

Trifluoroacetic acid in Croatia: evidence, monitoring gaps, and regulatory blind spots

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Abstract

Trifluoroacetic acid (TFA) is a persistent, highly mobile ultrashort-chain per- and polyfluoroalkyl substance (PFAS), increasingly detected in aquatic and other environmental compartments globally. Its occurrence, transport pathways and regulatory treatment are insufficiently described in several regions of Southeastern Europe, including Croatia. This study aimed to collate the available information on TFA occurrences, regulatory frameworks, and relevant studies to characterise its status in Croatia and define research, monitoring and policy gaps. Recent European screening initiatives detected TFA at concentrations of approximately 620 ng/L in a surface water sample from the Sava River and 160 ng/L in a tap water sample from Samobor. A synthesis of environmental fate studies suggests several plausible pathways contributing to TFA contamination: atmospheric deposition following the degradation of fluorinated refrigerant gases, releases from landfills and waste disposal, and agricultural inputs arising from the degradation of PFAS pesticide active substances. Critical monitoring gaps were identified, in particular the lack of publicly available data on TFA concentrations in Croatian groundwater, which is an important knowledge gap given the extensive and interconnected aquifer systems of the Dinaric Karst, as well as limited information on the occurrence of TFA in agricultural soils, crops and food matrices. Addressing these blind spots requires validation and implementation of appropriate analytical methods, including direct injection LC-MS/MS for TFA in water; expansion of routine water monitoring to explicitly include TFA and other ultrashort-chain PFAS; and inclusion of the potential for TFA formation and leaching in environmental risk assessments of pesticide active substances that form TFA.

Keywords: Drinking water monitoring; Fluorinated gases; Landfills; PFAS pesticides; Ultrashort-chain PFAS.

Introduction

Per- and polyfluoroalkyl substances (PFAS) comprise a large and diverse class of synthetic organofluorine compounds characterised by highly fluorinated carbon structures and, in many cases, exceptionally strong carbon-fluorine (C-F) bonds. Their chemical stability, surface-active properties, and resistance to degradation have led to widespread use in industrial applications, fire-fighting foams, refrigerants, consumer products, pharmaceuticals and some agricultural formulations over several decades. Their persistence in the environment, combined with the high mobility and potential for bioaccumulation of many PFAS compounds, has led to their widespread detection and growing regulatory concern. This is why they are often referred to as „forever chemicals”.

Historically, environmental monitoring and risk assessment have focused primarily on well-studied long-chain perfluoroalkyl acids, including perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS). As regulatory restrictions on several legacy PFAS increased, the use of shorter-chain PFAS and alternative fluorinated substances expanded. Among these compounds, trifluoroacetic acid (TFA; CF_3COOH) is the smallest perfluoroalkyl carboxylic acid, containing two carbon atoms (C_2), and is mostly classified as an ultrashort-chain PFAS. TFA is now recognised as a widespread and persistent environmental contaminant, particularly in aquatic

systems. Its very high water affinity and limited sorption to soils contribute to its high environmental mobility and potential for transport into groundwater and surface waters.

TFA can arise from both direct emissions and the environmental transformation of precursor substances. Important sources and pathways include:

1. *Atmospheric degradation and deposition:* TFA can be formed through the atmospheric transformation of certain fluorinated gases, including hydrofluorocarbons (HFCs) and hydrofluoroolefins (HFOs), used primarily as refrigerants, but also in other applications. Atmospheric TFA and its precursors can subsequently reach terrestrial and aquatic environments through wet and dry deposition (David et al., 2021; Garavagno et al., 2024; Holland et al., 2026).
2. The spatial and temporal pattern of this pathway depends on the atmospheric lifetime and transformation yield of the precursor. HFO-1234yf is short-lived (on the order of a few days) and is converted to trifluoroacetyl fluoride, which hydrolyses rapidly to TFA; consequently, its contribution is expected to occur comparatively close to emission regions. By contrast, HFC-134a has an atmospheric lifetime of approximately 14 years and is more widely dispersed before degradation. Published modelling has treated the TFA yield from HFC-134a as significantly lower than that from HFO-1234yf, although recent mechanistic work has questioned the feasibility of parts of the previously proposed HFC-134a oxidation pathway (David et al., 2021; Garavagno et al., 2024; Holland et al., 2026; Vincent et al., 2026).
3. *Transformation of fluorinated pesticides:* Certain pesticide active substances containing trifluoromethyl (-CF₃) groups can degrade to TFA in soil and other environmental compartments. Recent experimental research has demonstrated TFA formation from several pesticide active substances (Johnsen et al., 2026), while broader agricultural research identifies pesticides, rainfall/atmospheric deposition, irrigation water and biosolids among potential sources of TFA to agricultural systems (Ashworth, 2026).
4. In a 52-week laboratory experiment using three agricultural soils, Johnsen et al. (2026) detected TFA formation from all seven tested C-CF₃ pesticides: trifluralin, fluazifop-P-butyl, fluazinam, tau-fluvalinate, diflufenican, fluopyram and mefentrifluconazole. Formation varied by compound and soil, demonstrating that molecular structure alone does not determine the quantity of TFA formed under soil conditions.

The relative importance of individual pathways is expected to differ geographically and according to land use, industry presence, atmospheric conditions, hydrology and agricultural intensity. Consequently, the presence of TFA in a particular water body cannot be used to assign contamination to a specific source.

TFA is highly mobile and persistent in the environment. Its low affinity for soil solids means that it remains primarily dissolved in water, allowing its movement through agricultural soils and the vadose zone into groundwater and through surface-water systems.

Once present in the environment, TFA has no obvious degradation pathway and occurs predominantly as freely dissolved trifluoroacetate, being transported with flowing water and accumulating in terminal water bodies. It has low conventional bioaccumulation potential in animals but can accumulate in plants. Its high water solubility and low octanol-water partition coefficient make conventional lipid-driven bioaccumulation in biota unlikely; this should be distinguished from uptake and accumulation in particular plant tissues, which remains relevant to food-chain exposure (Hanson et al., 2024).

In June 2026, ECHA's Committee for Risk Assessment (RAC) adopted an opinion recommending the harmonised classification of TFA as toxic to reproduction, Category 1B (Repr. 1B; H360Df), as well as persistent, mobile and toxic (PMT) and very persistent and very mobile (vPvM) (ECHA RAC, 2026). This recommended classification is not yet legally binding as its incorporation into the CLP Regulation is pending. In July 2026, the European Food Safety Authority (EFSA) published a new assessment of dietary exposure to TFA and reduced the acceptable daily intake from 0.05 to 0.014 mg/kg body weight per day. EFSA noted that TFA can originate from several PFAS-related sources, including certain industrial gases and active substances used in pesticides, and can occur in groundwater, soil and food crops (EFSA et al., 2026).

Evidence concerning historical background concentrations is limited. Nielsen et al. (2001) analysed five samples of pre-industrial freshwater from Greenland and Denmark and detected no TFA above 2 ng/L. The authors

interpreted these results as evidence against TFA being a naturally occurring trace component of freshwater, although the small sample set does not exclude all natural formation pathways.

TFA and the Croatian regulatory context

In Croatia, monitoring of PFAS in drinking water is now implemented under the national legislation transposing Directive (EU) 2020/2184 on the quality of water intended for human consumption. The EU framework establishes a parametric value of 0.10 µg/L for the “*Sum of PFAS*”, covering 20 specified PFAS, as Member States were required to comply with this parameter from 12 January 2026.

However, the *TFA is not one of the 20 PFAS included in the drinking-water “Sum of PFAS” parameter*. Therefore, compliance with the 0.10 µg/L value for the 20-PFAS sum does not establish the absence of TFA. This distinction is important because TFA's ultrashort-chain structure and high mobility make it analytically and environmentally different from the longer-chain PFAS compounds.

In 2026, the EU legislative process on environmental-quality standards agreed to add TFA to the group of PFAS monitored in surface waters, expanding the relevant PFAS sum from 24 to 25 compounds (Directive (EU) 2026/805). For groundwater, the agreed framework retains a standard for the sum of 20 PFAS aligned with the drinking-water framework while explicitly providing for consideration of a separate TFA quality standard in a future review.

In this context, Croatia represents an important case for assessing the extent to which existing monitoring covers this highly mobile ultrashort-chain PFAS. In particular, the availability of TFA measurements in Croatian surface waters, drinking water, groundwater, agricultural soils and food remains an important consideration for establishing national baseline values and determining monitoring priorities.

Objectives

This study therefore aims to:

- *Assess the available empirical evidence* on TFA occurrence in Croatian surface waters and drinking water, including data obtained in the recent European and national screening initiatives;
- *Evaluate the Croatian regulatory and monitoring framework* for TFA in the context of current EU requirements and emerging environmental-quality standards;
- *Characterise potential TFA sources and transport pathways* relevant to Croatia, with particular attention to atmospheric deposition and the environmental transformation of fluorinated pesticide active substances;
- *Identify critical monitoring and data gaps*, particularly concerning groundwater, agricultural soils, crops and food matrices; and
- *Develop evidence-based recommendations* for analytical monitoring, environmental surveillance, pesticide risk assessment and regulatory implementation.

Materials and methods

Study design

This study was designed as a structured narrative evidence review aimed at identifying, categorising and critically interpreting publicly available evidence on the occurrence of trifluoroacetic acid (TFA) and related per- and polyfluoroalkyl substances (PFAS) in Croatia.

The main focus of the study was to determine whether publicly available evidence exists on the presence of TFA in different environmental media in Croatia and to assess the extent to which existing monitoring systems enable the identification and assessment of TFA contamination. Particular attention was paid to distinguishing data relating directly to TFA from data relating to PFAS as a broader group of chemicals.

The study did not involve primary sampling or laboratory analysis. The analysis was based on existing publicly available data from official reports, scientific and technical literature, research projects, reports by civil society organisations, and relevant European regulatory and institutional documents.

Research questions

The analysis was conducted with the aim of answering the following research questions:

1. What publicly available evidence exists on the occurrence of TFA in the environment of the Republic of Croatia?
2. In which environmental media are data on the presence of TFA available?
3. What TFA concentrations have been recorded in Croatian samples to date?
4. To what extent do existing Croatian environmental and water monitoring systems address TFA?
5. Are there significant gaps in the available data on TFA in surface water, groundwater, water intended for human consumption, soil, food and biota?
6. To what extent can existing data on PFAS be used to assess the occurrence of TFA?
7. What potential sources and environmental pathways of TFA can be identified on the basis of the available literature and regulatory documents?

Search strategy and data sources

For the purposes of the study, publicly available data were collected from several groups of sources.

Searches were conducted between 1 August and 25 August 2026, with the final source verification performed on 25 August 2026. Sources searched included Google Scholar and Google Search; the websites and document repositories of the Croatian Institute of Public Health (HZJZ), Hrvatske vode, the Josip Juraj Strossmayer Water Institute, the Croatian Veterinary Institute, the European Food Safety Authority (EFSA), the European Chemicals Agency (ECHA), the European Commission, the European Parliament and EUR-Lex; and the websites of Pesticide Action Network Europe (PAN Europe) and Earth Trek (Zemljane staze). Publisher websites, DOI records, and the reference lists of eligible publications and reports were also searched to identify additional relevant material. Searches were restricted to sources in Croatian and English and were conducted by Natalija Svrtan.

The first group comprised official Croatian sources, including reports and documents from the Croatian Institute of Public Health (HZJZ), Hrvatske vode, the Josip Juraj Strossmayer Water Institute, the Croatian Agency for Agriculture and Food (HAPIH), and other competent public authorities and institutions.

Importance is given to the monitoring of water intended for human consumption. The HZJZ report for 2025 states that PFAS testing was conducted on 473 samples of water intended for human consumption, including 77 raw-water samples and 396 treated-water samples (HZJZ, 2026a). Twenty PFAS compounds comprising the “Sum of PFAS” parameter were analysed.

The second group comprised European and international institutional sources, including documents from European Union institutions, relevant regulatory documents, and publicly available responses and documents from the European Commission and the European Parliament.

The third group comprised scientific and technical sources, including scientific publications and technical reports on the occurrence of TFA and PFAS compounds, their sources, environmental persistence, mobility, and potential pathways of environmental transport.

The fourth group comprised research reports by civil society organisations, particularly PAN Europe, containing data obtained through the analysis of surface water, groundwater and water intended for human consumption samples from several European countries. Earth Trek participated in the collection of the Croatian sample in one such study. The available materials state that the study of surface water and groundwater covered ten EU Member States, including Croatia.

The search focused on combinations of terms in Croatian and English, including:

- “trifluoroacetic acid”;
- “trifluorooktenska kiselina”;
- “TFA Croatia”;
- “TFA Hrvatska”;
- “PFAS Croatia”;
- “PFAS Hrvatska”;
- “TFA water Croatia”;
- “TFA drinking water Croatia”;
- “TFA groundwater Croatia”;
- “TFA surface water Croatia”;
- “PFAS monitoring Croatia”;
- “PFAS pesticides Croatia”.

For each identified source, the references and related documents were also reviewed to identify additional data relevant to Croatia.

Study-selection counts were not recorded prospectively and could not be reconstructed reliably. Sources were selected according to their relevance to the predefined research questions and eligibility criteria. All sources included in the final synthesis are documented in the reference list. No formal review protocol was prepared or registered.

Inclusion and exclusion criteria

Sources were included in the analysis if they contained:

1. direct data on measured TFA concentrations in Croatia;
2. data on PFAS monitoring in the Croatian environment;
3. information on the methods and scope of national monitoring relevant to TFA;

4. data on the occurrence of TFA or PFAS in Croatian surface water, groundwater, water intended for human consumption, soil, food or biota;
 5. information relevant to identifying gaps in the existing monitoring system;
 6. European data used as a reference context for interpreting Croatian findings.
- Sources were excluded if they did not contain sufficient information to identify the environmental medium, location, substance analysed or methodology, as well as sources containing only general information on PFAS without a connection to Croatia or relevance to the interpretation of TFA.

Data extraction and categorisation

For each included source, the following data were collected where available:

- author or institution;
- year of publication;
- type of source;
- geographical location;
- environmental medium;
- substance analysed;
- number of samples;
- analytical method;
- limit of detection and/or limit of quantification;
- measured concentration;
- unit of measurement;
- regulatory or reference value, where applicable;
- information on the potential source of contamination;
- limitations of the available data.

The data were then classified according to environmental medium into the following categories:

1. water intended for human consumption;
2. surface water;
3. groundwater;
4. soil;
5. food;
6. fish and other aquatic organisms;
7. wildlife and other biota.

Sources containing direct TFA measurements were specifically identified, while data on other PFAS substances were analysed separately. This approach was taken to avoid equating general PFAS monitoring with TFA monitoring.

Assessment of the scope of existing monitoring

To assess the ability of the existing monitoring system to identify TFA contamination, the following were analysed:

- coverage of environmental media;

- number and spatial distribution of samples;
- types of PFAS compounds analysed;
- inclusion or exclusion of TFA from analytical methods;
- monitoring frequency;
- public availability of results;
- existence of national reference or regulatory values.

Particular attention was paid to distinguishing between the parameters “Total PFAS” and “Sum of PFAS” and the direct determination of individual compounds. In the Croatian framework for water intended for human consumption, “Sum of PFAS” is defined as a group of substances listed in the relevant annex to the legislation, while HZJZ documentation describes the analysis of 20 PFAS substances.

Therefore, the results of existing PFAS monitoring were interpreted as an indication of the presence of the PFAS compounds analysed, but not automatically as evidence of the absence of TFA in samples in which TFA was not directly determined.

Identification of data gaps

Gaps in the available data were identified by comparing the existing evidence across different environmental media.

Each environmental medium was classified according to the level of data availability as follows:

- *good data availability* - *systematic or relatively extensive measurements are available;*
- *limited data availability* - *individual or spatially and temporally limited data are available;*
- *major data gap* - *no systematic monitoring exists or no publicly available data were identified.*

According to the initial analysis of the available materials, there is concrete publicly available evidence of TFA in Croatian surface water and water intended for human consumption. For the Sava River sample, a concentration of 620 ng/L is reported, while 160 ng/L TFA was recorded in a sample of water intended for human consumption, taken in the city of Samobor, Zagreb County.

Data availability is more limited for groundwater, food, soil and biota. A European wine screening provides two individual Croatian food-matrices results: 21 µg/kg TFA in a 2023 Malvazija from Istria and 48 µg/kg in a 2024 Graševina from Vukovarsko-srijemska County. These two observations document occurrence but cannot establish a Croatian concentration range or representative national food baseline. The PFASsFoodWildlife project, coordinated by the Croatian Veterinary Institute with HAPIH and other Croatian research institutions as partners, is investigating more than 20 PFAS substances in food of animal origin and selected animal species during 2024-2027. Public project descriptions do not specify whether TFA is included among the target analytes.

Analysis of potential sources and contamination pathways

Potential sources and pathways of TFA were analysed based on the available scientific literature, technical reports and regulatory documents.

The following sources and pathways were considered:

- use of fluorinated chemicals;
- application of PFAS pesticides and their degradation;
- fluorinated gases in cooling systems and other industrial applications;
- atmospheric transport and deposition;
- wastewater;
- surface-water and groundwater transport.

The analysis of potential sources was not used to attribute a specific Croatian finding to an individual source of contamination. The presence of a particular potential source in an area was not considered evidence of a causal relationship with the measured TFA concentration. Potential sources were interpreted solely as possible environmental pathways requiring further investigation and analyses.

Study limitations

The main limitation of this study is the fact that the analysis is based on publicly available secondary data. The quantity, quality and comparability of the available information vary across environmental media and sources.

Because the search included grey literature and institutional webpages without independent duplicate screening or formal quality assessment, the review may be affected by selection and publication bias, changes in online sources, and variations in evidence quality. Organisational screening reports should be distinguished from peer-reviewed studies, and their sampling and analytical documentation should be cited directly.

Another limitation is that different studies and monitoring programmes do not necessarily analyse the same groups of PFAS compounds or use the same analytical methods, limits of detection and limits of quantification. Therefore, data on individual PFAS compounds cannot automatically be used as a substitute for TFA data.

Due to the limited number of identified Croatian TFA measurements, the results of this analysis cannot be used to estimate the national average TFA concentration or to calculate the spatial or temporal distribution of contamination in the Republic of Croatia. For this reason, the findings are interpreted as evidence of documented occurrence rather than as a representative assessment of the overall TFA pollution in Croatia.

The results of this study provide a starting point for future systematic measurements of TFA in different environmental media and for the development of a national monitoring programme that would enable a more reliable assessment of the distribution, sources and potential exposure pathways of TFA in the Republic of Croatia.

Use of generative AI and editorial assistance

During the preparation of this manuscript, the author used OpenAI's ChatGPT for spelling and grammar checking, improving clarity and structure, formatting, and assistance with the preparation of tables and figure. The author critically reviewed and revised all AI-assisted inputs, independently verified the factual statements, numerical data and references against the cited sources, and takes full responsibility for the final content of the manuscript. Generative AI was not used as an author and did not determine the study conclusions.

Results

Available evidence on TFA in Croatian waters

Despite the historical lack of short-chain per- and polyfluoroalkyl substances (PFAS) surveillance in Croatia, screening campaigns have confirmed the presence of trifluoroacetic acid (TFA) in both surface water and drinking water resources.

- Surface waters:** In an international multi-country screening study conducted by Pesticide Action Network (PAN) Europe in collaboration with Croatian non-governmental organisation Earth Trek (Zemljane staze) in April 2024, surface water sampling was carried out across ten EU member states. The Croatian surface water sample retrieved from the Sava River revealed a TFA concentration of approximately 620 ng/L. Across the 23 European surface-water samples, TFA concentrations ranged from 370 to 3,300 ng/L, with a reported mean of 1,220 ng/L, placing the Sava River sample among the lower concentrations reported in the European screening campaign (PAN Europe, 2024a).
- Drinking water (Water intended for human consumption):** In the related PAN Europe screening of drinking water, the Croatian tap-water sample collected in Samobor contained 160 ng/L TFA (Earth Trek, 2024b). Across 11 EU countries, TFA was quantified in 34 of 36 tap-water samples (94%), at concentrations ranging from below the 20 ng/L detection limit to 4,100 ng/L; the reported mean was 740 ng/L. The programme also included 17 mineral-water and two spring-water samples, of which 12 of 19 contained TFA, with concentrations ranging from below detection to 3,200 ng/L and a reported mean of 278 ng/L. In the four composite drinking-water samples analysed for TFA and 24 additional PFAS, TFA accounted for more than 98% of the combined PFAS burden. These European screening results provide context for the Samobor observation but are not a statistically representative assessment of Croatian drinking water. The verified Croatian water measurements are summarised in Table 1.

Table 1 Reported TFA and PFAS measurements relevant to Croatian water matrices

Environmental medium and sampling location	Parameter / analyte	Reported result and data origin	Interpretation and limitations
Surface water Sava River, Croatia	Trifluoroacetic acid (TFA)	Approximately 620 ng/L PAN Europe surface-water screening (2024a)	Single screening result documenting TFA occurrence at the sampled location and time. It is not nationally representative and does not permit source attribution or a direct regulatory-compliance assessment.
Tap water Samobor, Zagreb County, Croatia	Trifluoroacetic acid (TFA)	160 ng/L PAN Europe drinking-water screening; Earth Trek (2024b)	Single screening result; not nationally representative. The 0.10 µg/L 'Sum of PFAS' value is not applicable to this result because TFA is excluded from that 20-PFAS parameter.

Environmental medium and sampling location	Parameter / analyte	Reported result and data origin	Interpretation and limitations
Raw water (spring) Tonkovića vrilo, Croatia	PFAS (20-compound analytical panel)	5.2 ng/L (0.0052 µg/L) HZJZ supplementary monitoring/official communication, 2026	Single result from additional monitoring conducted in 2026. The reported concentration was below the 0.10 µg/L parametric value applicable to the ‘Sum of PFAS’. TFA was not included in the analytical panel; consequently, this result provides no information on the occurrence or concentration of TFA.

Note. LOQ = limit of quantification; EQS = environmental quality standard; HZJZ = Croatian Institute of Public Health. The table distinguishes direct TFA observations from measurements of other PFAS parameters.

Official national PFAS monitoring framework

Official Croatian drinking-water monitoring currently covers specified PFAS parameters, but TFA is not included in the 20-compound “Sum of PFAS” analytical panel.

Water intended for human consumption (HZJZ surveillance data)

Under the national legislative framework established pursuant to Directive (EU) 2020/2184, the Croatian Institute of Public Health (HZJZ) conducted targeted exploratory surveillance of drinking water in 2025. Monitoring of the PFAS parameters laid down in Directive (EU) 2020/2184 became mandatory from 12 January 2026 and was incorporated into the Croatian national monitoring programme for 2026.

- *Sample distribution:* A total of 473 samples were analysed across consumption sites nationwide, comprising 77 raw water samples and 396 treated-water samples collected at points of consumption (HZJZ, 2026a).
- *Analytical method:* Quantification was executed via direct injection Liquid Chromatography - Tandem Mass Spectrometry (LC-MS/MS) with a Limit of Quantification (LOQ) of 1.5 ng/L (0.0015 µg/L) per individual compound.
- *Analyte spectrum:* The methodology targeted 20 specific per- and polyfluoroalkyl substances defining the regulatory parameter “Sum of PFAS” (Maximum Admissible Concentration [MAC] = 0.10 µg/L or 100 ng/L). “Sum of PFAS” means the sum of per- and polyfluoroalkyl substances considered a concern as regards water intended for human consumption listed in point 3 of Part B of Annex III of Directive. This is a subset of ‘PFAS Total’ substances that contain a perfluoroalkyl moiety with three or more carbons (i.e. –CnF2n–, n ≥ 3) or a perfluoroalkylether moiety with two or more carbons (i.e. –CnF2nOCmF2m–, n and m ≥ 1).
- *Detection rates:*
 - In raw water, concentrations above the LOQ for the “Sum of 20 PFAS” were detected in 5 samples (6.5%), geographically located in Primorsko-goranska and Zadarska counties. Concentrations ranged from 0.0032 µg/L to 0.044 µg/L (maximum recorded in karst aquifers).

- In treated drinking water, concentrations above the LOQ were reported in eight samples. The HZJZ report describes this as 2.2%. The samples originated from Primorsko-goranska, Zadarska and Zagreb counties, and the reported concentrations ranged from 0.0021 to 0.025 µg/L. All quantified values were below the 0.10 µg/L parametric value for the “Sum of PFAS”.
- Additional monitoring in 2026: In an official communication published in August 2026, HZJZ reported that 14 PFAS analyses had been conducted during 2026 through the national drinking-water monitoring programme, source-water monitoring and monitoring performed by the water supplier. PFAS were detected in only one of these samples, collected from the Tonkovića vrilo spring, at a reported concentration of 0.0052 µg/L (5.2 ng/L). HZJZ stated that this concentration was approximately 20 times lower than the applicable maximum admissible value and lower than the highest concentrations reported in raw groundwater from Croatian karst areas during the 2025 exploratory monitoring. The result concerns the analysed 20-PFAS panel and does not provide information on TFA, which was not included among the target analytes (HZJZ, 2026b).
- *Analytical Exclusion of TFA*: Because TFA possesses a two-carbon chain (C₂HF₃O₂), it falls entirely outside the 20-compound list constituting the regulatory “Sum of PFAS” parameter. Because TFA was not included in the analytical panel, the 473-sample HZJZ dataset generated no TFA concentration results.

Surface water monitoring (PFOS focus)

Surface water monitoring conducted by Hrvatske vode and the Josip Juraj Strossmayer Water Institute focuses primarily on designated Environmental Quality Standard (EQS) priority substances, notably perfluorooctane sulfonate (PFOS). For instance, targeted testing in Ličko-senjska County (sampling sites: Lika - Bilaj, Lika - Ostrvica bridge, Lika - Budak, and the Brlog - Gusić polje reservoir) confirmed PFOS concentrations consistently below the LOQ <0.00065 µg/L (<0.65 ng/L). These monitoring protocols do not routinely incorporate ultrashort-chain PFAS like TFA.

Contextual evidence from food and PFAS-pesticide residue screening

Wine screening: A 2025 European campaign analysed 10 older wines and 39 more recent wines from ten countries. TFA was detected in all 39 recent wines, with a median concentration of 110 µg/L and a maximum of 320 µg/L, while it was not detected in wines produced before 1988; the accompanying report describes a marked increase after 2010 (Earth Trek, 2025b). The underlying sample table reports two Croatian results in mass-based units: a 2023 Malvazija from Istria contained 21 µg/kg TFA and 11 µg/kg metalaxyl, while a 2024 Graševina from Vukovarsko-srijemska County contained 48 µg/kg TFA and 10 µg/kg boscalid. Each sample had one pesticide or metabolite above the limit of detection. These two samples document TFA occurrence in Croatian wine but are insufficient to characterise national occurrence or infer the source of TFA in either sample (PAN Europe, 2025).

PFAS-pesticide residues in fruit and vegetables: An Earth Trek summary of the ‘Toxic Harvest’ analysis, based on official pesticide-residue monitoring data, reported that 10.6% of 847 Croatian fruit samples collected during 2014-2021 contained at least one PFAS pesticide residue. The proportion increased from 1.5% in 2014 to 14.7% in 2021. For vegetables, the reported proportion increased from 0.8% to 14.6% over the same period. Among Croatian-grown products sampled in 2021, residues were detected in 8% of fruit and 12% of vegetables; the most frequently affected categories reported were apples (15%), melons (10%) and strawberries (10%) among fruit, and cucumbers (33%), carrots (21%) and peppers (10%) among vegetables. These results concern residues of PFAS pesticide active substances, not TFA measurements, and therefore provide contextual evidence of pesticide use and dietary exposure pathways rather than direct evidence of TFA in Croatian produce (Earth Trek, 2024a).

440

441 Comprehensive data gap matrix across environmental compartments

442

443 Comparing verified evidence with institutional programmes reveals critical monitoring gaps across Croatian
 444 environmental compartments. The availability of Croatian TFA and PFAS data and the principal monitoring gaps
 445 are summarised in Table 2.

446 *Table 2 Availability of Croatian TFA and PFAS data across environmental matrices and principal monitoring*
 447 *gaps*

Environmental matrix	Data availability	Current publicly available evidence or monitoring	Principal limitation / monitoring need
<i>Drinking water</i>	Limited	HZJZ reports national monitoring of the 20 PFAS included in the regulatory ‘Sum of PFAS’ parameter. TFA is not included in that analytical panel. One PAN Europe screening sample from Samobor contained 160 ng/L TFA (HZJZ, 2026a; PAN Europe, 2024b; Earth Trek, 2024b).	The HZJZ dataset provides no TFA results. No systematic publicly available national dataset describing TFA occurrence, spatial distribution or temporal trends in Croatian drinking water was identified. Public documentation does not establish whether Croatian laboratories routinely use a method validated and accredited specifically for TFA.
<i>Surface water</i>	Limited	A PAN Europe screening sample from the Sava River contained approximately 620 ng/L TFA. This is a single measurement from one place and time (PAN Europe 2024a).	No systematic multi-year Croatian surface-water monitoring dataset for TFA was identified. The single screening result is not nationally representative and cannot establish temporal trends, spatial distribution or source attribution.
<i>Groundwater</i>	Major gap	No systematic publicly available Croatian groundwater monitoring dataset reporting TFA concentrations was identified in this review.	National occurrence, spatial distribution and temporal trends cannot be assessed from publicly accessible data. This is a priority gap because Croatian drinking-water resources include vulnerable and highly connected karst aquifers.
<i>Agricultural soil</i>	Major gap	No publicly available systematic Croatian monitoring data on TFA in agricultural soil were identified. International studies demonstrate that several C-CF ₃ pesticide active substances can form TFA in soil.	Croatian data are needed on TFA concentrations, formation under representative soil and climatic conditions, and movement from soil into drainage water and groundwater. International findings cannot quantify contributions in Croatia.
<i>Food and feed</i>	Limited / major gap	Two Croatian wines were quantified for TFA: Malvazija, 21 µg/kg, and Graševina, 48 µg/kg (PAN Europe, 2025). Separate Croatian fruit and vegetable data concern residues of PFAS pesticide active substances, not TFA. The Croatian Veterinary Institute-led PFASsFoodWildlife project examines more than 20 PFAS in food of animal origin and animal species.	Two wine samples cannot establish a national food baseline. No systematic Croatian TFA monitoring programme for crops, feed or food was identified. The public PFASsFoodWildlife project description does not establish that TFA is included among the target analytes.

Environmental matrix	Data availability	Current publicly available evidence or monitoring	Principal limitation / monitoring need
<i>Biota and wildlife</i>	Major gap	The Croatian Veterinary Institute leads the ongoing PFASsFoodWildlife project on more than 20 PFAS in animal species from aquatic and terrestrial habitats, with HAPIH and other institutions participating as partners (Croatian Veterinary Institute, 2024-2027).	The publicly available project description does not confirm that TFA is a target analyte. No publicly available Croatian dataset on TFA occurrence or uptake in aquatic or terrestrial biota was identified.
<i>Wastewater and landfill leachate</i>	Major gap	International literature identifies wastewater treatment discharges, landfill leachate and waste disposal as plausible TFA pathways. No publicly available Croatian TFA-specific monitoring results for these matrices were identified in this review.	Croatian measurements are required before the occurrence or contribution of these pathways can be characterised. International evidence alone cannot demonstrate that landfills or wastewater are important TFA sources in Croatia.

Note. The classifications describe the publicly available evidence identified in this review and do not establish that no unpublished or non-public monitoring data exist. PFASsFoodWildlife is led by the Croatian Veterinary Institute; HAPIH participates as a project partner. TFA = trifluoroacetic acid; PFAS = per- and polyfluoroalkyl substances; HZJZ = Croatian Institute of Public Health.

Discussion

Environmental significance of reported TFA levels in Croatia

In a 2024 European monitoring campaign conducted by PAN Europe and its members, TFA was detected in 34 of 36 tap-water samples (94%), at concentrations ranging from below 20 to 4,100 ng/L, with a mean concentration of 740 ng/L. The Croatian tap-water sample, collected in Samobor, contained 160 ng/L TFA. This result should not be assessed against the 100 ng/L “Sum of PFAS” parametric value established by Directive (EU) 2020/2184, because TFA is not among the 20 PFAS included in that parameter. Although the measured TFA concentration is numerically higher than 100 ng/L, this does not indicate non-compliance with the “Sum of PFAS” requirement. The Directive also establishes a separate “PFAS Total” parametric value of 500 ng/L; however, this is a regulatory parametric value rather than a health-based guidance value, and the assessment of the Samobor result against it would require confirmation that Croatia applies the “PFAS Total” parameter and that the analytical method used covers TFA. Consequently, the reported concentration documents the presence of TFA in Croatian tap water but, by itself, does not establish either compliance or non-compliance with the applicable drinking-water standards (Earth Trek, 2024b; Directive (EU) 2020/2184).

Identification of potential sources and transport pathways in Croatia

Because this evaluation relies on secondary evidence, direct source attribution for specific sampling sites cannot be established. Nevertheless, peer-reviewed literature and regulatory reports identify several anthropogenic pathways potentially relevant to TFA occurrence in Croatia, including degradation of C- CF_3 pesticide active ingredients, atmospheric transformation and deposition of fluorinated gases and other precursors, and releases associated with landfills and waste disposal. Their occurrence and relative contributions in Croatia have not been established through a Croatian source-apportionment study.

The principal plausible pathways considered in this review are summarised in Figure 1.

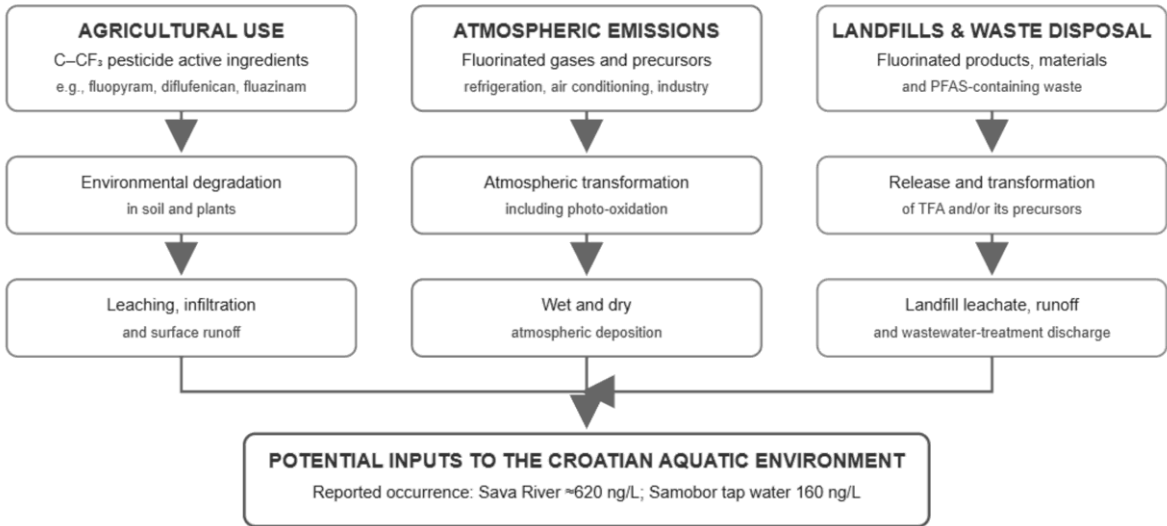


Fig. 1 Plausible anthropogenic pathways relevant to TFA occurrence in Croatia.

The pathways shown represent plausible mechanisms identified from European and international evidence; their occurrence and relative contributions in Croatia have not been established by a Croatian source-apportionment

study. The reported water concentrations demonstrate the occurrence of TFA but do not identify the sources responsible

Agricultural degradation of C-CF₃ pesticides

Johnsen et al. (2026) monitored seven C-CF₃ pesticides over 52 weeks in three agricultural soils and detected TFA formation from every tested active substance. The tested compounds were trifluralin, fluazifop-P-butyl, fluazinam, tau-fluvalinate, diflufenican, fluopyram and mefentrifluconazole. Formation differed both among compounds and among soils, confirming that the presence of a C-CF₃ moiety indicates potential to form TFA but does not by itself determine the transformation rate.

- *Conversion efficiencies:* The highest reported formation was 10.7% of the applied fluopyram in one soil, compared with 3.3% and 7.9% in the other two soils. Formation amounted to 5.3%-6.5% for fluazinam, 2.4%-5.2% for diflufenican, 3.0%-5.3% for fluazifop-P-butyl, 1.1%-2.2% for trifluralin, 0.8%-3.3% for mefentrifluconazole and 0.4%-1.0% for tau-fluvalinate (Johnsen et al., 2026).
- *Leaching modelling and priority substances:* Environmental emission and FOCUS groundwater modelling across EU crop cultivation scenarios indicate nine active substances as major sources of TFA leaching into subterranean aquifers: diflufenican, flonicamid, fluazifop-P-butyl, fluazinam, flufenacet, fluopyram, flutolanil, picolinafen, and trifloxystrobin (Diehle et al., 2025).
- *Relevance to Croatia:* Using the measured formation fractions, Johnsen et al. (2026) estimated that, for some crop and growth-stage scenarios, annual TFA contributions from C-CF₃ pesticide applications to net precipitation infiltrating arable topsoil may be comparable to atmospheric contributions beneath treated fields. This finding indicates the plausibility of an agricultural pathway but cannot quantify its importance in Croatia without national pesticide-use data, information on application rates and timing, and measurements or fate modelling under representative Croatian soil and climatic conditions.

Atmospheric oxidation of hydrofluoroolefins (HFOs) and hydrofluorocarbons (HFCs)

Atmospheric transformation of fluorinated gases is a plausible diffuse input pathway, but its contribution to the Croatian TFA measurements has not been quantified.

- HFO-1234yf, used particularly in mobile air conditioning, reacts rapidly with atmospheric hydroxyl radicals and forms trifluoroacetyl fluoride, which hydrolyses to TFA. Its short lifetime and comparatively high TFA yield favour formation and deposition nearer to emission regions. HFC-134a is longer-lived and more globally dispersed, and earlier atmospheric models assumed a lower TFA yield (Kotamarthi et al. (1998)). However, theoretical calculations by Vincent et al. (2026) indicated that the proposed reaction pathways leading to TFA and trifluoroacetyl fluoride require too much energy to occur readily under atmospheric conditions. Their study did not rule out atmospheric TFA formation from HFC-134a, but it challenges the previously proposed mechanism; the magnitude of this source should therefore be treated as uncertain (David et al., 2021; Garavagno et al., 2024; Vincent et al., 2026).
- Using 2023 emissions and the STOCHEM-CRI chemical transport model, Holland et al. (2026) predicted that HFO-1234yf already contributed more to atmospheric TFA generation and deposition over Europe than HFC-134a, despite estimated global HFC-134a emissions being 22 times greater. The model estimated global TFA production from HFO-1234yf at 26%-75% of that from HFC-134a. Earlier modelling of complete conversion of mobile air-conditioning refrigerants to HFO-1234yf estimated a mean European TFA deposition rate of 0.52 kg km⁻² year⁻¹ and showed that regional deposition occurred mainly by emissions within the same region (Wang et al., 2018). Other modelling suggests that a

significant amount can also be transported beyond the emission region and that rainwater concentrations depend strongly on precipitation (David et al., 2021). Atmospheric deposition should therefore not be considered as spatially uniform, but it varies depending on emissions, transport, chemistry, rainfall and geography. These are model-derived results, not measurements of atmospheric deposition in Croatia, and they cannot identify the source of the Sava River or Zagreb County observations.

Landfills, waste disposal and wastewater pathways

Landfills may act as secondary sources of TFA because municipal and industrial waste streams contain fluorinated products, materials and chemical residues that may already contain TFA or substances that are precursors of TFA. Water percolating through deposited waste can mobilise these highly soluble substances and transport them into landfill leachate. In a Swedish investigation of waters associated with landfills, firefighting training sites and a hazardous waste facility, ultrashort-chain perfluoroalkyl acids were detected in all analysed samples. TFA was associated particularly with samples originating from the landfills, and concentrations in landfill leachate ranged from below 34 to 6,900 ng/L. However, the observed concentrations varied considerably among sites, indicating that waste composition, landfill age, hydrology and leachate management influence the magnitude of releases (Björnsdotter et al., 2019).

TFA from the landfill leachate may reach the aquatic environment through several pathways: leakage or runoff, discharge after the on-site treatment, and transfer to municipal wastewater treatment plants. Wastewater treatment plants should be primarily considered as a collection and transfer points for TFA and its precursors rather than as their original source. Evidence from the German water cycle indicates that TFA was not effectively removed by conventional biological wastewater treatment or by a retention-soil filter used to treat combined sewer overflows. Because TFA dissolves easily in water and does not readily bind to particles, it is expected to remain in the water and pass through wastewater treatment, unless a treatment method specifically designed to remove or destroy ultrashort-chain PFAS is used. (Scheurer et al., 2017).

Wastewater may also contain fluorinated pesticide residues, pharmaceuticals, industrial chemicals and their transformation products. Conventional treatment can change the composition of PFAS mixtures, and biological treatment may transform some precursor substances into more persistent perfluoroalkyl acids. Still, the formation of TFA should not be assumed for every fluorinated precursor or treatment process. The laboratory work examining selected PFAS pesticides and pharmaceuticals in the wastewater treatment processes found variable transformation products but negligible TFA formation potential for the tested substances. This finding indicates that wastewater effluent may transport TFA already present in influent streams, while the extent of additional TFA formation during treatment is substance- and process-specific and remains uncertain (Kim et al., 2022; Li et al., 2026).

No publicly available Croatian measurements of TFA in landfill leachate, untreated or treated municipal wastewater, sewage sludge, or receiving waters immediately upstream and downstream of wastewater treatment discharges were identified in this review. Consequently, landfills and wastewater pathways should be treated as plausible sources and transport routes relevant to Croatia, not as demonstrated contributors to the TFA concentrations measured in the Sava River or Samobor tap-water sample. Their potential importance could be assessed through coordinated monitoring of landfill leachate, wastewater influent and effluent, sewage sludge, groundwater near disposal sites, and receiving surface waters. The monitoring should measure TFA directly and, where feasible, include precursor-sensitive or total-organic-fluorine approaches to distinguish existing TFA from compounds with the potential to form it.

Critical monitoring deficits and regulatory gaps in Croatia

The analysis highlights three major structural gaps in Croatia's environmental surveillance framework:

574

575 The regulatory "chain-length blind spot"

576

577 The primary compliance parameter for drinking water in Croatia, the "Sum of PFAS", covers 20 specifically listed
578 PFAS and does not include TFA. Compliance with this parameter provides no information on the presence or
579 concentration of TFA and should not be interpreted as evidence of its absence.

580

581 Analytical and methodological barriers

582

583 Standard solid-phase extraction (SPE) methods optimised for hydrophobic, longer-chain PFAS generally provide
584 poor retention of TFA because of its high polarity, high water solubility and low octanol-water partition coefficient.
585 Quantitative determination of TFA therefore requires an analytical method specifically validated for this
586 compound, such as direct-injection liquid chromatography-tandem mass spectrometry (LC-MS/MS) or ion
587 chromatography-mass spectrometry (IC-MS). Although HZJZ reports using direct-injection LC-MS/MS for its 20-
588 PFAS analytical panel, the available documentation does not establish whether this method has been validated and
589 accredited specifically for TFA or whether such TFA-specific methods are routinely applied by Croatian public-
590 health and water-management laboratories. Direct confirmation from the relevant laboratories is therefore
591 required.

592

593 Data absences across karst aquifers, soils, and food matrices

594

- 595
- 596 • *Karst hydrology vulnerability*: While limited surface water data exists, systematic baseline data for
597 Croatian groundwater are absent. Publicly available Croatian groundwater data are insufficient to
598 establish a national baseline for TFA. In Croatia's extensive karst regions (Dinaric region), rapid conduit
599 flow and minimal soil attenuation increase the vulnerability of subterranean drinking water sources to
fast-percolating mobile short-chain acids.
 - 600 • *Limited food and agricultural data*: Two Croatian wines provide direct but isolated food-matrix
601 observations: 21 µg/kg TFA in Malvazija and 48 µg/kg in Graševina (PAN Europe, 2025). No systematic
602 Croatian TFA measurements in food crops, soils or animal-derived foods were identified. Separate
603 Croatian data show residues of PFAS pesticide active substances in fruit and vegetables, but these are not
604 measurements of TFA or its formation in Croatian soils. Because TFA moves easily through water and
605 can be taken up by plants, it is important to distinguish between conventional bioaccumulation in lipids
606 and the accumulation of TFA in plant tissues (Earth Trek, 2024a, 2025b; Hanson et al., 2024).

607

608 Implications for human health and exposure

609

610 The limited Croatian measurements identified in this review do not allow conclusions about human health risks.
611 The concentration of approximately 620 ng/L (PAN Europe, 2024a) measured in the Sava River represents a
612 surface-water observation and should not be interpreted as a direct estimate of human exposure. The concentration
613 of 160 ng/L detected in the Samobor tap-water sample provides evidence that exposure through drinking water
614 occurred, but a single sample cannot establish the concentration range, temporal variability or exposure of the
615 wider Croatian population.

As an illustrative calculation, consumption of two litres per day of water containing 160 ng/L TFA would result in an intake of approximately 0.32 µg TFA per day. For an adult weighing 70 kg, this corresponds to approximately 0.0000046 mg/kg body weight per day, considerably below the EFSA acceptable daily intake of 0.014 mg/kg body weight per day established in 2026. This comparison should not be interpreted as a formal risk assessment. It considers only one drinking water measurement and excludes exposure from food, other beverages and environmental sources, as well as possible variation in water consumption, body weight and TFA concentrations over time. The available Croatian evidence is therefore insufficient to characterise aggregate population exposure.

Nevertheless, toxicological concern regarding TFA has increased. A GLP-compliant prenatal developmental toxicity study conducted under OECD Test Guideline 414 and submitted by the REACH registrants in 2021 reported eye and skeletal abnormalities in rabbit fetuses following maternal exposure to sodium trifluoroacetate. A developmental no-observed-adverse-effect level could not be established because adverse fetal findings occurred at the lowest tested dose of 180 mg/kg body weight per day. A subsequent mechanistic study in rabbits reproduced characteristic ocular abnormalities at lower dose levels. These animal findings do not quantify human risk at environmental exposure concentrations, but they provided important evidence for the regulatory assessment of TFA's developmental toxicity (EFSA, 2024; EFSA et al., 2026).

In June 2026, ECHA's Committee for Risk Assessment recommended the harmonised classification of TFA as toxic to reproduction, Category 1B (Repr. 1B; H360Df), indicating that it may harm the unborn child and is suspected of damaging fertility. The recommendation also classified TFA as persistent, mobile and toxic (PMT) and very persistent and very mobile (vPvM) (ECHA RAC, 2026). The recommended classification is not yet legally binding, pending its incorporation into the CLP Regulation, but it strengthens the scientific and regulatory basis for limiting exposure and improving surveillance of TFA in drinking water and food (ECHA RAC, 2026).

Oral intake through water and food is currently the most documented pathway of population exposure. Dermal exposure is insufficiently characterised. Espartero et al. (2025) showed that certain short-chain PFAS can permeate human skin in vitro more readily than the tested long-chain PFAS. TFA was not included in that study. Although its small molecular size could favour diffusion, its near-complete ionisation and extremely low lipid affinity may limit partitioning into the lipid-rich stratum corneum. The dermal permeability of TFA therefore cannot be reliably inferred from molecular size or from results obtained for other short-chain PFAS. The findings nevertheless indicate that dermal exposure should not automatically be excluded when evaluating prolonged or repeated contact with water contaminated with TFA and that direct experimental investigation under environmentally relevant conditions is required.

The principal health relevance of the Croatian findings therefore lies not in demonstrating an immediate health risk, but in documenting an exposure pathway that is not included in the current "Sum of PFAS" drinking-water parameter. TFA's extreme persistence means that continued emissions may increase environmental concentrations and cumulative exposure over time. Systematic monitoring of drinking water, groundwater, food and relevant exposure pathways is necessary before the magnitude and distribution of health risks in Croatia can be adequately assessed.

Policy context and implications

In April 2025, Earth Trek and supporting Croatian organisations sent open letters to the ministries responsible for agriculture, environmental protection and health. They called for targeted analyses of TFA and other PFAS in surface water, groundwater, drinking water, soils, sediments and aquatic organisms; public disclosure of the results; explicit inclusion of TFA in national monitoring; support for EU water-quality standards for TFA; and restrictions on PFAS pesticides accompanied by the adoption of safer alternatives (Earth Trek, 2025a). This source documents stakeholder demands rather than empirical evidence of contamination and is included only to characterise the national policy response.

The evidence reviewed here supports the need to strengthen Croatia's capacity to identify and monitor ultrashort-chain PFAS. Existing regulatory monitoring based on the "Sum of PFAS" parameter does not capture TFA, while

the available Croatian occurrence data remain too limited for a representative exposure or risk assessment. Addressing this gap requires validated analytical capacity, the inclusion of TFA as an independent monitoring parameter, improved consideration of TFA formation and leaching in pesticide risk assessment, and coordinated research across water, soil and food matrices. The specific measures arising from these findings are summarised in the Key Recommendations for Research and Policy.

Key recommendations for research and policy

1. *Expand analytical capacity:* Develop and harmonise validated analytical methods, including direct-injection LC-MS/MS, in relevant Croatian public-health and environmental laboratories. The methods should provide limits of detection and quantification suitable for measuring TFA at environmentally relevant concentrations and should be supported by appropriate quality-assurance and interlaboratory-comparison procedures.
2. *Integrate TFA into national water monitoring:* Include TFA as a separate parameter in national monitoring programmes for drinking water, groundwater and surface water, independently of the 20 compounds covered by the regulatory “Sum of PFAS” parameter. Monitoring should be sufficiently frequent and geographically representative to identify spatial and temporal variation, with particular attention to drinking water sources, agricultural areas and vulnerable karst aquifers.
3. *Ensure transparent and comparable reporting:* Publish sampling locations, dates, water-matrix information, analytical methods, limits of detection and quantification, and individual TFA results in accessible formats. Results for TFA should be reported separately from grouped PFAS parameters to prevent compliance with the “Sum of PFAS” value from being misinterpreted as evidence of the absence of TFA.
4. *Strengthen pesticide risk assessment:* Ensure that national and EU assessments of pesticides containing C-CF₃ groups adequately consider their potential to form TFA. Assessments should address formation in soil and other environmental compartments, persistence, mobility, accumulation resulting from repeated use, and leaching into groundwater and surface water. Existing authorisations should be reconsidered where new evidence indicates that these pathways were not adequately assessed.
5. *Expand food, soil and agricultural research:* Include TFA in relevant food and environmental matrices within future national food-safety and environmental research initiatives and, where feasible, within ongoing programmes such as the Croatian Veterinary Institute-led PFASsFoodWildlife project. Research should examine TFA in agricultural soils, irrigation water, crops, including grapes and wine, and food of animal origin, while distinguishing measured TFA from residues of PFAS pesticide active substances.
6. *Assess aggregate human exposure:* Conduct exposure assessments combining representative data from drinking water, food and other relevant sources. Assessments should consider differences in body weight, water and food consumption, age and duration of exposure and should include potentially more highly exposed or vulnerable population groups. Comparisons with health-based guidance values should account for aggregate exposure from all measured sources rather than relying on isolated samples.
7. *Address toxicological and dermal-exposure uncertainties:* Support research on the toxicokinetics and long-term effects of TFA exposure, including developmental and reproductive toxicity at environmentally relevant exposure levels. Direct experimental studies should investigate whether TFA can permeate intact human skin under realistic water-contact conditions. Until such evidence becomes available, dermal uptake should be treated as an unresolved exposure pathway rather than assumed to be either significant or negligible.
8. *Incorporate evolving health evidence into policy:* National risk-management decisions should be periodically reviewed in light of updated EFSA health-based guidance values and the evolving harmonised classification of TFA under the CLP Regulation. The absence of a specific legally binding drinking-water limit for TFA should not prevent monitoring, exposure assessment or proportionate measures to reduce avoidable emissions.

Conclusion

This evidence review provides a synthesis of the currently available evidence on TFA occurrence in Croatian environmental matrices and examines the scope and limitations of existing monitoring.

- *Documented environmental occurrence:* Available screening evidence documents TFA occurrence in a surface-water sample from the Sava River (approximately 620 ng/L) and a tap-water sample from Samobor (160 ng/L). These concentrations fall within the broad range reported in European screening studies. However, because the Croatian evidence is limited to two samples collected at specific locations and times, it cannot be used to determine the prevalence, spatial distribution or temporal variation of TFA contamination in Croatian aquatic environments and drinking-water supplies.
- *Regulatory and analytical blind spots:* The national monitoring programmes reviewed here are based primarily on defined PFAS parameters that do not include TFA. The drinking-water “Sum of PFAS” parameter covers 20 specified PFAS and does not include TFA. Although the EU water-policy framework is evolving, the evidence reviewed here does not demonstrate that TFA is currently monitored routinely as an independent parameter in Croatia.
- *Critical data deficits:* Severe data gaps persist across major environmental compartments in Croatia. No public baseline was identified for TFA in groundwater aquifers or agricultural soils. Food evidence is limited to two quantified Croatian wines (21 and 48 µg/kg TFA), while PFAS-pesticide residue data for Croatian produce do not constitute TFA measurements. Systematic national data for TFA in crops, animal-derived foods and biota therefore remain unavailable.
- *Plausible contamination pathways:* European and international literature identifies several anthropogenic pathways potentially relevant to TFA occurrence in Croatia: atmospheric transformation, transport and deposition of fluorinated gases and other volatile precursors, including HFO-1234yf and certain HFCs; environmental degradation of C-CF₃ pesticide active substances, such as fluopyram, fluazinam and diflufenican; and releases associated with landfills and waste disposal, including landfill leachate, runoff and wastewater treatment discharges. However, their occurrence and relative contributions in Croatia have not been established through a Croatian source-apportionment study.
- *Human-health relevance and exposure uncertainties:* Experimental evidence of prenatal developmental toxicity in animals and ECHA’s recommended classification of TFA as toxic to reproduction, Category 1B, increase the health relevance of continued environmental exposure. The Samobor measurement confirms that exposure through drinking water can occur, but a single sample cannot characterise population exposure or establish a health risk. Aggregate exposure through drinking water, food and other sources has not been assessed for Croatia. Dermal permeability of TFA also remains unresolved: findings for other short-chain PFAS indicate that dermal exposure should not automatically be excluded, but they cannot be used to predict TFA absorption without direct experimental evidence.

The available evidence therefore documents TFA occurrence in Croatian water and food matrices but remains insufficient to characterise the national contamination burden, population exposure or associated health risks. Establishing a reliable national baseline will require validated analytical capacity, representative and transparent monitoring across water, soil and food matrices, assessment of aggregate human exposure and integration of emerging toxicological evidence into environmental and public-health policy.

755 **Statements and Declarations**

756

757 Author contributions

758

759 Natalija Svrtan: Conceptualisation, methodology, investigation, literature search, data curation, formal analysis,
760 interpretation, visualisation, and writing - original draft, review and editing. The author approved the final version
761 of the manuscript and accepts responsibility for the integrity and accuracy of the work.

762 All authors have read, understood, and have complied as applicable with the statement on “Ethical responsibilities
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769

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771

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778

779 Ethics approval and consent to participate

780

781 Not applicable. This evidence review involved no human participants, personal data, animals, or primary biological
782 sampling.

783

784 Consent for publication

785

786 Not applicable.

787

788 Data availability

789

790 No new primary datasets were generated for this study. The review is based on publicly available scientific
791 publications, institutional documents, regulatory materials and screening reports cited in the manuscript. The
792 Croatian measurement results discussed in the review were extracted from the cited publicly available sources. No
793 supplementary dataset or source-extraction table accompanies this article.

794

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