences in urbanicity with some of the children living closer to the capital, Bissau. However, there are no known PFAS pollution sources in neither Bissau, Oio, Cacheu, nor Biombo except for the assumed PFAS pollution from the Atlantic Ocean (González-Gaya et al., 2019), the atmosphere, and rainwater (Cousins et al., 2022; Kurwadkar et al., 2022), and as the villages were sampled due to their proximity to Bissau, rainfall is fairly similar across the three regions. The regional differences in child serum-PFAS concentrations in our study could be due to dietary differences between the regions. Fish is a major part of the diet in all regions, and families in Oio are likely to consume more freshwater fish, while families from Cacheu and Biombo might have better access to marine food, due to proximity to the ocean (Fig. 1). PFAS exposure has been associated with intake of marine diet (Dassuncao et al., 2018) and also found in freshwater fish (Barbo et al., 2023). However, PFAS contamination of fresh water fish is likely to depend on the proximity of surface water to manufacturing facilities, landfills, and airports. Thus PFAS concentrations in Guinea-Bissau freshwater fish could be very different from those found in industrialized counties. In a study from four West African countries (Benin, Cameroon, Mali, and Nigeria), PFAS were found in fish samples with a detection rate of 89% for PFOS and PFUnDA and 67% for PFNA, PFDA and perfluorododecanoic acid (PFDoA) (Vaccher et al., 2020). In Cameroon, marine fish contained more PFOS, but slightly less PFNA, PFDA, and PFUnDA than fresh water fish (Vaccher et al., 2020). PFAS concentrations in marine and fresh water fish from Guinea-Bissau are unknown.

In addition to fish, exposure to PFAS in Guinea-Bissau could also occur via contaminated soil and water due to the global spread of PFAS via the ocean, atmosphere, and rainwater. Thus, across Africa, PFAS have been detected in ambient air and water systems (KoneTraore et al., 2021). In addition, Guinea-Bissau's import of pesticides have increased due to population growth and gradual increase in agricultural activities (Domingos Raimundo Lopes, 2018), and the imported pesticides could potentially contain PFAS (United States Environmental Protection Agency (EPA), 2022). Soil contamination can lead to uptake of PFAS in

Table 4
Associations between indicators of socioeconomic status and child serum-PFAS concentrations in linear regression models.

Socio-economics status (SES)		Procent difference in child serum-PFAS concentration (95% CI)					
		PFHxS	PFOS	PFOA	PFNA	PFDA	PFUnDA
Maternal education (ref:none)							
1–11 years	crude (n 237[a])	8.0 (−5.4, 23.4)	13.1 (−3.2, 32.1)	7.5 (−7.7, 25.3)	−5.1 (−19.0, 11.2)	−0.7 (−11.4, 11.4)	−4.0 (−13.2, 6.2)
	adjusted[b] (n 234[a])	3.6 (−10.2, 19.5)	7.7 (−5.6, 23.0)	7.9 (−8.4, 27.1)	−8.5 (−26.6, 14.2)	−0.8 (−10.3, 9.7)	−7.2 (−21.2, 9.4)
	mutually adjusted[c] (n 225[a])	4.5 (−9.7, 20.9)	9.1 (−4.9, 25.2)	11.8 (−5.7, 32.6)	−3.3 (−23.4, 21.9)	2.6 (−8.2, 14.6)	−3.6 (−18.3, 13.9)
unknow	crude (n 237[a])	−7.4 (−21.7, 9.5)	4.0 (−17.9, 31.8)	18.8 (−5.5, 49.4)	−5.4 (−24.5, 18.6)	5.0 (−12.6, 26.3)	−12.1 (−26.8, 5.5)
	adjusted[b] (n 234[a])	−5.7 (−20.5, 11.9)	13.7 (−8.1, 40.8)	21.7 (−6.4, 58.1)	0.5 (−20.9, 27.7)	12.6 (−7.5, 37.0)	−8.3 (−25.5, 12.8)
	mutually adjusted[c] (n 225[a])	−4.2 (−20.8, 16.0)	13.2 (−11.0, 44.0)	22.5 (-7.7, 62.5)	1.7 (−21.0, 30.9)	14.5 (−8.9, 44.0)	−7.6 (−27.2, 17.3)
Roof type (ref: straw roof)							
hard roof	crude (n 233[a])	4.1 (−8.6, 18.6)	−4.5 (−19.6, 13.4)	−8.3 (−20.3, 5.5)	−26.0 (−36.2, −14.3)	−5.7 (−16.9, 7.0)	−8.9 (−18.4, 1.6)
	adjusted[b] (n 230[a])	1.2 (−11.1, 15.1)	−6.6 (−17.2, 5.4)	−7.7 (−19.4, 5.6)	−24.6 (−34.5, −13.3)	−4.7 (−14.0, 5.7)	−10.2 (−19.1, −0.3)
	mutually adjusted[c] (n 225[a])	1.9 (−9.5, 14.9)	−4.3 (−16.7, 10.1)	−7.7 (−19.2, 5.5)	−24.7 (−35.2, −12.4)	-1.1 (−13.8, 13.3)	−7.0 (−18.7, 6.4)
Bathroom in compound							
yes	crude (n 231[a])	−0.9 (−15.5, 16.2)	11.9 (−2.5, 28.5)	10.3 (−8.3, 32.7)	17.1 (−3.2, 41.6)	8.1 (−7.4, 26.1)	11.5 (−6.2, 32.6)
	adjusted[b] (n 228[a])	0.4 (−12.9, 15.7)	14.6 (−2.3, 34.3)	10.2 (−7.8, 31.7)	17.2 (−1.8, 39.8)	8.6 (−4.7, 23.7)	13.7 (−3.4, 33.9)
	mutually adjusted[c] (n 225[a])	2.0 (−10.3, 16.1)	12.6 (−2.9, 30.5)	7.9 (−8.5, 27.2)	7.6 (−10.2, 29.1)	5.5 (−7.6, 20.4)	11.1 (−7.4, 33.3)
Owns a mobile phone							
yes	crude (n 231[a])	2.6 (−11.5, 7.2)	12.1 (−2.8, 29.2)	−0.4 (−9.9, 10.2)	3.1 (−14.9, 24.9)	4.6 (−8.9, 20.1)	0.1 (−12.3, 14.2)
	adjusted[b] (n 228[a])	−5.4 (−14.0, 4.2)	10.2 (−4.7, 27.4)	−0.9 (−10.4, 9.7)	4.6 (−12.3, 24.7)	5.4 (−8.6, 21.5)	0.2 (−13.1, 15.5)
	mutually adjusted[c] (n 225[a])	−6.8 (−15.1, 2.2)	6.8 (−7.6, 23.4)	−3.8 (−13.1, 6.6)	4.8 (−12.0, 24.8)	3.3 (−9.9, 18.5)	0.9 (−11.5, 15.1)
Radio in house							
yes	crude (n231[a])	8.6 (−3.6, 22.4)	6.0 (−9.6, 24.2)	7.9 (−6.6, 24.7)	−13.2 (−30.8, 8.9)	2.0 (−11.0, 16.9)	−2.2 (−12.0, 8.6)
	adjusted[b] (n 228[a])	7.4 (−4.4, 20.6)	5.7 (−9.6, 23.6)	11.2 (−3.8, 28.5)	−9.5 (−28.3, 14.3)	3.0 (−8.1, 15.3)	−4.2 (−12.2, 4.6)
	mutually adjusted[c] (n 225[a])	7.1 (−5.7, 21.7)	5.8 (−10.4, 25.0)	10.2 (−6.1, 29.3)	−7.3 (−25.8, 15.8)	4.1 (−8.8, 18.8)	−0.1 (−9.6, 10.4)
Generator/solar panel in house							
yes	crude (n 232[a])	0.4 (−12.4, 15.1)	3.0 (−13.9, 23.1)	−0.2 (−16.8, 19.7)	−8.3 (−26.1, 13.8)	−6.4 (−20.5, 10.2)	−4.7 (−15.8, 7.7)
	adjusted[b] (n 229[a])	−0.8 (−12.8, 12.8)	2.9 (−15.3, 25.1)	1.6 (−16.5, 23.7)	−5.7 (−26.9, 21.8)	−4.5 (−20.3, 14.5)	−4.5 (−16.6, 9.4)
	mutually adjusted[c] (n 225[a])	−4.0 (−14.7, 8.0)	1.4 (−15.1, 21.1)	−0.3 (−17.3, 20.2)	2.7 (−21.2, 33.7)	−5.0 (−21.0, 14.1)	−0.1 (−13.0, 14.7)
Number of persons sleeping in the bed of the child							
per person	crude (n 237[a])	−4.9 (−10.1, 0.6)	−5.7 (−12.5, 1.7)	−9.3 (−15.3, −2.8)	−1.7 (−13.0, 11.1)	−2.2 (−9.6, 5.7)	5.0 (−1.9, 12.5)
	adjusted[b] (n 234[a])	−3.1 (−9.4, 3.6)	−5.3 (−12.7, 2.8)	−9.6 (−16.0, −2.8)	−3.7 (−15.7, 10.1)	−3.1 (−10.3, 4.6)	5.4 (−2.8, 14.3)
	mutually adjusted[c] (n 225[a])	−3.7 (−11.3, 4.5)	−4.4 (−13.7, 6.0)	−8.5 (−17.2, 1.0)	−4.2 (−15.7, 8.9)	−1.4 (−10.3, 8.4)	5.8 (−3.8, 16.2)
Number of persons sleeping in the bedroom of the child							
per person	crude (n 237[a])	−1.7 (−5.4, 2.3)	−2.3 (−5.4, 0.8)	−2.4 (−5.9, 1.2)	−0.5 (−4.6, 3.9)	−1.0 (−3.9, 2.0)	0.2 (−3.1, 3.6)
	adjusted[b] (n 234[a])	−1.6 (−5.2, 2.2)	−3.9 (−7.2, −0.5)	−3.4 (−6.8, 0.2)	−2.8 (−7.9, 2.6)	−3.0 (−6.0, 0.1)	−0.7 (−3.9, 2.6)
	mutually adjusted[c] (n 225[a])	−1.7 (−5.9, 2.7)	−3.0 (−7.3, 1.6)	−1.7 (−6.3, 3.1)	−0.6 (−6.9, 6.2)	−3.1 (−7.3, 1.3)	−1.2 (−5.5, 3.2)

CI: confidence interval.
[a] n is one lower for all PFNA analyses.
[b] Adjusted for maternal age, parity and residence location.
[c] Adjusted for maternal age, parity, residence location, and other SES factors.

plants, including fruits (Brendel et al., 2018; Costello and Lee, 2020) and roots (Costello and Lee, 2020; Ghisi et al., 2019). Rice, sweet potatoes and fruits are parts of the daily diet in Guinea-Bissau (Domingos Raimundo Lopes, 2018) and these foods may constitute sources of exposure. Geographical differences in agricultural land use may thus explain the regional differences in serum-PFAS concentrations, but we do not have data to support this.

4.2. Maternal age and parity

In accordance with previous studies from North America (Kingsley et al., 2018), Taiwan (Lien et al., 2013) and Sweden (Mamsen et al., 2019), our study showed slightly higher infant serum-concentrations of PFHxS with older maternal age at childbirth. One reason might be that maternal serum-PFAS concentrations tend to increase with age since these chemicals are poorly excreted and thus accumulate in the body (ATSDR, 2021; EFSA CONTAM Panel et al., 2020). Furthermore, older women have a larger placenta, and their children might therefore be exposed to increased transplacental PFAS transmission during fetal life.

Because PFAS are transferred across the placenta and through breastmilk, maternal serum-PFAS concentrations decrease with increasing parity (ATSDR, 2021), and accordingly, infant serum-PFAS concentrations will be lower with higher maternal parity. In our study, higher parity was likewise associated with lower child serum-PFHxS concentrations.

4.3. Breastfeeding, child age, weight at inclusion, and sex

As a consequence of PFAS transfer in breastmilk, several previous studies have shown higher average child serum-PFAS concentrations with increased duration of breastfeeding (Mogensen et al., 2015; Mondal et al., 2014; Papadopoulou et al., 2016). Likewise, we found that infants breastfed without supplementary solid foods at inclusion had higher average concentrations of most PFAS, but the associations were not statistically significant, possibly due to limited variance in data since almost all children in Guinea-Bissau are breastfed.

Although not statistically significant, higher infant weight was associated with lower serum concentrations of most PFAS among the Guinea-Bissau children after adjusting for child age, sex, and breastfeeding, perhaps because smaller bodies exposed to the same amount of chemicals as larger bodies, will result in higher concentrations. However, due to the cross-sectional nature of this study, we cannot exclude the possibility of PFAS exposure having affected infant growth, as prenatal PFAS exposure have been associated with reduced body weight (ATSDR, 2021; Lee et al., 2021).

Though again we did not find significant associations between child age and serum-PFAS concentrations, older children had slightly higher serum concentrations of most PFAS, while taking into regard differences in child weight and breastfeeding. Likewise, previous studies have shown increasing PFAS concentrations in German children from birth to the age of 6 months (Fromme et al., 2010) and in Faroese children from birth to 11 months of age (Mogensen et al., 2015).

Median serum-concentrations of most PFAS were slightly lower

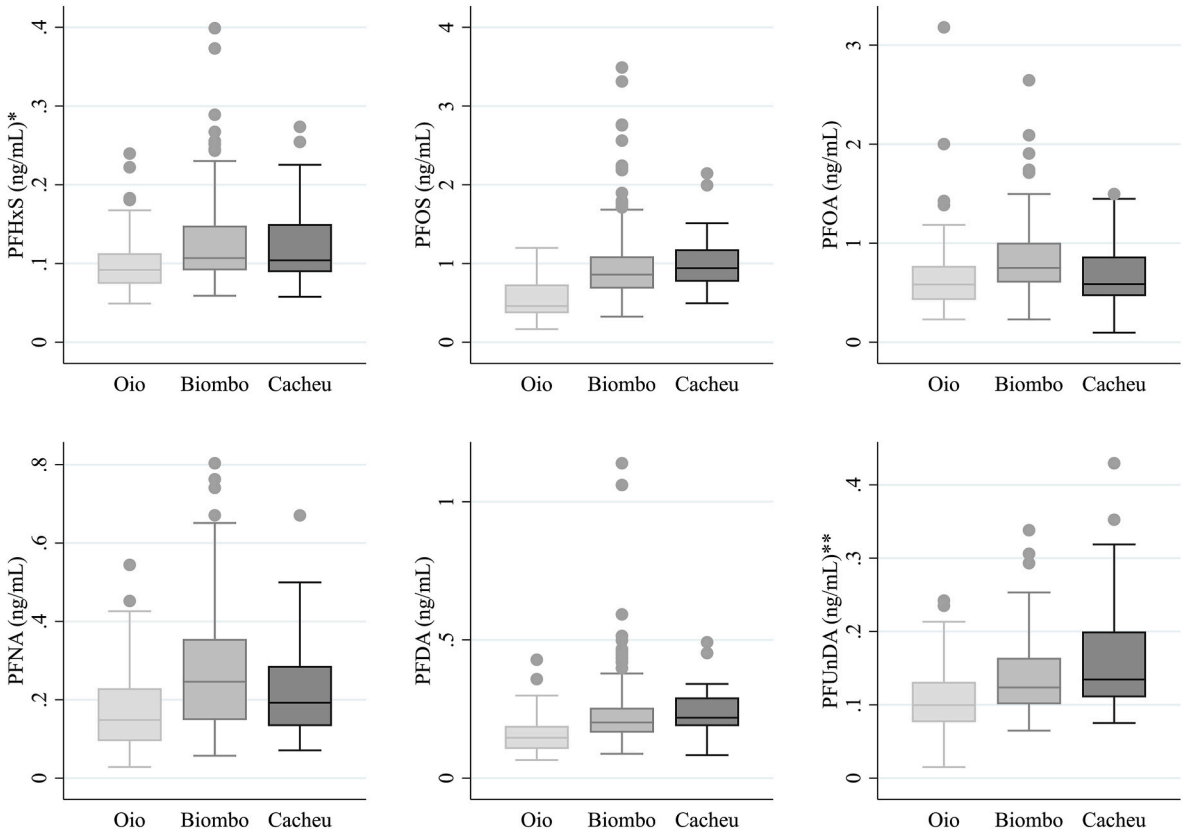

Fig. 3. Child serum-PFAS concentrations (ng/mL) by residence location. The box and whisker plots indicate minimum values, 25th, 50th and 75th percentiles, maximum values and outliers.
*One child from Biombo with a serum-PFHxS concentration of 1.8 ng/mL was excluded from the graph.**One child from Cacheu with a serum-PFUnDA concentration of 4.2 ng/mL was excluded from the graph.

Table 5
Association between residence location and child serum-PFAS concentrations in linear regression models.

		% difference in child serum-PFAS concentration (95% CI)					
		PFHxS	PFOS	PFOA	PFNA	PFDA	PFUnDA
Residence location (ref: Oio)							
Biombo	crude (n 237[a])	28.4 (10.5, 49.2)	81.5 (46.2, 125.2)	24.9 (1.7, 53.4)	63.9 (28.5, 109.0)	44.8 (23.8, 69.4)	26.8 (11.6, 44.2)
	Adjusted[b] (n 237[a])	27.0 (9.0, 48.0)	81.9 (45.7, 127.1)	25.6 (3.0, 53.2)	65.7 (29.6, 111.8)	46.9 (25.1, 72.6)	27.5 (12.2, 44.8)
Cacheu	crude (n 237[a])	23.8 (0.6, 52.3)	95.2 (54.6, 146.4)	−2.6 (−22.9, 23.1)	37.1 (2.7, 83.0)	51.4 (17.3, 95.4)	64.7 (12.5, 141.2)
	Adjusted[b] (n 237[a])	20.7 (−3.4, 50.9)	94.1 (52.4, 147.1)	−3.2 (−22.5, 20.9)	41.4 (5.8, 89.1)	55.9 (21.4, 100.1)	68.8 (14.8, 148.0)

CI: confidence interval.
[a] n is one lower for all PFNA analyses.
[b] Adjusted for maternal education.

among boys, but none of the differences were statistically significant, and existing studies have likewise reported conflicting results on sex-differences. Studies on infants from Spain, Taiwan, and North America (Kingsley et al., 2018; Lien et al., 2013; Manzano-Salgado et al., 2015) have found lower serum-PFAS among boys, while a Danish-Swedish study (Mamsen et al., 2019) and Chinese study (Pan et al., 2017) detected *higher* PFAS concentrations in boys.

4.4. Socioeconomic status (SES)

In high-income countries, high SES has sometimes been associated with higher PFAS concentrations (Colles et al., 2020; Montazeri et al., 2019; Tyrrell et al., 2013). In these countries, employment and income are often used as indicators of SES, but in rural Guinea-Bissau, maternal education, household assets (radio, mobile phone, generator), and housing conditions (compound with bathroom, hard roof on house, number of people in same bed and bedroom), are better indicators of economic wealth. Using these indicators, we mostly found slightly lower serum-PFAS concentrations among children with lower SES indicating that increased SES may provide access to more PFAS-containing consumer products (Ssebugere et al., 2020), even in this setting. However, our results were not consistent across all types of PFAS, and having a straw roof was associated with *higher* serum-PFDA concentrations. This might, however, be a spurious association.

4.5. Strengths and limitations

Our study took advantage of data collected for a previous study (Fisker et al., 2018) and data from the unique health and demographic surveillance system under the Bandim Health Project, which gave us access to detailed data that are otherwise difficult to collect in a rural African setting. However, the aim of the previous study was unrelated to

the aim of this study, and therefore, we did not have information available about all potential predictors of serum-PFAS concentrations. Potential predictors that would have been of interest include maternal diet including intake of marine and freshwater fish, use of PFAS-containing products (clothing, carpets and furniture), and PFAS concentrations in house dust, drinking water, rainwater, fish, crops, and soil. Furthermore, in the present study, PFAS were not measured in maternal serum nor in umbilical cord blood, and we were thus unable to estimate to what extent PFAS was transferred to the infants from the mother via breastfeeding and at the fetal stage via the placenta.

Despite the lack of some information, we were able to identify several predictors of infant serum-PFAS concentrations. This information may be useful when identifying potential confounders in future research on the health effects of PFAS in low-income settings.

5. Conclusion

This study contributes to the limited knowledge about sources of PFAS exposure in African infants. Our results suggest that particularly location of residence was an important determinant among Guinea-Bissau infants, pointing towards important environmental sources due to the global spread of PFAS. Child serum-PFAS concentrations ranged from 0.10 (PFHxS) to 0.77 (PFOS) ng/mL, which is lower than in most Western countries. However, due to the persistent nature of these chemicals, permanent exposure can lead to health problems in children (ATSDR, 2021; EFSA CONTAM Panel et al., 2020; Fenton et al., 2021; Liew et al., 2018). Thus, although serum-PFAS concentrations are relatively low among infants in Guinea-Bissau, the exposure may well have clinical implications (Timmermann et al., 2020), especially if the sources of exposure are not removed or reduced.

Credit statement

Marzanna Marianna Sørensen: Formal analysis, investigation, writing – original draft, Ane Bærent Fisker: Data curation, funding acquisition, investigation, writing – review & editing, Christine Dalgård: Supervision, writing – review & editing, Kristoffer Jarlov Jensen: Methodology, writing – review & editing, Flemming Nielsen: Formal analysis, methodology, writing – review & editing, Christine Stabell Benn: Methodology, writing – review & editing, Philippe Grandjean: Methodology, writing – review & editing, Amalie Timmermann: Conceptualization, funding acquisition, investigation, supervision, writing – review & editing.

Funding

This study was supported by the Danish Health Foundation (Helsefonden) (17-B-0255). In addition, the original trial was supported by the European Union FP7 support for Optimising the Impact and Cost-Effectiveness of Child Health Intervention Programmes of Vaccines and Micronutrients in Low-Income Countries (OPTIMUNISE; Health-F3-2011-261,375).

Ethical approval

The original study was approved by the ethical review committee in Guinea-Bissau (Comité Nacional de Etica na Saúde) and in Denmark (Danish Central Ethical Committee [consultative approval]). Re-use of the blood samples for PFAS analyses were approved by the ethical committee of the Capital region of Denmark (Journal number H-21066975).

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Amalie Timmermann reports financial support was provided by Danish Health Foundation (Helsefonden). Ane B Fisker reports financial support was provided by OPTIMUNISE. Philippe Grandjean reports a relationship with Legal cases involving PFAS exposed populations that includes: paid expert testimony.

Data availability

The authors do not have permission to share data.

References

ATSDR, 2021. Toxicological Profile for Perfluoroalkyls. Agency for Toxic Substances and Disease Registry (ATSDR).
Barbo, N., et al., 2023. Locally caught freshwater fish across the United States are likely a significant source of exposure to PFOS and other perfluorinated compounds. Environ. Res. 220.
Brendel, S., et al., 2018. Short-chain Perfluoroalkyl Acids: Environmental Concerns and a Regulatory Strategy under REACH, vol. 30. Environmental Sciences Europe.
Colles, A., et al., 2020. Perfluorinated substances in the Flemish population (Belgium): levels and determinants of variability in exposure. Chemosphere 242, 125250.
Correia, S., 2017. Statistical Software Components S457874. In: Reghdfe: Stata Module for Linear and Instrumental-Variable/gmm Regression Absorbing Multiple Levels of Fixed Effects. Boston College Department of Economics. https://ideas.repec.org/c/boc/bocode/s457874.html.
Costello, M.C.S., Lee, L.S., 2020. Sources, Fate, and Plant Uptake in Agricultural Systems of Per- and Polyfluoroalkyl Substances. Current Pollution Reports.
Cousins, I.T., et al., 2022. Outside the safe operating space of a new planetary boundary for per- and polyfluoroalkyl substances (PFAS). Environ. Sci. Technol. 56, 11172–11179.
Dassuncao, C., et al., 2018. Shifting global exposures to poly- and perfluoroalkyl substances (PFASs) evident in longitudinal birth cohorts from a seafood-consuming population. Environ. Sci. Technol. 52, 3738–3747.
Domingo, J.L., Nadal, M., 2019. Human exposure to per- and polyfluoroalkyl substances (PFAS) through drinking water: a review of the recent scientific literature. Environ. Res. 177, 108648.
Domingos Raimundo Lopes, N., 2018. Management of soil contaminants in Guinea - Bissau. Int. J. Environ. Monit. Anal. 6, 26.
EFSA CONTAM Panel, et al., 2020. Risk to human health related to the presence of perfluoroalkyl substances in food. EFSA J. 18, e06223.
Fenton, S.E., et al., 2021. Per- and polyfluoroalkyl substance toxicity and human health review: current state of knowledge and strategies for informing future research. Environ. Toxicol. Chem. 40, 606–630.
Fisker, A.B., et al., 2018. A two-center randomized trial of an additional early dose of measles vaccine: effects on mortality and measles antibody levels. Clin. Infect. Dis. 66, 1573–1580.
Free Vector Maps, 2022. Map of Guinea-Bissau with Regions - Single Color 2022.
Fromme, H., et al., 2010. Pre- and postnatal exposure to perfluorinated compounds (PFCs). Environ. Sci. Technol. 44, 7123–7129.
Ghisi, R., et al., 2019. Accumulation of perfluorinated alkyl substances (PFAS) in agricultural plants: a review. Environ. Res. 169, 326–341.
González-Gaya, B., et al., 2019. Vertical transport and sinks of perfluoroalkyl substances in the global open ocean. Environ. Sci. J. Integr. Environ. Res.: Process. Impacts 21, 1957–1969.
Gyllenhammar, I., et al., 2018. Perfluoroalkyl acids (PFAAs) in serum from 2–4-month-old infants: influence of maternal serum concentration, gestational age, breast-feeding, and contaminated drinking water. Environ. Sci. Technol. 52, 7101–7110.
Hanssen, L., et al., 2010. Perfluorinated compounds in maternal serum and cord blood from selected areas of South Africa: results of a pilot study. J. Environ. Monit. 12, 1355–1361.
Højsager, F.D., et al., 2022. Prenatal and early postnatal exposure to perfluoroalkyl substances and bone mineral content and density in the Odense child cohort. Environ. Int. 167, 107417.
IPEN, 2019. PFAS Pollution across the Middle East and Asia.
Kingsley, S.L., et al., 2018. Variability and predictors of serum perfluoroalkyl substance concentrations during pregnancy and early childhood. Environ. Res. 165, 247–257.
KoneTraore, H., et al., 2021. Third Regional Monitoring Report. In: Global Monitoring Plan for Persistent Organic Pollutants under the Stockholm Convention Article 16 on Effectiveness Evaluation. African Region.
Kurwadkar, S., et al., 2022. Per- and polyfluoroalkyl substances in water and wastewater: a critical review of their global occurrence and distribution. Sci. Total Environ. 809, 151003.
Lee, Y.J., et al., 2021. Early-life exposure to per- and poly-fluorinated alkyl substances and growth, adiposity, and puberty in children: a systematic review. Front. Endocrinol. 12, 683297.
Lien, G.-W., et al., 2013. Neonatal–maternal factors and perfluoroalkyl substances in cord blood. Chemosphere 92, 843–850.
Liew, Z., et al., 2018. Developmental exposures to perfluoroalkyl substances (PFASs): an update of associated health outcomes. Current Environmental Health Reports 5, 1–19.

Macheka, L.R., et al., 2022. Occurrence and infant exposure assessment of per and polyfluoroalkyl substances in breast milk from South Africa. Chemosphere 288, 132601.
Mamsen, L.S., et al., 2019. Concentrations of perfluoroalkyl substances (PFASs) in human embryonic and fetal organs from first, second, and third trimester pregnancies. Environ. Int. 124, 482–492.
Manzano-Salgado, C.B., et al., 2015. Transfer of perfluoroalkyl substances from mother to fetus in a Spanish birth cohort. Environ. Res. 142, 471–478.
Manzano-Salgado, C.B., et al., 2016. Variability of perfluoroalkyl substance concentrations in pregnant women by socio-demographic and dietary factors in a Spanish birth cohort. Environ. Int. 92–93, 357–365.
Mogensen, U.B., et al., 2015. Breastfeeding as an exposure pathway for perfluorinated alkylates. Environ. Sci. Technol. 49, 10466–10473.
Mondal, D., et al., 2014. Breastfeeding: a potential excretion route for mothers and implications for infant exposure to perfluoroalkyl acids. Environ. Health Perspect. 122, 187–192.
Montazeri, P., et al., 2019. Socioeconomic position and exposure to multiple environmental chemical contaminants in six European mother-child cohorts. Int. J. Hyg Environ. Health 222, 864–872.
Muller, M.H.B., et al., 2019. Prenatal exposure to persistent organic pollutants in Northern Tanzania and their distribution between breast milk, maternal blood, placenta and cord blood. Environ. Res. 170, 433–442.
Pan, Y., et al., 2017. Novel chlorinated polyfluorinated ether sulfonates and legacy per-/polyfluoroalkyl substances: placental transfer and relationship with serum albumin and glomerular filtration rate. Environ. Sci. Technol. 51, 634–644.
Papadopoulou, E., et al., 2016. Exposure of Norwegian toddlers to perfluoroalkyl substances (PFAS): the association with breastfeeding and maternal PFAS concentrations. Environ. Int. 94, 687–694.
Pelch, K.E., et al., 2019. PFAS health effects database: protocol for a systematic evidence map. Environ. Int. 130, 104851.
Poothong, S., et al., 2020. Multiple pathways of human exposure to poly- and perfluoroalkyl substances (PFASs): from external exposure to human blood. Environ. Int. 134, 105244.
Ssebugere, P., et al., 2020. Environmental levels and human body burdens of per- and poly-fluoroalkyl substances in Africa: a critical review. Sci. Total Environ. 739, 139913.
Sunderland, E.M., et al., 2019. A review of the pathways of human exposure to poly- and perfluoroalkyl substances (PFASs) and present understanding of health effects. J. Expo. Sci. Environ. Epidemiol. 29, 131–147.
Thysen, S.M., et al., 2019. Cohort profile : Bandim health project's (BHP) rural health and demographic surveillance system (HDSS)—a nationally representative HDSS in Guinea-Bissau. BMJ Open 9, e028775.
Timmermann, C.A.G., et al., 2020. Serum perfluoroalkyl substances, vaccine responses, and morbidity in a cohort of Guinea-Bissau children. Environ. Health Perspect. 128, 087002.
Tyrrell, J., et al., 2013. Associations between socioeconomic status and environmental toxicant concentrations in adults in the USA: NHANES 2001–2010. Environ. Int. 59, 328–335.
United States Environmental Protection Agency (EPA), 2022. Per- and Polyfluoroalkyl Substances (PFAS) in Pesticide and Other Packaging, vol. 2022.
Vaccher, V., et al., 2020. Levels of persistent organic pollutants (POPs) in foods from the first regional Sub-Saharan Africa Total Diet Study. Environ. Int. 135, 105413.
Winkens, K., et al., 2017. Early life exposure to per- and polyfluoroalkyl substances (PFASs): a critical review. Emerging Contaminants 3, 55–68.
Ye, X., et al., 2018. Per- and polyfluoroalkyl substances in sera from children 3 to 11 years of age participating in the National Health and Nutrition Examination Survey 2013–2014. Int. J. Hyg Environ. Health 221, 9–16.