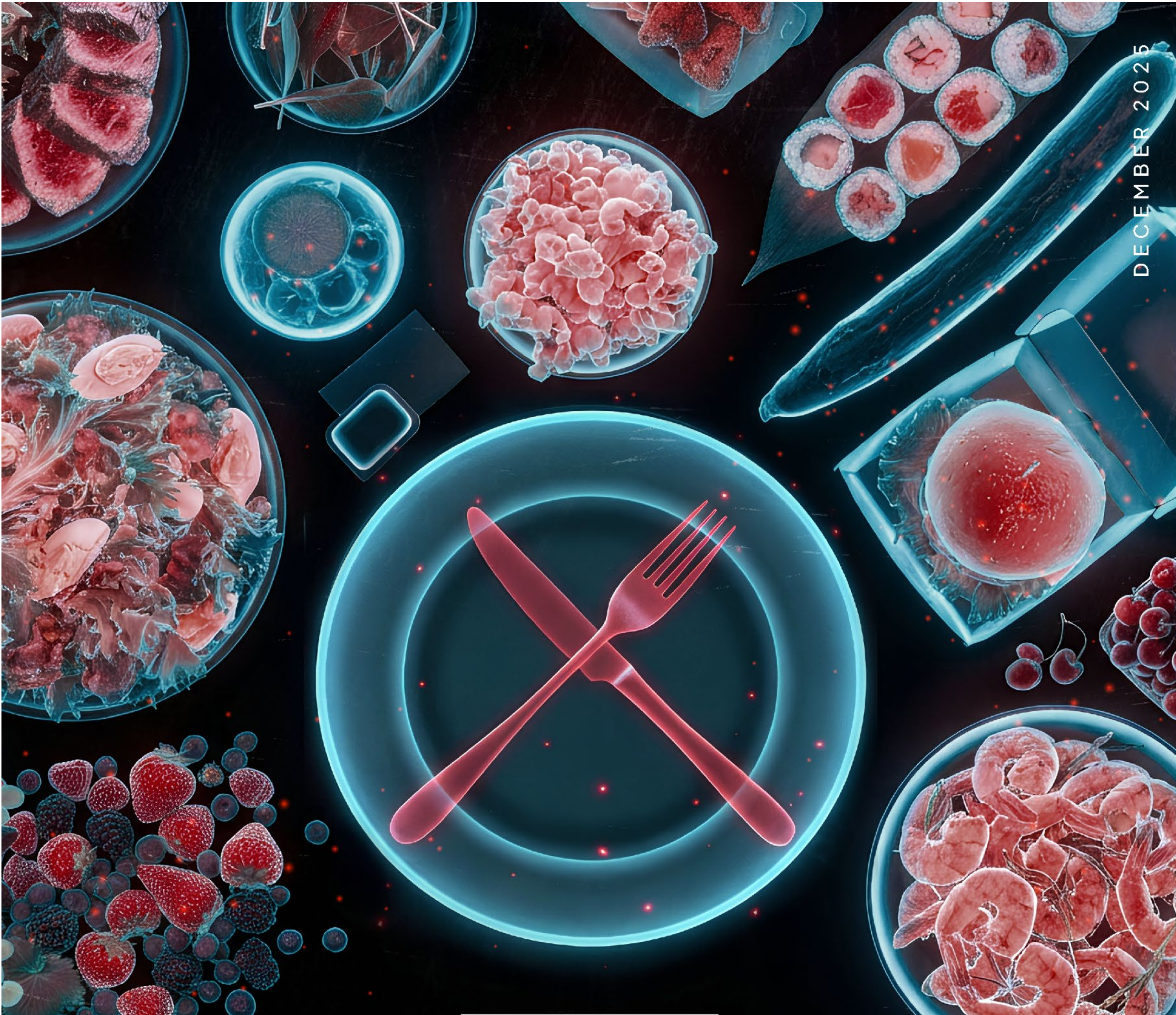
DECEMBER 2025



SYSTEMIQ

Invisible Ingredients

Tackling toxic chemicals in the food system

Technical annex

I: Imperative for change—human health

Human health cost estimates

This sub-section presents a mapping of toxic chemicals, associated health outcomes, and available cost estimates. Due to significant data gaps and varying methodologies, ranging from direct medical costs to indirect productivity losses and intangible welfare impacts, the estimates do not comprehensively capture the full spectrum of adverse health effects. The figure below illustrates this mapping, indicating where cost estimates are drawn directly from published studies and where extrapolations have been applied to fill gaps.

- ✓✓ **Evidenced and costed** (direct **and** indirect cost)
- ✓ **Evidenced and costed** (direct **or** indirect cost)
- ⚠ **Health outcome** Toxic chemical pair evidenced but not costed
- ✗ **Health outcome** Toxic chemical pair is not evidenced
- (extrapolated) Extrapolated costs

Health outcome categories[1]	Health outcome	Phthalate	Bisphenol	Pesticide	PFAS
Reproductive system	Infertility (male[2] / couple)	✓	⚠ (extrapolated)	⚠ (extrapolated)	✓
	Ovarian reserve[3]	⚠	⚠	⚠	⚠
	Uterus fibroid	✗	⚠	✓	⚠
	Endometriosis	✓	⚠ (extrapolated)	⚠ (extrapolated)	✓✓
Cancer	Kidney cancer	✗	⚠	⚠	✓✓
	Testicular cancer	✗	✗	⚠	✓✓
	Breast cancer	⚠ (extrapolated)	⚠ (extrapolated)	⚠ (extrapolated)	✓✓
	Prostate cancer	✗	⚠ (extrapolated)	⚠ (extrapolated)	⚠ (extrapolated)
	Liver cancer	✗	✗	⚠	⚠
Endocrine diseases	Hypothyroidism	✗	⚠	✗	✓✓
	PCOS	⚠ (extrapolated)	⚠ (extrapolated)	⚠ (extrapolated)	✓
	Diabetes	✓	⚠	✓	✓
	Gestational diabetes	✗	⚠	⚠	✓✓
Nutritional / metabolic Diseases	Adult obesity	✓✓	⚠ (extrapolated)	⚠ (extrapolated)	✓✓
	Childhood obesity	✗	✓	✓	✓
Cardiovascular diseases	Hypertension / cardiovascular	✓✓[4] (extrapolated)	✓	⚠ (extrapolated)	⚠ (extrapolated)
Respiratory diseases	Pneumonia	✗	✗	⚠	✓✓
Genitourinary diseases	Renal dysfunction	⚠ (extrapolated)	⚠ (extrapolated)	⚠ (extrapolated)	⚠ (extrapolated)
Neurodevelopmental and developmental disorders	Intellectual disability	⚠	⚠	✓✓	⚠
	Birth defects	⚠	⚠	⚠	✓✓[5]
Immune system diseases	Immunotoxicity	✗	⚠	⚠	⚠
	Number of studies analysed	20+	10+	25+	30+

Figure 1. Overview of available cost estimates by toxic chemical-health outcome pairs

Below is the list of key literature sources used in the analysis. All cost estimates were adjusted for inflation and converted to 2023 US dollars to ensure consistency and comparability.

Table 1. Sources of Cost Estimates by Toxic Chemical and Health Outcome

Health Outcome Category	**Health Outcome**	**Original Country / Region**	**Toxic Chemical Group**	**Study Name**	**Remarks**
Developmental	IQ Point Loss and Intellectual Disability	United States of America	Pesticide	Attina et al. (2016)	Costs were extrapolated to the EU using U.S. figures, as the U.S. estimates are based on organophosphates that have already been banned in the EU. Previous EU estimates do not reflect this ban and therefore overstate current costs, which are expected to be lower. The U.S. figure, by contrast, represents costs under a context of partial restrictions.
Metabolic	Childhood obesity	European Union	Pesticide	(Trasande et al., 2016)	
Endocrine	Adult diabetes	European Union	Pesticide	(Trasande et al., 2016)	
Reproductive	Uterine fibroid	European Union	Pesticide	(Trasande et al., 2016)	
Developmental	Low birth-weight	United States of America	PFAS	(Obsekov et al., 2023)	Scaled to EU using population multiplier, adjusted for currency difference, inflation and population differences.
Metabolic	Childhood obesity	United States of America	PFAS	(Obsekov et al., 2023)	Scaled to EU using population multiplier, adjusted for currency difference, inflation and population differences.
Cancer	Kidney cancer	United States of America	PFAS	(Obsekov et al., 2023)	Scaled to EU using population multiplier, adjusted for currency difference, inflation and population differences.
Cancer	Testicular cancer	United States of America	PFAS	(Obsekov et al., 2023)	Scaled to EU using population multiplier, adjusted for currency difference, inflation and population differences.
Endocrine	Hypothyroidism	United States of America	PFAS	(Obsekov et al., 2023)	Scaled to EU using population multiplier, adjusted for currency

					difference, inflation and population differences.
Metabolic	Adult obesity	United States of America	PFAS	(Obsekov et al., 2023)	Scaled to EU using population multiplier, adjusted for currency difference, inflation and population differences.
Endocrine	Type II diabetes	United States of America	PFAS	(Obsekov et al., 2023)	Scaled to EU using population multiplier, adjusted for currency difference, inflation and population differences.
Endocrine	Gestational diabetes	United States of America	PFAS	(Obsekov et al., 2023)	Scaled to EU using population multiplier, adjusted for currency difference, inflation and population differences.
Reproductive	Endometriosis	United States of America	PFAS	(Obsekov et al., 2023)	Scaled to EU using population multiplier, adjusted for currency difference, inflation and population differences.
Endocrine	PCOS	United States of America	PFAS	(Obsekov et al., 2023)	Scaled to EU using population multiplier, adjusted for currency difference, inflation and population differences.
Reproductive	Couple infertility	United States of America	PFAS	(Obsekov et al., 2023)	Scaled to EU using population multiplier, adjusted for currency difference, inflation and population differences.
Cancer	Breast cancer	United States of America	PFAS	(Obsekov et al., 2023)	Scaled to EU using population multiplier, adjusted for currency difference, inflation and population differences.
Respiratory	Pneumonia	United States of America	PFAS	(Obsekov et al., 2023)	Scaled to EU using population multiplier, adjusted for currency difference, inflation and population differences.
All Cause	All Cause Mortality	United States of America	Phthalate	(Trasande et al., 2022)	Scaled to EU using population multiplier, adjusted for currency difference, inflation and population differences.
Metabolic	Adult obesity	European Union	Phthalate	(Trasande et al., 2016)	
Endocrine	Adult diabetes	European Union	Phthalate	(Trasande et al., 2016)	

Reproductive	Endometriosis	European Union	Phthalate	(Trasande et al., 2016)	
Reproductive	Male infertility	European Union	Phthalate	(Trasande et al., 2016)	
Metabolic	Childhood obesity	European Union	Bisphenol	(Trasande et al., 2016)	
Circulatory	Coronary Heart Disease	United States of America	Bisphenol	(Landrigan et al., 2023)[i]	Scaled to EU using population multiplier, adjusted for currency difference, inflation and population differences.
Circulatory	Stroke	United States of America	Bisphenol	(Landrigan et al., 2023)[ii]	Scaled to EU using population multiplier, adjusted for currency difference, inflation and population differences.

To extrapolate costs for health outcomes associated with a toxic chemical but not yet costed, attribution factors derived from outcomes with existing cost estimates were applied. Where the literature indicates an association between a toxic chemical and a particular health outcome, and overall disease costs for that outcome have been estimated, the following formula was used:

Estimated cost = Known EU health cost × Attribution factor

For the attribution factor, the 75th percentile (P75) was used as a conservative upper estimate. This value is likely conservative, given the attribution rates refer only to a subset of the toxic chemicals in each group and costs (mostly direct medical costs). We also considered P50 as a low estimate, and an average of P50 and P75. This method was applied only to health outcomes without existing cost estimates to ensure that no costs were double counted. Of course, only considering already costed health outcomes (i.e., excluding the extrapolations) implicitly assumes that the impact of all other known or suspected harms is zero.

The table below provides the assumed P50 and P75 by toxic chemical group.

Table 2. P50 and P75 attribution rates used to extrapolate health cost

Group	P50	P75
Pesticides	0.2%	2.7%
PFAS	3.1%	6.8%
Phthalates	0.7%	5.0%
Bisphenols	3.9%	7.6%

[i] While Cropper et al. (2024) provides more recent estimates for health impacts of bisphenols, the paper uses a different methodology from the other papers considered (employing value of statistical life), resulting in significantly higher costs. To ensure more like-to-like comparison, Landrigan et al. (2023) was used.
[ii] While Cropper et al. (2024) provides more recent estimates for health impacts of bisphenols, the paper uses a different methodology from the other papers considered (employing value of statistical life), resulting in significantly higher costs. To ensure more like-to-like comparison, Landrigan et al. (2023) was used.

Regional Extrapolation:

The analysis is anchored in 2015 exposure data, with Europe used as the baseline, given the most robust based estimates of costs. Costs are then extrapolated to other regions using three multipliers: attribution factor, welfare costs, and population. For the United States, robust cost estimates are available and were used directly, with multipliers applied only to provide indicative checks. In regions with limited data, extrapolations are based on combinations of available evidence, as shown in Table 3 below. The attribution factors and welfare cost multipliers are derived from the global cost estimates presented in (Cropper et al., 2024), though coverage is incomplete (for example, only three countries are represented for Asia), which may lead to under- or overestimation in regions with high internal variability. Whereas the population multipliers are based on the 2015 population data by the United Nations.

Regionally, estimates of costs vary with attribution rates of disease to toxic chemicals, population size, and the welfare cost of disease. While biomonitoring data suggest only moderate differences in exposures between regions, disparities in population scale and welfare impacts account for most of the variations in costs. Looking forward, the burden is expected to rise rapidly in developing regions as populations and economies grow, amplifying health costs and placing the heaviest strain on communities least able to absorb them if action is not taken.

Table 3. Regional extrapolation multiplier

Region	Attribution Factor	Welfare Cost	Population	Remarks
Africa	0.8	0.1	3	
Asia	0.8	0.5	10	
Europe	1.0	1.0	1.7	Reference group, multiplier applies for population only to scale from EU 27 to all of Europe.
Latin America	0.7	0.8	1.4	No data—attribution factor multiplier assumes the same as Asia (only) as exposure is among the lowest. Welfare cost multiplier is average between Latin America and Asia.
North America	0.7	1.4	1	The population multiplier is applied to scale results from the US to the broader North American region. The AF multiplier is used solely for cost extrapolation, with primary cost data sourced from US-based studies. The cost multiplier is not applied to scale costs up to North America; rather, it is used to adjust (scale down) US costs to European levels.
Oceania	1.0	1.0	0.1	No data—assumes the same as Europe.

Estimated cost attribution to the food system:

The analysis attributes cost specifically to the food system, applying the multipliers outlined below. The percentage of attribution to food-related exposures is drawn either from existing literature or, where direct estimates are unavailable, from indicative values as detailed in the table.

Table 4. Food system attribution assumptions

No	Toxic Chemical Group	Dietary Exposure	Min. Food System Attribution	Max. Food System Attribution	Avg. Food System Attribution
1	Pesticides	**Very High**	80%	100%	90%
	1. Study findings: (Hyland et al., 2019) finds 37-95% reduction in pesticide concentration found in urine when adopting organic diet 2. Usage: Largely used for crop protection for direct application on produce, with exception of usage in biofuel and textile (cotton) 3. Route to food system: residues on produce and potential leakage into irrigation and drinking water 4. Human exposure: ingestion of treated food/water				
2	PFAS	**High to Very High**	60%	100%	80%
	1. Study findings: multiple studies estimated 55-100% human exposure of PFOS and PFOA comes from diet / food packaging / drinking water 2. Usage: Used in food contact materials to provide grease-proof barrier and crop protection (insecticides and fungicides) for direct application on produce 3. Route to food system: residues on produce, migration from packaging and bioaccumulation in water system leading to contaminated fish, meat and crops 4. Human exposure: ingestion of contaminated food and drinking water				
3	Phthalates	**High**	60%	80%	70%
	1. Usage: plasticizers in PVC films used for floorings, wire coatings, medical tubing, toys and some food packaging. Packaging accounts for ~20% of global PVC demand 2. Route to food system: migration to foods during storage and heat treatment 3. Human exposure: dietary ingestion of contaminated food 4. ECHA report states phthalates exposure from food accounts for 75% of total exposure				
4	Bisphenols	**High**	60%	80%	70%
	1. Study findings: (Trasande, 2014) found 66% reduction in BPA concentration found in urine when removing BPA exposure from diet 2. Usage: epoxy-resin can linings for canned foods, polycarbonate drink and food containers 3. Route to food system: migrates into food/beverage, accentuated by heat or long storage 4. Human exposure: dietary ingestion of contaminated food				

II: Toxic chemical exposure across regions

This section presents the regional exposure data used in the analysis, including all available datasets and corresponding remarks. The tables below compile the most recent publicly available biomonitoring and environmental concentration data for each toxic chemical group, supplemented where necessary with literature-based estimates. Due to limited temporal alignment across studies, the exposure data should be interpreted as indicative of relative exposure levels rather than precise contemporaneous values. Data years vary across sources, and in many cases represent the latest measurements available for each region.

For Europe, exposure data are typically drawn from a single representative country dataset with robust coverage. North America includes data from both the United States and Canada, normalized using a population-weighted average. For Oceania, data primarily reflect Australia, which provides the region's most comprehensive monitoring. For Latin America, Africa, and Asia, exposure data for bisphenols and phthalates are taken from (Acevedo, Kahn, Pierce, Carrasco, et al., 2025) and (Acevedo, Kahn, Pierce, Albergamo, et al., 2025), while data for PFAS and pesticides are more limited and drawn from a small number of country-level studies. In several cases, regional estimates are therefore based on one or two countries and should be regarded as indicative rather than fully representative.

It is important to note that the exposure data presented here reflect only specific subclasses within each toxic chemical group. For bisphenols, only BPA concentrations are included; for phthalates, estimates are based on a combination of four metabolites, MEHHP, MEOHP, MECPP, and MEHP, representing exposure to DEHP. PFAS exposure includes only PFOS, PFOA, PFHxS, and PFNA, while pesticides data cover pyrethroids as a representative class, which has not been widely restricted in any region. As such, these results capture only a subset of total exposure, and overall population exposure to each toxic chemical group is likely higher than indicated.

Tables 5 to 10 present the exposure data used in this analysis for each region, along with corresponding remarks on data sources, coverage, and representativeness.

Table 5. Europe toxic chemicals exposure data

Group	Sub-Group	Unit	Value	Collection Year	Remarks
Bisphenols	BPA	ng/mL urine	1.3	2019	Based on Danish biomonitoring data
Phthalates	DEHP (MEHHP)	ng/mL urine	1.9	2022	Based on German biomonitoring data
Phthalates	DEHP (MEOHP)	ng/mL urine	1.2	2022	
Phthalates	DEHP (MECPP)	ng/mL urine	2.1	2022	
Phthalates	DEHP (MEHP)	ng/mL urine	0.6	2022	
PFAS	PFOS	ng/mL blood serum	1.8	2019	Based on German biomonitoring data
PFAS	PFOA	ng/mL blood serum	1.9	2019	
PFAS	PFHxS	ng/mL blood serum	0.5	2019	
PFAS	PFNA	ng/mL blood serum	0.4	2019	
Pesticides	3-PBA (pyrethroids)	ng/mL urine	0.16	2017	Based on Swedish biomonitoring data

Table 6. North America toxic chemicals exposure data

Group	Sub-Group	Unit	Value	Data Collection Year	Remarks
Bisphenols	BPA	ng/mL urine	1.06	2016 for US; 2018-2019 for Canada	Weighted average value based on population size
Phthalates	DEHP (MEHHP)	ng/mL urine	4.60	2018 for US; 2018-2019 for Canada	
Phthalates	DEHP (MEOHP)	ng/mL urine	3.01		
Phthalates	DEHP (MECPP)	ng/mL urine	7.11		
Phthalates	DEHP (MEHP)	ng/mL urine	0.09		
PFAS	PFOS	ng/mL blood serum	4.08	2018 for US; 2018-2019 for Canada	
PFAS	PFOA	ng/mL blood serum	1.40		
PFAS	PFHxS	ng/mL blood serum	1.05		
PFAS	PFNA	ng/mL blood serum	0.41		
Pesticides	3-PBA (pyrethroids)	ng/mL urine	0.73	2017-2018 for US; 2018-2019 for Canada	

Table 7. Latin America and the Caribbean toxic chemicals exposure data

Group	Sub-Group	Unit	Value	Data Collection Year
Bisphenols	BPA	ng/mL urine	4.95	2023
Phthalates	DEHP (MEHHP)	ng/mL urine	12.26	2023
Phthalates	DEHP (MEOHP)	ng/mL urine	3.50	2023
Phthalates	DEHP (MECPP)	ng/mL urine	32.47	2023
Phthalates	DEHP (MEHP)	ng/mL urine	2.70	2023
PFAS	PFOS	ng/mL blood serum	6.70	Not specified
PFAS	PFOA	ng/mL blood serum	3.00	Not specified
PFAS	PFHxS	ng/mL blood serum	1.20	Not specified
PFAS	PFNA	ng/mL blood serum	0.05	Not specified
Pesticides	3-PBA (pyrethroids)	ng/mL urine	n/a	No Data

Table 8. Africa toxic chemicals exposure data

Group	Sub-Group	Unit	Value	Data Collection Year
Bisphenols	BPA	ng/mL urine	5.61	2023
Phthalates	DEHP (MEHHP)	ng/mL urine	15.83	2023
Phthalates	DEHP (MEOHP)	ng/mL urine	9.02	2023
Phthalates	DEHP (MECPP)	ng/mL urine	62.40	2023
Phthalates	DEHP (MEHP)	ng/mL urine	2.34	2023
PFAS	PFOS	ng/mL blood serum	n/a	No data
PFAS	PFOA	ng/mL blood serum	n/a	No data
PFAS	PFHxS	ng/mL blood serum	n/a	No data
PFAS	PFNA	ng/mL blood serum	n/a	No data
Pesticides	3-PBA (pyrethroids)	ng/mL urine	n/a	No data

Table 9. Asia toxic chemicals exposure data

Group	Sub-Group	Unit	Value	Data Collection Year	Remarks
Bisphenols	BPA	ng/mL urine	6.36	2023	
Phthalates	DEHP (MEHHP)	ng/mL urine	14.66	2023	
Phthalates	DEHP (MEOHP)	ng/mL urine	6.02	2023	
Phthalates	DEHP (MECPP)	ng/mL urine	20.79	2023	
Phthalates	DEHP (MEHP)	ng/mL urine	5.99	2023	
PFAS	PFOS	ng/mL blood serum	10.00	2013-2021	Eastern and Southeastern Asia data
PFAS	PFOA	ng/mL blood serum	3.50	2013-2021	Eastern and Southeastern Asia data
PFAS	PFHxS	ng/mL blood serum	2.00	2013-2021	Eastern and Southeastern Asia data
PFAS	PFNA	ng/mL blood serum	0.70	2013-2021	Eastern and Southeastern Asia data
Pesticides	3-PBA (pyrethroids)	ng/mL urine	5.15	Various	China, Japan, South Korea and Thailand data (weighted average based on population)

Table 10. Oceania toxic chemicals exposure data

Group	Sub-Group	Unit	Value	Data Collection Year	Remarks
Bisphenols	BPA	ng/mL urine	2.98	2023	Based on Australia data
Phthalates	DEHP (MEHHP)	ng/mL urine	12.13	2023	
Phthalates	DEHP (MEOHP)	ng/mL urine	5.57	2023	
Phthalates	DEHP (MECPP)	ng/mL urine	16.58	2023	
Phthalates	DEHP (MEHP)	ng/mL urine	-	2023	
PFAS	PFOS	ng/mL blood serum	1.12	2022-2024	
PFAS	PFOA	ng/mL blood serum	0.83	2022-2024	
PFAS	PFHxS	ng/mL blood serum	0.56	2022-2024	
PFAS	PFNA	ng/mL blood serum	n/a	No data	Not detected
Pesticides	3-PBA (pyrethroids)	ng/mL urine	n/a	No data	No data

III: Imperative for change—fertility

The fertility analysis examines the impact of toxic chemical exposures on age-specific fertility rates across five regions: Europe, North America, Latin America, Africa, and Asia. Given significant data limitations, this is a high-level assessment using scientific assessments to estimate the combined impact of exposure to the four groups of toxic chemicals. The principal metric evaluated is the number of missing births attributable to toxic chemical exposure, compared with a baseline scenario. The analysis draws on UN population projections, using data on the number of females by age group, age-specific fertility rates, survival rates, and total births.

Three scenarios are explored: **a) low-exposure case**, assuming all regions experience minimal toxic chemical exposure; **b) central case**, based on the latest available regional exposure data; and **c) a high-exposure case**, assuming uniformly elevated exposure levels across all regions. Below are the assumptions used under the central case scenario:

Table 11. Assumptions of exposure levels by region and toxic chemical group

Country/Region	Bisphenols	Phthalates	PFAS	Pesticides
Europe	High	Low	Medium	Low
North America	High	Low	High	Low
Latin America	High	Low	Low	Medium
Africa	High	Low	Low	High
Asia	High	Low	High	High

Exposure levels vary by region, though the underlying data are patchy, particularly outside the EU and United States, and are not drawn from the same reference year. To ensure comparability, exposure concentrations are benchmarked against the EU safety threshold (or otherwise specified): values above the threshold are classified as high, values below 50% of the threshold as low, and values within 50% of the threshold as medium. While there is evidence that these chemicals are not safe at any level, partially reflected in a continual lowering of thresholds as more research emerges, this is the most objective threshold we have been able to establish. In absence of our conservative estimate, the current default is to exclude any impact from toxic chemicals on demographic modelling.

Data for Africa and Latin America remain especially limited, creating greater uncertainty in regional estimates, actual exposures may be higher or lower than indicated. For PFAS, available biomonitoring data typically capture only a subset of compounds, while many others remain unmeasured. Given that PFAS are so diverse, highly persistent and bioaccumulative, total human exposure is likely underestimated. While most studies show declining trends for identified PFAS in general populations, some suggest an increase in the relative contribution from presently unidentified PFAS (T. Miaz et al., 2020). For bisphenols, the exposure assessment reflects the newly lowered tolerable daily intake (TDI) established by the European Food Safety Authority (EFSA), which significantly reduces the threshold and therefore results in higher relative exposure values compared to earlier benchmarks.

Exposure Level Insights

PFAS exposures are generally low in Africa and Latin America, potentially reflecting lower use and their distance from major manufacturing sites, but high in Asia, where production is concentrated. Within Asia, exposures vary by sub-region, with Southeast Asia generally lower than East Asia; however, due to limited data availability, Asian estimates are largely based on East Asia, which may lead to regional overestimation.

For pesticides, exposure data remain highly fragmented and are therefore approximated using pesticide use patterns across regions.

Bisphenol and phthalate exposure data draw on two papers by Acevedo et al. (2025) for Latin America, Asia, Africa, and Oceania, and on NHANES and EU biomonitoring for the U.S. and EU. Bisphenol exposures are consistently high relative to the new EU safety threshold, with the EU reporting the lowest levels and Africa the highest, whereas phthalate exposures remain well below the threshold across most regions.

Penalties on Age Specific Fertility Rates

Table 12. Assumption of penalties on age specific fertility rates by exposure level across toxic chemicals

Group	Exposure Level	20_24	25_29	30_34	35_39	40_44	45_49
Pesticides	Low	0.5%	0.5%	0.4%	0.4%	0.3%	0.3%
	Medium	1.0%	1.0%	0.8%	0.8%	0.5%	0.5%
	High	2.0%	2.0%	1.5%	1.5%	1.0%	1.0%
PFAS	Low	0.5%	0.5%	0.4%	0.4%	0.3%	0.3%
	Medium	1.0%	1.0%	0.8%	0.8%	0.5%	0.5%
	High	2.0%	2.0%	1.5%	1.5%	1.0%	1.0%
Phthalates	Low	1.0%	1.0%	0.8%	0.8%	0.5%	0.5%
	Medium	1.5%	1.5%	1.1%	1.1%	0.8%	0.8%
	High	3.0%	3.0%	2.3%	2.3%	1.5%	1.5%
Bisphenols	Low	0.5%	0.5%	0.4%	0.4%	0.3%	0.3%
	Medium	1.5%	1.5%	1.1%	1.1%	0.8%	0.8%
	High	2.5%	2.5%	1.9%	1.9%	1.3%	1.3%

We anchor each chemical group based on studies that report fecundability ratios (FR, a per-cycle probability of conception relative to unexposed). Note, we also conducted an analysis focused on the correlation between chemical exposure and falling sperm counts. This resulted in a higher estimate of missing births. However, we were unable to consolidate male and female exposure in a consistent way that avoids risks of double-counting, so are presenting the FR analysis as a conservative baseline. Below are the FR used in the analysis alongside its sources:

Table 13. Reported Fecundability ratio due to toxic chemicals exposure in general population

Group	FR	Source
Pesticides	0.91	(Hu et al., 2018)—Average of organophosphate and pyrethroids adjusted FR (based on Q2 and Q3 FR)
PFAS	0.91	(Wang et al., 2023)—average of PFOA and PFOS ratio
Phthalates	0.78	(Thomsen et al., 2016)
Bisphenols	0.88	(Philips et al., 2018)

Adverse changes are derived from FRs reported in human time-to-pregnancy studies for PFAS, pesticides, phthalates, and bisphenols. A lower FR corresponds to increased harm, with each group-level FR translated into an age-specific fertility rate (ASFR) adjustment that incorporates fixed age attenuations. Class effects are combined multiplicatively, with the overall reduction per age band capped at 10%. The evidence base generally indicates that phthalates have the strongest adverse association with fecundability, while PFAS and bisphenols also show adverse but smaller, and relatively similar, effects. To reflect this, group changes are maintained within a narrow, conservative range. These adverse changes provide the inputs for adjusting ASFRs (and thus projected births) relative to the UN baseline figures.

IV: Imperative for change—ecology

This sub-section presents the methodology for costing and quantifying impacts on ecological health due to toxic chemicals. At the time of writing, there is no uniform quantification method to value nature. Therefore, varying methods are used as a proxy to put a value on nature and quantify ecosystem losses.

Due to significant data gaps, ecological health impacts are only assessed for pesticides and PFAS. Although literature findings do support ecological health impacts from phthalates and bisphenols, no case studies and methodologies were found that could be used as a relevant proxy to cost these impacts.

We quantify ecological health costs via two complementary models:

- **A. Agricultural productivity losses (pesticides only)**
- **B. Drinking-water treatment costs (pesticides and PFAS)**

Both models produce **annual costs** expressed in **constant 2024 USD**, and both intentionally constitute **lower bounds** given the exclusions noted below.

A) Agricultural productivity losses

Assessed toxic chemicals: pesticides

We estimate a global annual cost for pesticide-related agricultural losses using (Pimental, 2005) as the base. The study's total loss is first converted to 2024 USD (CPI only). We then scale directly to the global level by multiplying the base cost by the ratio of global pesticide use (tonnes ai) to the study's reference pesticide volume (tonnes ai), implicitly assuming a constant per-kg ai impact worldwide. The resulting figure is fully attributed to the food system (recognizing that the source includes some non-food crops).

This approach is intentionally conservative: it captures losses linked to pollinator decline, loss of natural enemies, crop damage/growth suppression, and pesticide resistance, while excluding soil-health decline, non-target vegetation damage, and bioaccumulation effects. Key caveats are transferability of per-kg impacts from U.S. conditions to other regions and the use of static parameters (no escalation in incidence or price beyond CPI).

B) Drinking water treatment costs

Assessed toxic chemicals: pesticides and PFAS

We estimate a global annual cost to upgrade municipal drinking-water treatment to current safety limits for pesticides and PFAS. Per-capita/system cost ranges from Bommelaer & Devaux (2011, France) for pesticides and (Goldenman et al., 2019) for EU & U.S. for PFAS are converted to 2024 USD via CPI + PPP, with a one-off energy/reagent uplift. Global costs are calculated as: Global cost = per-capita treatment cost × (global population × assumed exposed share). PFAS exposure is modeled as a scenario band; pesticide exposure is the share of population served by utilities requiring pesticide-treatment upgrades. All costs are allocated to the food system (production/processing water demand).

Notes & caveats:

- We use France's safety limit as the compliance benchmark and apply it globally, while we acknowledge that national standards differ.
- Results reflect meeting current limits, not full removal. Unit costs are EU-based and held constant after CPI/PPP/uplift (no regional price differentiation, no learning).
- The boundary is treatment plants only—no monitoring, source clean-ups, supply replacement, or remediation of rivers/soils/sediments.
- No regional differences in pollution or concentration profiles are modeled; exposure shares are scenario assumptions. Estimates are thus conservative lower bounds.

Identified caveats and uncertainties

- **Chemical scope gap—**cost models exclude bisphenols and phthalates altogether; figures capture only pesticides and PFAS.
- **Partial cost ledger—**many impacts (biodiversity loss, long-term soil degradation, human-health co-benefits, etc.) are unpriced, so the headline numbers represent just a fraction of total harm and almost certainly under-estimate true societal costs
- **Exclusion of reinforcement loops—**models do not capture the complete loop (except pesticide resistance) whereby ecosystem damage drives greater use of toxic chemicals, compounding future costs
- **Static assumptions on magnitude**—key parameters such as *share of population exposed, percentage crop damage,* and other incidence rates are frozen at the time of paper's publication levels, even though they may have changed—and may keep changing—over time
- **Static snapshots**—contamination levels, treatment prices and ecological damages derived from the sources are held constant; in reality they may rise over time
- **Regional heterogeneity—**applying national averages (France, U.S.) to EU and global scales masks spatial variability in exposure, regulation and remediation capacity
- **"Unknown unknowns"**—evidence remains patchy; significant research gaps mean additional cost categories may surface as the science matures

V: Pesticides marginal abatement cost curve

This annex sets out the methodology used to assess pesticide-use reduction potential and costs across four pathways. It describes the analytical framework, data sources, and key assumptions underpinning the Marginal Abatement Cost Curve (MACC) in Section 3, including region-specific adaptations for the EU, Brazil, and India. At the end of this section, a description of the analysis conducted to assess the impact of toxicity versus volume reductions using the EU Harmonised Risk Indicator methodology highlights why volume reductions are a partial but crucial element of risk reduction.

"Baseline" refers to the most recent available data (2020–2025); "Target" refers to the near term (next 10–20 years).

Analytical framework

1. **Evidence base:** Literature-derived assumptions and regional datasets (farm structure, land use, pesticide consumption, etc.).
2. **Quantitative modelling**: Reduction potential and associated costs across four levers:

A. Organic farming,
B. Integrated Pest Management (IPM),
C. Precision agriculture (current and emerging technologies),
D. Substitution by safe alternatives.

For each lever we derive net costs (USD/year) and pesticide savings (tonnes active ingredient (ai)/ year); these feed into the MACC construction.

Key data inputs

Baseline pesticide volumes: EU

The European Union (EU) baseline for pesticide use was derived using a land-use-weighted approach, ensuring representativeness across major farming systems. All calculations refer to the 2023 agricultural year, consistent with the latest available FAOSTAT reporting of total pesticide consumption by country (Table 3).

Methodology

National-level pesticide consumption data (total tons applied) were obtained from FAOSTAT (2023) and combined with Utilized Agricultural Area (UAA) data disaggregated by land use category—arable land, grazing, and horticulture—from the EUSTAT database (Table 4).

We estimated average pesticide intensities for arable and horticulture using a constrained least-squares fit across Member States, while fixing grazing at 0.5 kg/ha. For each country i, with UAA (excl. organic) by land use (A_{i,a}, A_{i,h}, A_{i,g}) and FAOSTAT total use (T_i) (kg), we solved:

$$\min_{(I_a,\, I_h \geq 0)} \Sigma_i \left[T_i - \left(I_a A_{(i,a)} + I_h A_{(i,h)} + 0.5\, A_{(i,g)} \right) \right]^2$$

where (I_a) and (I_h) are the EU-average arable and horticulture intensities (kg/ha). Areas by farm use are from Table 4 (reclassified to arable/horticulture/grazing and excluding organic UAA). The fitted intensities are ~2.2 kg/ha (arable) and ~7.1 kg/ha (horticulture); predicted volumes aggregate to the EU total within rounding error.

Results

The resulting average EU pesticide intensities were estimated as follows:

Grazing land: 0.5 kg / ha

Arable land: 2.2 kg / ha

Horticulture: 7.1 kg / ha

When multiplied by their respective land areas, this yields an estimated total baseline pesticide consumption of ~323 thousand tons, as detailed in Table 1. The constrained least-squares fit (grazing fixed at 0.5 kg/ha) produces an EU-wide baseline that overestimates total FAOSTAT pesticide volume by ~11%.

Organic farmland, representing ~9.5 % of total UAA, was excluded from the pesticide intensity analysis under the assumption that synthetic pesticide use on certified organic land is negligible to zero. This adjustment ensures that baseline intensities reflect only conventional agricultural practices subject to synthetic pesticide use.

Land use	**Baseline UAA** (10^3 ha)	**Pesticide intensity** (ton / ha)	**Baseline pesticide volume** (kg)	**Share of total pesticide volume** (%)
Grazing	31,004	0.5	15,502	5%
Arable land	99,376	2.2	236,479	68%
Horticulture	12,141	7.1	92,551	27%
Total	142,521	n/a	344,533	100%

Table Data Input—1—UAA and Pesticide Volume Used as Baseline in the Quantitative Analysis (excl. organic area) [Systemiq Analysis, based on FAOSTAT Pesticide Volume Data (2023) and *Eurostat Main farm land use by NUTS 2 region* Data (2020)]

Land use	**Organic area (thousand ha)**	**Organic share of total land use area (%)**	**Share of total organic area (%)**
Grazing	8,732	22%	60%
Arable	4,292	4%	29%
Horticulture	1,628	12%	11%

Table Data Input—2 Organic Area by Land Use Type (EC, 2023)

Note: Organic area distribution was derived from the European Commission Agricultural Market Brief—Organic Farming in the EU: A Decade of Growth (2023). For the purpose of this analysis, reported crop groupings were recategorized into three consolidated land use classes:

- Grazing land includes permanent grassland and green fodder;
- Arable land includes cereals, industrial crops, dry pulses, and other annual crops;
- Horticulture includes permanent crops such as fruits, olives, and vineyards.

This harmonization allows alignment between organic area data and the UAA categories used for pesticide intensity calculations.

Country	Value (tons)	Country	Value (tons)	Country	Value (tons)
Austria	5,251	France	65,415	Malta	106
Belgium	4,801	Germany	40,494	Netherlands	7,263
Bulgaria	3,430	Greece	4,217	Poland	19,963
Croatia	1,224	Hungary	6,443	Portugal	7,857
Cyprus	825	Ireland	2,274	Romania	9,157
Czechia	4,573	Italy	39,571	Slovakia	1,792
Denmark	3,314	Latvia	1,666	Slovenia	695
Estonia	709	Lithuania	3,013	Spain	52,907
Finland	3,251	Luxembourg	116	Sweden	2,033

Table Data Input—3 Reported National Pesticide Volumes for Agricultural Consumption in year 2023 (tons active ingredients); (FAOSTAT, 2023)

Farm Land Use	Area (10^3 ha)	Assigned Land Use Category
Various granivores combined	207	Grazing
Non-classified farms	242	Mixed/Other
Specialist horticulture indoor	295	Horticulture
Other horticulture	368	Horticulture
Specialist horticulture outdoor	728	Horticulture
Specialist poultry	1,043	Grazing
Mixed Grazing, mainly granivores	1,267	Grazing / arable
Various permanent crops combined	1,673	Horticulture
Mixed Grazing, mainly grazing	1,970	Grazing / arable

Farm Land Use	Area (10^3 ha)	Assigned Land Use Category
Specialist fruit and citrus fruit	3,227	Horticulture
Specialist vineyards	3,501	Horticulture
Specialist olives	3,610	Horticulture
Mixed cropping	5,146	Arable Land
Various crops and Grazing combined	5,951	Arable Land
Field crops-grazing Grazing combined	9,629	Arable Land
Sheep, goats and other grazing Grazing	9,891	Grazing
Specialist cattle-rearing and fattening	16,889	Grazing
Specialist dairying	18,217	Arable Land

Cattle-dairying, rearing and fattening combined	2,684	Grazing	General field cropping	25,105	Arable Land
Specialist pigs	2,906	Grazing	Specialist cereals, oilseed and protein crops	42,866	Arable Land

Table Data Input—4 Farm Land Use Classification and Assigned Land Use Category (EUSTAT, NUTS-2 Level 2020 data)

Baseline pesticide volumes: Brazil and India

Because country coverage and sub-national disaggregation are not comparable to the EU's 27-state panel, we did not fit least-squares models outside the EU. Instead, we derived land-use-specific intensities by scaling EU intensities to each country's totals and areas. This proportional allocation preserves each country's national total while distributing it across land uses in line with the EU intensity pattern, adjusted for the country's area mix. To avoid overstating use on extensive pasture, grazing intensity for Brazil was capped at the EU level. As organic UAA share is minimal based on FAOSTAT data, these were assumed zero for simplicity in the analysis.

Country	Land use type	UAA (million ha)	Pesticide consumption (10^3 tons)	Pesticide intensity (kg/ha)
Brazil	Grazing	126	63	0.50
	Arable	56	510	9.17
	Horticulture	8	228	29.3
India	Grazing	10	0	0.04
	Arable	154	30	0.20
	Horticulture	14	9	0.63

Table Data Input—5 UAA and pesticide consumption per region per land use type (FAOSTAT, 2023), with computed pesticide intensities based on EU intensity ratio

Pesticide price proxy

Based on data from the Pesticide Atlas (Heinrich Böll Stiftung et al., 2022), global market volume equals circa 4 million tons ai and market value equals circa USD 84.5 bn—the implied average price is ~USD 21,125 / ton ai (~ USD 21/kg). This single proxy is used throughout the analysis for simplicity, noting it averages across products, formulations, regions and crops.

Quantitative analysis

To estimate realistic reductions, we apply measures in a source-first sequence that removes avoidable use before optimizing and replacing what remains. This avoids double counting and reflects how changes are adopted on farms.

- **Avoid at source (IPM, organics):** redesign practices to eliminate or sharply cut demand for pesticides.
- **Optimize necessary use (precision ag):** target applications to time, place, and dose on the residual volume.
- **Replace the remainder (substitution):** swap any unavoidable use with lower-/non-toxic alternatives.

Each step applies only to the residual volume after the previous lever.

Organics—Reduction analysis

- **Organic yield and system backfill:** We assume a 30% yield gap for land converted to organic relative to conventional yields. To keep total output constant, the system requires additional conventional farmland equal to 30% of the newly converted organic area (simple backfill assumption). This added conventional area contributes to pesticide use at conventional intensities.
- **Net pesticide savings:** Net savings are calculated as the reduction from converting land to organic minus the additional pesticide use on the backfill conventional area required to compensate the organic yield gap.
- **EU illustration:** To reach 25% organic UAA, an additional 24.6 million ha converts to organic. To offset the 30% yield loss, the system adds ~7.4 million ha of conventional farmland (30% of 24.6 million ha), and this area is counted with conventional pesticide intensities in the baseline/abatement calculations.

Region	**Baseline adoption** (share of total UAA)	**Target adoption** (share of total UAA)
EU	10%	25%
Brazil	0%	5%

Table QA—6 Baseline and target organically farmed area used in analysis
EU baseline (European Commission, 2023), target (European Commission, 2025)
Note: Brazil baseline organics assumed equal to zero for simplicity as organic farmland for Brazil is minimal at time of writing (FAOSTAT, 2025) *and target adoption share was estimated.*

Organics—Cost analysis

Scope: Costs are calculated for converted organic area only (incremental beyond baseline), by region and land use. Backfill area is added to keep output constant (per the 30% yield-gap assumption in the reduction analysis).

Method

1. **Running-cost differential.** Apply the annual incremental running cost/ha of organic versus conventional to the converted hectares (this embeds changes in input use, practices, and the effect of reduced pesticide purchases—therefore, no separate pesticide-savings benefits are included in the analysis).
2. **Backfill opportunity cost.** Multiply backfill area by region-specific farmland rental (proxy for opportunity cost) to obtain annual opportunity cost.
3. **Total annual cost.** Net cost = (running-cost differential x converted hectares) + (rental × backfill hectares).

4. **Accounting.** Costs are area-based and reported annually; no price-learning is assumed. Converted organic hectares are excluded from synthetic pesticide use; backfill hectares are counted with conventional intensities in the volume model (as specified in the reduction analysis).

IPM—reduction analysis

Scope. IPM is applied after organics and before precision agriculture, acting on the post-organics residual pesticide volume. IPM is modelled as a practice change that reduces demand at source (e.g., crop rotation, cover crops, threshold spraying, biological control, mechanical / physical barriers, pheromone-based control)

Method

- Work at the level of land use x region (arable, horticulture, grazing).
- Apply IPM to eligible hectares only (primarily arable and horticulture; grazing limited to treated pasture systems).
- Compute savings as a reduction in intensity (kg ai/ha) on newly adopting hectares; aggregate to volume by multiplying by area.
- To avoid double counting, IPM acts on the residual after organics, and PA acts later only on the post-IPM residual.

Efficacy

- The 30% IPM efficacy used here is a conservative, literature-based anchor. Reported effects in individual studies are often higher, but outcomes are crop- and context-dependent (pest pressure, climate, rotation, scouting quality, biologicals availability, farmer skill). Because there is no single generalizable rate, we adopt 30% for comparability across regions and test higher/lower values in sensitivity analysis.
- Efficacy reflects a bundle of IPM measures (decision thresholds, crop rotation, non-chemical controls, targeted biologicals).
- No toxicity weighting is applied; reductions are volume-based in active ingredients.

Adoption accounting

- Baseline IPM already embedded in the baseline volume is not credited again.
- Only new adoption relative to baseline generates additional savings.
- Adoption is area-weighted (not farm-weighted). Where national baselines are missing, proxies are used.
- Adoption rates are averaged based on literature and crop system, farm type and region dependent

Farming approach	**Savings rate**
Business-as-usual	0%
Integrated Pest Management (IPM)	30%

Table IPM-1. IPM reduction factor compared to business-as-usual
(Savings = % reduction in intensity on newly adopted hectares; applied to post-organics residual. Represents average number based on bundled IPM practices.)

	Adoption rate per land use: baseline à target		
Region	**Grazing**	**Arable land**	**Horticulture**
EU	5% à 10%	20% à 50%	30% à 70%
Brazil	5% à 10%	30% à 70%	20% à 60%

Table IPM-2. IPM adoption by region and land use (baseline → target)
(Shares of eligible hectares; only new adoption beyond baseline yields additional savings.)

IPM—Cost analysis

Costs for IPM are set to zero. Reported IPM costs and benefits are highly context-dependent (crop, region, bundle of measures, implementation quality), so we avoid skew by not monetizing them here.

Precision agriculture—reduction analysis

Method: PA is applied to the residual baseline after sequentially applying organics first and IPM second. The post-IPM residual is split by pesticide type (herbicides, insecticides, fungicides). Savings on treated hectares are computed as baseline intensity (kg active ingredient (ai) / ha) x efficacy, then aggregated across land uses. Double counting is avoided by acting only on the residual.

Type shares and mapping

Pesticide-type shares come from FAOSTAT EU totals (herbicides/insecticides/fungicides). For simplicity, these shares are applied uniformly across arable, horticulture, and grazing in all countries (acknowledging real-world variation). Grazing remains in scope but with low adoption given low intensities.

Technology & efficacy

Two tiers are modelled—current and emerging[i]—with efficacy rates and type-specific mixes as per Table PA-1/PA-2. Efficacy acts on intensity; savings equal intensity x efficacy x treated hectares. We model active ingredients only (no adjuvants/formulations).

Adoption pathway (how baseline and changes are handled)

- **Baseline PA is already embedded in the baseline volume.** A fixed share of hectares (e.g., 10%) is assumed to be using conventional tech in the baseline. Those hectares do not receive any additional efficacy in the reduction model, because their effect is already reflected in the baseline intensity/volume.
- **Only changes from the baseline create abatement.** From this baseline, four mutually exclusive changes can occur in the scenario:
    1. No change: baseline PA share stays as is → no additional PA savings.
    2. Add conventional tech on new hectares: additional area adopts conventional tech → savings = (current-tech efficacy × baseline intensity × added hectares).
    3. Add emerging tech on new hectares: additional area adopts emerging tech (from zero) → savings = (emerging-tech efficacy × baseline intensity × added hectares).
    4. Upgrade existing current-tech hectares to emerging tech: baseline current-tech hectares are upgraded → savings = (emerging – current efficacy) × baseline intensity × upgraded hectares.
       (If the current-tech share declines and is replaced by emerging tech, we treat it as an upgrade of the reduced current-tech hectares.)
- **Accounting unit.** All calculations are done per pesticide type × land use, using area-weighted adoption and applying efficacy to intensity (kg ai/ha).

[i] *Conventional tech* refers to guidance/section control, basic variable-rate application (VRA), rate controllers, and GPS-enabled boom control. *Emerging tech* refers to AI camera-based spot spraying, advanced sensing/robotics, and high-resolution prescription maps. Efficacy values are average assumptions on treated hectares and may vary by crop, pest, and field conditions.

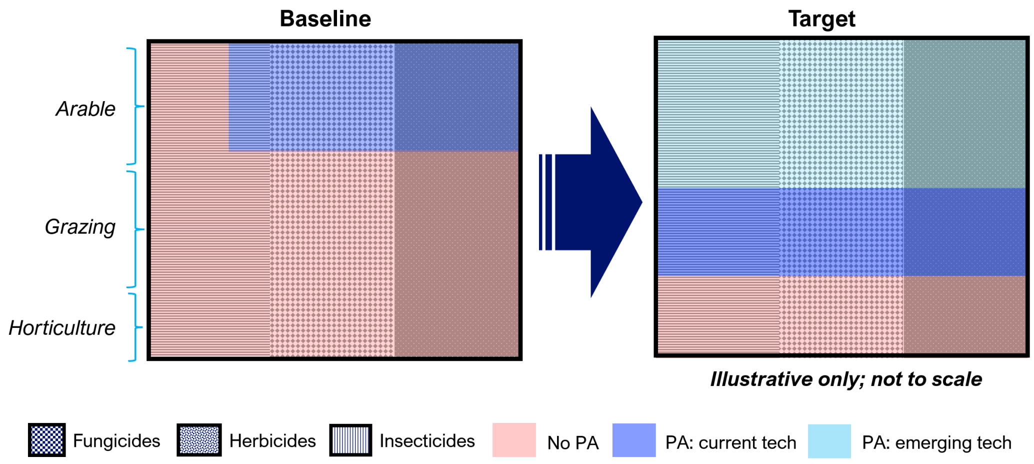


Figure PA-1. Baseline → Target precision-agriculture adoption (illustrative).
Conceptual illustration of how PA is applied to the residual pesticide volume by land use (arable, grazing, horticulture) and pesticide type (herbicides, insecticides, fungicides). Left panel shows baseline with current-tech coverage; right panel shows target with a mix of current and emerging tech. Note: Shares of adoption, land use, and pesticide type are purely illustrative and do not represent model values.

Quality checks. We enforce eligibility caps (treated area cannot exceed available area; efficacy cannot exceed the emerging-tech ceiling) and verify mass balance for every type × land-use cell: pre-PA residual = PA savings + PA residual.

Scope note. For simplicity, only herbicides, insecticides, and fungicides are modelled; other categories are treated as negligible.

Tech adoption	Efficacy rate
No PA	0%
PA: conventional tech	30%
PA: emerging tech	80%

Table PA-1. Precision agriculture technology tiers and efficacy
(Current vs. emerging; efficacy = % reduction on treated hectares; applied to residual after IPM/organics.)

	Share conventional tech	Share future tech
Insecticides	20 %	80%
Herbicides	70%	30%
Fungicides	30%	70%

Table PA-2. Type-specific PA technology mix (share of PA-treated hectares)
(For simplicity, we model only herbicides, insecticides, and fungicides, assuming they account for 100% of pesticide volume; all other types are treated as negligible.)

	Adoption rate per land use: baseline à target		
Region	Grazing	Arable land	Horticulture
EU	0% à 15%	20% à 80%	15% à 90%
Brazil	5% → 15%	20% → 90%	10% → 70%

Table PA-3. PA adoption by region and land use (baseline → target)
(Shares of eligible hectares; upgrades count incremental savings only.)

Metric	Conventional tech	Emerging tech
Unit operating area (ha)	1000	1500
CAPEX per unit (USD)	60,000	250,000
OPEX per unit (USD/year)	3,030	12,500
Unit lifetime	8	15

Table PA-4. PA cost estimates for two tech types: conventional tech
Source cost estimates: (Tona et al., 2018) (conventional tech) and (Greeneye Technology, 2024) (emerging tech)

Precision agriculture—cost analysis

Scope. Costs are calculated only for changes from the baseline (new adoptions and upgrades from current → emerging), by country and land use.

Method:

1. **Translate adoption to units.** Convert PA-adopted area (separately for current and emerging tech) into required equipment units using an assumed operating area per unit.
2. **Assign adopters and sharing.** Identify adopting farms from the farm-size distribution (largest first) until the target area is reached; this determines farms per unit (thus assuming equipment sharing schemes when farm size does not match/exceed optimal PA unit operating area).
3. **Timeliness factor.** If applicable, apply an operational buffer of 5% for sharing constraints (weather, downtime, overlapping spray windows), increasing the required unit count.
4. **Cost per unit.** Set CAPEX per unit (emerging as reference; current modelled as a fixed fraction of emerging). Annualize CAPEX over unit lifetime; OPEX as a fixed percentage of CAPEX. Vendor values are based on a confidential industry proxy; no price learning is assumed.
5. **Total annual cost.** Multiply required units by (annualized CAPEX + OPEX), summed separately for current and emerging.
6. **Annual savings.** Compute avoided pesticide purchases = (PA volume reduction) × (pesticide price).
7. **Net cost and MACC.** Net cost = total annual cost – annual savings. Net costs and associated abatement feed directly into the MACC construction.

Safe Alternatives—reduction analysis

Scope. Safe alternatives replace remaining synthetic pesticide use to meet the overall 80% reduction target (common across regions).

Method:

1. Compute residual synthetic volume after Organics → IPM → PA.
2. Set a substitution target such that cumulative reduction reaches 80% of baseline synthetic volume.
3. Substitution is treated as 1:1 replacement in active-ingredient mass (no efficacy or frequency adjustment) and is toxicity-motivated rather than volume-reducing.

Safe alternatives—cost analysis

Unit price proxy:

- **Synthetic reference price: used** the pesticide price proxy already defined in the annex (average USD/tonne ai).
- **Safe-alternative proxy:** derived a biopesticide price proxy from a referenced paper (Malinga & Laing, 2024) compiling multiple product listings (see Table SA-1). Computed the average price ratio between listed biopesticides and synthetics and apply this ratio as a multiplier to the synthetic price proxy (the working multiplier in this analysis is ~8×, per the source compilation).
- **Scale adjustment:** apply a 50% price reduction to the safe-alternative proxy to reflect expected price declines with scale (biologicals ≈ 10% of market today but expected to increase significantly).

Category	Trade name	Total cost (USD)	Average price (USD)
Biopesticide	Eco-Bb®	226.44	355.48
Biopesticide	Bolldex®	495.74	
Biopesticide	Delfin®	602.32	
Biopesticide	Bb endophyte	226.44	
Biopesticide	NOMU-PROTEC®	226.44	
Synthetic	Karate® EC	58.87	44.53
Synthetic	Chlorpyrifos® 480 EC	27.93	
Synthetic	Bandit® 350 SC	46.80	

Table SA-1. Biopesticide vs. synthetic pesticide price listings used to derive the safe-alternative price proxy (adopted from (Malinga & Laing, 2024))

Costing approach:

- **Incremental unit cost** (per tonne ai substituted) = (safe-alternative proxy price – synthetic proxy price) after the scale adjustment.
- **Total annual cost** = incremental unit cost × substituted volume (tonnes ai).
- **No additional costs/benefits are included** (e.g., application frequency, equipment, yield effects), due to heterogeneity and limited consistent data.

Assumptions & caveats:

- The safe alternative proxy is based on a single literature source summarizing multiple price points; it does not cover all possible safe alternatives and may over- or under-state costs for specific geographies/crops.
- Replacement is assumed 1:1 by ai mass; no adjustments for dose/formulation, pass frequency, or control spectrum.

Marginal Abatement Cost Curve

Using lever-level annual savings and net costs, tranches are ranked by cost-effectiveness (USD per tonne ai reduced) and stacked to show cumulative abatement. Sequencing follows Organics → IPM → PA → Substitution, and the curve is capped at 80%; substitution is trimmed as needed.

Axes: height = USD/t ai; width = t ai/yr (cumulative).

EU Harmonized Risk Indicator Analysis

To assess the importance of risk versus volume reductions, in absence of data using the novel ATAT methodology, we analyzed the simplified EU Harmonised Risk Indicator 1 using data from (Eurostat, 2025). Using the reported 2022 active ingredient volumes, a 75% reduction in pesticide volumes would be required. This is partially because since 2011, the EU has drastically reduced the reported volume of the most harmful "non-approved" active substances. However, not all EU member states are systematically reporting the volumes of such substances for emergency use (European Commission, 2025). This could mean smaller volume reductions are required to achieve an 80% risk reduction, as higher volumes of harmful substances could be reduced. Assuming a worst case, that the actual volumes of these most harmful substances remain unchanged since 2011, a 54% volume reduction would be required to realize an 80% risk reduction.

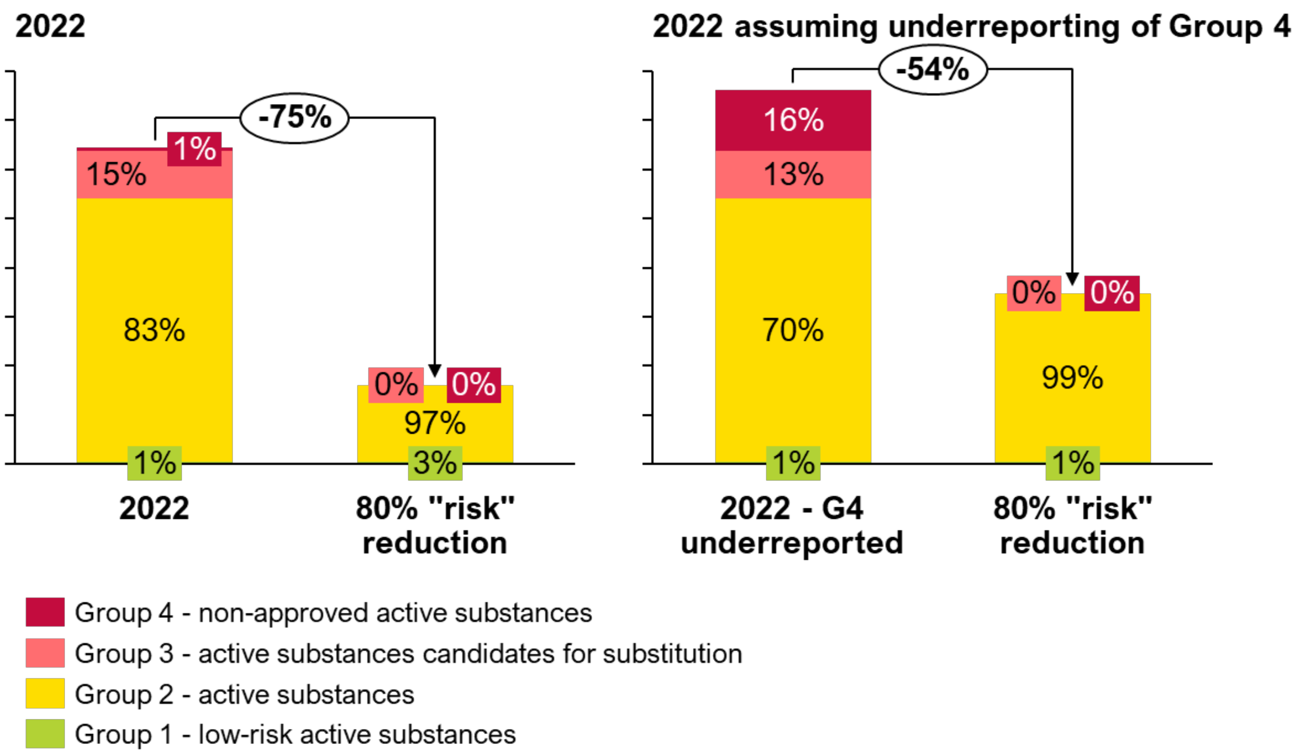


Figure PA-2. EU HRI1 Indicator assessment of an 80% risk reduction.
Note: The left side uses reported 2022 active ingredient volumes. As the European Commission and Eurostat note that volumes of emergency uses of non-approved substances are not tracked / reported by all members, the right side assumes a worst-case in which Group 4 volumes have not changed since 2011, while 2022 volumes are used for Group 1-3 volumes.
Source: Systemiq analysis using Eurostat data

VI: PFAS marginal abatement cost curve

This section outlines the analytical approach used to develop the PFAS Marginal Abatement Cost Curve (MACC). The analysis begins with a comprehensive review of PFAS use across industries, based on the latest ECHA Universal PFAS Restriction proposal (ECHA, 2025). From this, the top eight sectors were selected, which together account for approximately 94% of total PFAS use in the EU. In addition, technical textiles and energy were included given their expected rapid growth to 2040, despite representing a smaller share of current PFAS use. The analysis therefore considers not only current (2020 baseline) volumes but also projected volume growth through 2040 to reflect how sectoral dynamics and technological development may shift the overall abatement potential. In total, the analysis covers 10 sectors included in the restriction proposal.

The analysis excludes two sectors due to lack of comparable data from the evidence presented in the ECHA phaseout restriction. The ECHA proposal excludes pesticide-related volumes (~2% of 2020 EU use volumes), as they are already subject to "extensive environmental risk assessments" and their approval is subject to additional factors (e.g., resistance management). Instead, the proposal encourages measures to "minimize emissions from the use of PFAS active substances to be taken within the context of the respective sector-specific regulations" and mandatory reporting requirements. Similarly, the analysis excludes firefighting foams, which account for 0.3% of 2020 volume, but are a significant source of PFAS emissions. These are covered in a separate ECHA restriction proposal, and we were unable to assure the analysis would be comparable (ECHA, 2022). ECHA estimates costs of completely phasing out PFAS from firefighting foams at €390M (USD 429M) per year, including a broad range of costs beyond the direct capital and operating costs (e.g., cleaning of equipment, depreciation and disposal of PFAS-containing foams).

The MACC is representative of 2030 volumes, which are assumed to reflect both the expected substitution potential and cost indication at entry into force of the restriction. Given the diversity of PFAS uses and data limitations across applications, the analysis builds directly on the Universal PFAS Restriction Dossier developed by the ECHA, which serves as the foundation for the sectoral tonnage, substitution potential, and cost indication data. This uses data by sector and sub-use to generate a high-level, top-down assessment, complemented by targeted analysis. We did not conduct detailed bottom-up investigations for each sub-use. Consequently, this MACC is intended as an indicative view of potential costs and substitution pathways. A follow-up project aims to develop more granular, industry-specific cost assessments, recognizing the wide variability in PFAS use and substitution feasibility across applications.

Each industry is assessed, summarizing key insights from the Restriction Annex, including (i) tonnage by sub-use, (ii) indicative substitution potential, and (iii) indicative cost estimates linked to substitution. This data is used to assess industry-level substitutable volumes at different timeframes (at entry into force, after five years, and after twelve years), and the adjustment factors for OPEX and CAPEX applied to each sub-use.

General Methodology

The MACC generally follows a five-step analytical approach, as outlined below.

1. Defining the Baseline Cost Assumptions

   The first step establishes baseline cost parameters, operating expenditure (OPEX) and capital expenditure (CAPEX), for each industry.

   - Baseline OPEX is set equal to the average PFAS material cost in the EU (€19/kg).
   - Baseline CAPEX is derived using financial metrics from three sets of corporate finance statistics compiled by Professor Aswath Damodaran at the Stern School of Business at NYU (Damodaran, 2025), which includes indicators such as average capital expenditure, revenue, cost of goods sold (COGS) ratios, and operating costs by industry. The datasets used are the European Capital Expenditures, Acquisitions and R&D and Sales/Invested Capital Ratios; Operating and Net Margins by Industry Sector; and Market Capitalization by Industry.

   Each PFAS-using sector is linked to the most relevant proxy industries in the NYU Stern data. To better capture variations in cost structures, each sector is modeled as a composite of three proxy industries. For example, textiles are represented as a composite of apparel, furnishing and home furnishing, and specialty chemicals, providing a balanced reflection of different production and cost dynamics. The CAPEX-to-OPEX ratio for each composite industry is then used to estimate baseline CAPEX. Table PFAS-1. provides the industry proxies used in the analysis.

Table PFAS-1. Industry proxies used in the analysis

Industry	Rationale
Textiles	Primarily specialty chemical (75%) due to the upstream use; home furniture (20%) and apparel (5%) account for smaller fraction due to reflect end use.
F Gas	Fluorinated gases are produced and blended as specialty (70%)/commodity chemicals (20%); distribution/logistics resemble industrial gas/liquid distribution (10%).
Transport	Manufacturing mix spanning vehicle OEMs (45%) and component suppliers (40%); niche exposure to aerospace and marine platforms (15%).
Sealing	Gaskets, O-rings, seals and fluoroelastomers overlap rubber goods (45%), automotive components (30%), and industrial machinery (25%).
Firefighting foam	Foam concentrates (including F3/AFFF alternatives) align with specialty chemicals (80%); packaging/logistics (10%) and downstream environmental handling (10%) play smaller roles.
Electronics	Blend of chipmakers (60%), capital equipment vendors (20%), and general electronic device manufacturing (20%).
Construction	Includes insulation, roofing, sealants/adhesives and boards—anchored in building materials (55%) and supplies (35%), with specialty chemicals (10%).
FCM	Food-contact materials span packaging and containers (55%), paper and forestry products (20%), and polymers/inks/coatings reflect specialty chemicals (25%).
Medical	Devices/disposables primarily align to healthcare products (80%), with machinery (10%) and electronics (10%) as secondary elements.
Energy	Specialty chemicals (45%) dominate due to large share of battery production; electrical equipment (30%) captures grid integration, and power electronics; and Green & Renewable Energy reflects demand from renewables and storage integration (25%).
Technical textile	Industrial/high performance textiles used in autos, aerospace and construction with specialty coatings/resins; limited apparel and processing equipment.

2. Defining the Cost Adjustments

   Each industry is further divided into sub-uses (for example, textiles include home textiles, consumer apparel, professional and PPE, leather applications, home fabrics, and others). For each sub-use, an OPEX and CAPEX adjustment factor is defined based on cost indications from the PFAS Restriction Annex, which classifies costs as very low, low, moderate, high, or very high. These qualitative categories are translated into quantitative percentage adjustments, as shown in Table PFAS-2. In several cases, additional literature and cross-industry benchmarks were used to validate or refine these adjustment factors.

3. Calculating the Adjusted Costs

   Adjusted OPEX and CAPEX values are calculated by multiplying the baseline costs by the corresponding adjustment factors. The marginal cost of substitution is then derived as the difference between the adjusted and baseline costs. This step provides the marginal abatement cost for replacing PFAS within each sub-use. Table PFAS-2. provides the general cost adjustment proxy for different cost indication

Table PFAS-2. Cost adjustment proxy per cost indication

Cost Indication	**% Cost adjustment** (applies to both CAPEX and OPEX)
Low	-15% to <15%
Moderate	15% to <30%
High	30% to <50%
Very High	50% or above
Unclear	*Assumes covered in innovation*
Low Substitution Potential	*Assumes covered in innovation*

4. Determining Substitutable Volume

   This step quantifies the substitutable share of PFAS use in each sub-sector. Total PFAS volumes are taken from the Restriction Annex and adjusted based on the substitution potential identified in the proposal:

   - High substitution potential: 100% of volume assumed substitutable.
   - Mixed substitution potential: proportion equally distributed unless more detailed data are available in the restriction proposal.
   - Low substitution potential: 0% substitutable volume assumed.

   A summary of substitution potential across sectors and sub-uses is provided in Table PFAS-3, illustrating the relative ease or difficulty of substitution by application area.

5. Calculating Total Abatement Costs

   The total abatement cost is calculated as the product of the marginal cost of substitution and the substitutable volume. This yields an estimate of the total annualized cost of eliminating PFAS use for each industry and across the EU overall.

Table PFAS-3. Substitution potential across sectors and sub-uses

Industry	Sub-use	Substitution potential at EiF
Textiles	Home textiles	High
Textiles	Consumer apparel	High
Textiles	Professional apparel & PPE (combined in Annex)	Mixed
Textiles	Leather applications	High
Textiles	Home fabric treatments (sprays)	High
Textiles	Other & unspecified textile applications	Unknown
F Gas	Commercial refrigeration	High
F Gas	Domestic refrigeration	High
F Gas	Industrial refrigeration	Mixed
F Gas	Stationary air conditioning	Mixed
F Gas	Foam blowing (Closed cell)	Low
F Gas	Foam blowing (Open cell)	High
F Gas	Fire protection	Mixed
F Gas	Propellants (non-MDI)	Mixed
Transport	Mobile Air Conditioning (MAC)	Low
Transport	Transport Refrigeration (non-marine)	Low
Transport	Additives to hydraulic fluids (aerospace)	Low
Transport	Foam mouldings (e.g., aircraft interiors, sound/heat insulation in cars)	Low
Transport	Tubes and hoses in combustion engine systems	Low
Transport	Protective coatings and paints for transport vehicles	Low
Transport	Cable liners & coatings (including high-voltage insulators)	Low
Transport	2-BTP fire extinguishers for airplanes	Low
Transport	Reflective coatings for traffic signs	*High*
Transport	Devices for motion control solutions	*High*
Transport	Hydrophobic coatings for windshields	*High*
Transport	Other transport related uses	Low
Sealing	Industrial uses requiring a combination of all or many properties	Low
Sealing	Industrial uses requiring a combination of only some properties	High
Sealing	Professional uses	Low
Sealing	Consumer uses	Low
Construction	Architectural coatings and paints	High
Construction	Coil coating	High
Construction	Polymer additives used for fire safety purposes	Low
Construction	Film/foil for greenhouses	High
Construction	Processing aids for the production of non-PFAS polymers/plastics	Low
Construction	Bridge and building bearings	Low
Construction	Window frames	High
Construction	Plumbing applications	High
Construction	Surface protection (polymeric PFASs subject to degradation)	High
Construction	Wetting/levelling agents in e.g. coating, paints and adhesives	High
Construction	Processing aids for the production of construction articles	High
FCM	Paper and board packaging	High
FCM	Plastic packaging (Films and Sheets)	Low
FCM	Plastic packaging (fluorinated HDPE containers)	High
FCM	Inks, lacquers, and waxes for printing on food packaging	High
FCM	Non-stick consumer cookware	High
FCM	Non-stick coatings in industrial bakeware	Low
FCM	Miscellaneous packaging applications (e.g., beverage cans)	High

Table PFAS-3. Substitution potential across sectors and sub-uses (cont'd)

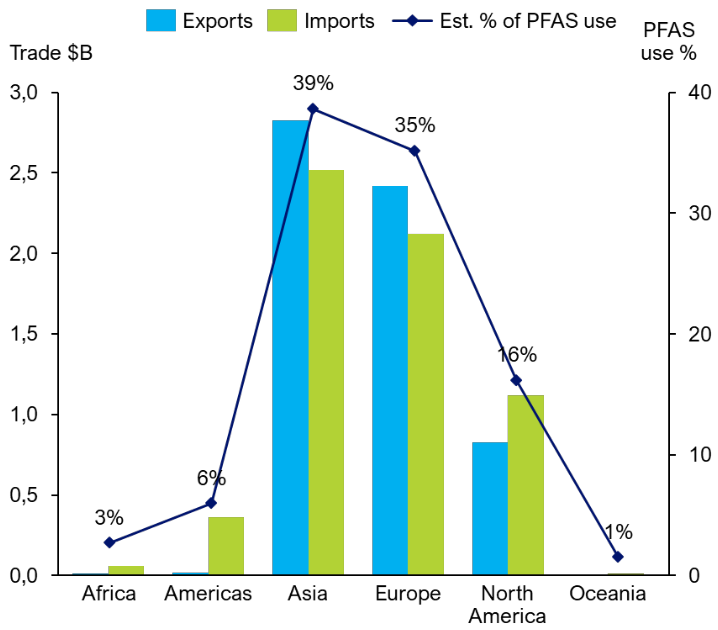
Industry	Sub-use	Substitution potential at EiF
Medical	Implantable Medical Devices (e.g., medical implants and meshes)	Low
Medical	Invasive Medical Devices (e.g., tubes and catheters, vision applications)	Low
Medical	Non-implantable/Non-invasive Medical Devices: Wound Treatment Products (e.g., bandages)	High
Medical	Non-implantable/Non-invasive Medical Devices: Other coating applications	High
Medical	Non-implantable/Non-invasive Medical Devices: Sterilisation Gases	High
Medical	Packaging of Medical Devices (e.g., PCTFE-based packaging, PPAs in flexible packaging, waxes for inks/lacquers)	Low
Technical Textile	Outdoor technical textiles	High
Technical Textile	Architectural membranes, other tensile fabrics and other construction applications	High
Technical Textile	Filtration and separation media	Low
Technical Textile	Removable covers for industrial process equipment	High
Technical Textile	Medical applications	Low
Technical Textile	Technical textiles in transport vehicles	Low
Electronics	Wires and cables	Low
Electronics	Insulation material of electronic components	Low
Electronics	Coating / film of electronic components	Low
Electronics	Electronic components	Low
Electronics	Photonics	Low
Electronics	Plastic additives	Low
Electronics	Heat transfer fluids	Low
Electronics	Vapor phase soldering	Low
Electronics	Electronic data storage	Low
Electronics	Semiconductor manufacturing	Low
Energy	Renewable energy generation	Mixed
Energy	Hydrogen technology	Low
Energy	Manufacturing of chemicals via electrolysis	Low
Energy	Batteries	Low
Energy	Electric Grids	Low

Regional Analysis

There is limited availability of reliable data on PFAS tonnage across regions outside the EU. As a result, rather than presenting absolute regional volumes in the MACC, the analysis applies the European sectoral distribution as a proxy for the percentage share of PFAS use that can be abated across different industries. This means that the relative share of PFAS use across sectors in other regions is assumed to mirror the European split, providing an indicative rather than definitive view of potential substitution volumes.

To supplement this assumption, an additional analysis was conducted using UN Comtrade data on trade volumes for 28 PFAS products, identifying regions and countries most active in PFAS trade. The findings show that China, the United States, Japan, France, and Italy are the top exporters, while the United States, Germany, China, Korea, and Japan are the top importers. At a regional level, Asia, North America, and Europe emerge as the principal regions involved in PFAS export and import flows. However, it is important to note that trade accounts for only about 20% of total PFAS market value, and therefore these figures should be interpreted solely as indicative of consumption patterns rather than domestic use.

PFAS exports and imports by region 2023
UN Comtrade data for 28 PFAS-HS codes



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