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Accumulation of PFAS in wine from a contaminated area: perfluorobutanoic acid (PFBA) as a molecular marker of PFAS groundwater contamination and implications of wine ingestion for human health

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ABSTRACT

Per- and polyfluoroalkyl substances (PFAS) are persistent contaminants of global concern, with food and drinking water representing major exposure pathways. Despite the regional relevance of wine as an agricultural product, the relationship between PFAS occurrence in wine and natural waters has been scarcely investigated. This study assessed the presence and composition of PFAS in wines produced within and around a highly contaminated area in Italy, examined their relationship with PFAS in groundwater, and considered the potential implications for human exposure. Seventy-six wines were analysed by UPLC-MS/MS. At least one PFAS was quantified in seventy-three wines. Short-chain PFAS dominated the contamination profiles, with PFBA (perfluorobutanoic acid) quantified in 93.5% of samples (median concentration: 196 ng/L, maximum: 18,067 ng/L), followed by PFPeA and PFBS (quantified in 61.5%, and 51.3% of samples, respectively). Higher PFBA concentrations were associated with wines from production areas overlapping the contamination plume ($p = 0.009$). PFBA was highly correlated with the other most quantified PFAS in wine (PFPeA, PFBS, and PFHxA). In contrast to groundwater, long-chain PFAS were rarely detected in wine (<10%). Regression analysis revealed a significant positive association between PFBA concentrations in wine and the nearest groundwater point for vineyards within 75 m of the aquifer (+0.48% in PFBA concentration in wine for each +1% PFBA in groundwater, $p = 0.001$), suggesting spatially mediated transfer from contaminated groundwater, and identifying PFBA as molecular marker of PFAS contamination. Estimated dietary intakes indicated exceedance of the EFSA tolerable weekly intake for 1 wine under the highest consumption scenarios, and for 3-8 wines when relative potency factors were applied. For 3 wines, the estimated daily intake of specific PFAS exceeded the corresponding oral reference doses. These findings indicate that, in PFAS-contaminated areas, wine may act both as a bioindicator of groundwater contamination and as a potentially relevant dietary exposure pathway.

1. Introduction

Per- and polyfluoroalkyl substances (PFAS) are a class of highly fluorinated chemicals of global concern because of their high environmental persistence and ubiquitous diffusion (Evich et al., 2022), bioaccumulation potential (Cheng et al., 2021), and negative health effects (Fenton et al., 2021). Contaminated food and water are considered the primary exposure pathways for humans (Sunderland et al., 2019), and PFAS occurrence has been documented in wild and farmed animal and plant species as well as in food products (Bonato et al., 2025; EFSA Contam Panel et al., 2020).

PFAS-contaminated hotspots relative to natural and drinking waters are particularly critical in terms of exposure. One of the most relevant PFAS contamination events at the global level occurred in North-East Italy (Veneto Region). A fluorochemical manufacturing facility was identified as the main contributor for the decades-long release of fluorinated organic monomers and the improper disposal of PFAS contaminated industrial waste, which caused groundwater (GW), surface water (SW), and drinking water (DW) contamination over an area of approximately 190 km^2 and impacting more than 100,000 residents, mainly through the ingestion of tap water (Ingelido et al., 2018; Lava et al., 2021; Pitter et al., 2020a). According to the Environmental Protection Agency of the Veneto Region (ARPAV, 2025), the contamination was primarily attributed to perfluoroalkyl acids (PFAA), specifically perfluorocarboxylic and perfluorosulfonic acids (PFCA and PFSA) with perfluoroalkyl carbon-chain length ≥3. Following the discovery of the contamination in 2013 (Ingelido et al., 2020), the Regional Authorities implemented containment measures (e.g., installation of activated carbon filters in water treatment plants and exploitation of uncontaminated aquifers), to limit DW pollution. Nevertheless, GW and SW contamination persists (ARPAV, 2025). Monitoring and surveillance of the exposed populations revealed significantly higher serum PFAS levels among residents of the contaminated area compared to controls, with evidence linking exposure to adverse health outcomes and highlighting multiple

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exposure pathways, including contaminated water and possibly locally produced food and beverages (Biggeri et al., 2024; Girardi and Merler, 2019; Ingelido et al., 2018; Pitter et al., 2020a, 2020b). Because of the widespread use of SW and GW for agricultural purposes, the monitoring of food and beverages produced and grown within the contaminated area was set up by authorities (Gallocchio et al., 2022; Ingelido et al., 2018; Zamboni et al., 2021).

PFAS in soil and water can be taken up by plants and transferred in edible tissues (Blaine et al., 2014; Ghisi et al., 2019; Wen et al., 2014; Zhang et al., 2020). Consequently, assessing PFAS occurrence in the vegetal matrix as well as in plant-derived food products can provide crucial insights into their transfer potential within terrestrial food webs, local contamination profiles, and support long-term exposure assessments.

Wine is derived from the fruits of the grapevine (Vitis spp.), a perennial woody crop managed through annual pruning and canopy control. The vineyards are commonly irrigated via drip irrigation in the root area (Chaves et al., 2010; Pisciotta et al., 2018) using water from sources such as GW aquifers, as grapevines may require substantial irrigation inputs during dry periods (Mirás-Avalos et al., 2021). The grapevine may accumulate and translocate pollutants like metals and biocides through irrigation water, atmospheric deposition, or contaminated soils towards roots, vine canes, grapes (Chopin et al., 2008; Dorosh et al., 2021; Dumitriu et al., 2021; Liviz et al., 2025; Schusterova et al., 2021).

Recently, PFAS have been quantified in grapes and in wine (Affricano et al., 2026; Burtscher-Schaden et al., 2025; Freeling and Mira de Orduña Heidinger, 2025; Li et al., 2019; Van Leeuw et al., 2024), revealing their potential role as a dietary source and environmental exposure indicators of PFAS. For example, wine and beer consumption was positively associated with increased levels of PFAS in blood serum of Spanish consumers (Bartolomé et al., 2017). However, excluding ultra-short-chain PFAS, the currently available literature on PFAS occurrence in such matrices remains very limited.

Among agricultural products, wine has a strong economic relevance in the Veneto Region. In the sole province of Vicenza, approx. 100,000 tons of wine grapes (around 25% of the total agricultural production) were produced in 2019 (Vicenza Province, 2019).

In the Veneto Region, GW is broadly used for civil, industrial and agricultural purposes (Palma et al., 2023; Schiavo, 2024), as is the GW aquifer underlying the Vicenza province (Altissimo et al., 2014).

Extraction wells are spread all over the resurgences area of the Veneto Region (ARPAV, 2022), and it is known that private artesian wells are widely present in the contaminated area (Veneto Region, 2019), but most of them are not officially registered and their use for agricultural purposes cannot be ruled out (Pitter et al., 2020a), despite the restrictions on their use by local and regional authorities.

Despite this, the occurrence of PFAS in wines produced in the contaminated area has not yet been systematically assessed, nor has the relationship between PFAS concentrations in wine and underlying groundwater contamination been explored.

In order to determine whether wine can act as a bioindicator of environmental contamination linked to the use of contaminated water, and to identify which PFAS compounds may serve as reliable molecular markers (Dorosh et al., 2021; Zhang et al., 2020), the aims of this study were: 1) to assess the occurrence and profile of PFAS in wines produced from grapes grown within and around the contaminated area; 2) to investigate the relationship between the occurrence of PFAS in wines and in GW used for irrigation; and 3) to determine if wine consumption may represent a relevant exposure pathway for humans in this setting. To this end, we analysed 76 wine samples collected within and around the areas with the highest human exposure (the Red and Orange Areas, see section 2.1), compared the PFAS profile in wine with GW data from the regional monitoring network, and estimated dietary exposure under different wine consumption scenarios.

2. Study area, materials, methods, and data treatment

2.1. Study area

The contaminated area is located in between the Provinces of Vicenza, Verona, and Padua of the Veneto Region (Fig. 1A). The GW contamination plume as defined by ARPAV (Fig. 1A–B), originates halfway through the Agno Valley (Municipality of Trissino), extending towards Vicenza municipality to the East, and Montagnana municipality to the south, with the upper half running between the Lessini Mountains and the Berici Hills (Fig. 1B). Fig. S1 reports on hydrogeological aspects that are relevant to the contamination. Further details are reported elsewhere (Lava et al., 2021). Since 2013, several measures have been undertaken to assess the extent of the contamination and limit the exposure of the local population to PFAS. ARPAV set up a surveillance network (nowadays encompassing 53 sampling points) to define the extent of GW contamination (ARPAV, 2024). The municipalities within the impacted area were grouped in the so-called Red and Orange areas (Menegatto et al., 2023), which are based on the exposure levels of PFAS in surface water, groundwater, private wells and public drinking water (Ingelido et al., 2020, 2018). The red area encompasses 23 municipalities and parts of 7 additional municipalities, while the orange area encompasses sub-areas of additional twelve municipalities (Veneto Region, 2018) (Fig. 1C). Table S1 details all the municipalities involved.

Winemaking represents a relevant agricultural activity in the area under study, with an approximate production area of 9000 ha (about 14% of the total agricultural surface) vineyards among all the municipalities involved (totally or partially) in 2020 according to the Italian National Institute of Statistics (ISTAT, 2020).

2.2. Wine denominations and origin

The selection of the wines was based primarily on their geographical denomination/labelling, such as DOC and IGT denominations.

DOC (*Denominazione di Origine Controllata*) and IGT (*Indicazione Geografica Tipica*) are official Italian wine denominations corresponding, respectively, to the EU Protected Designation of Origin (PDO) and Protected Geographical Indication (PGI) schemes (European Parliament and Council of the European Union, 2013, 2024). DOC wines must be produced from grapes originating exclusively from the delimited geographical area and are subject to strict rules concerning - among others - maximum yield per hectare, allowed grape varieties, winemaking techniques, aging duration, alcohol content. Therefore, the acquisition of local DOC wines was privileged. Areas of the DOCs relevant to this study are reported in Fig. 1D, except for the DOC "Delle Venezie", which covers the whole Veneto and Friuli-Venezia Giulia Regions and the Trento Province. For IGT wines, at least 85% of the grapes must originate from the designated area. Some of the wines sampled were labelled as Veneto IGT, i.e. the grapes must come mainly from anywhere within the Veneto Region. For this reason, the Veneto IGT area is not shown in Fig. 1D. Additional information on the wine denomination system can be found in Table S2.

2.3. Sampling campaigns

A total of 76 wine bottles were bought between November 2023 (first campaign) and October-November 2024 (second campaign). Other relevant information on each wine (e.g., harvest year, denomination, grape variety, wine colour) is reported in Tables S3 and S4.

In the first campaign, 17 wine bottles were purchased from 8 resellers (wineries or supermarkets) located in the red or orange areas and labelled as "W1" to "W17". Of these wines, 71% are DOCs, 38% IGT and 11% have no denomination. All the wines are still wines, except for W10 and W13, which are sparkling wines. Red wines represent 59% of the samples, while the harvest year is comprised between 2019 and 2023. The second campaign was aimed at collecting wines from locally

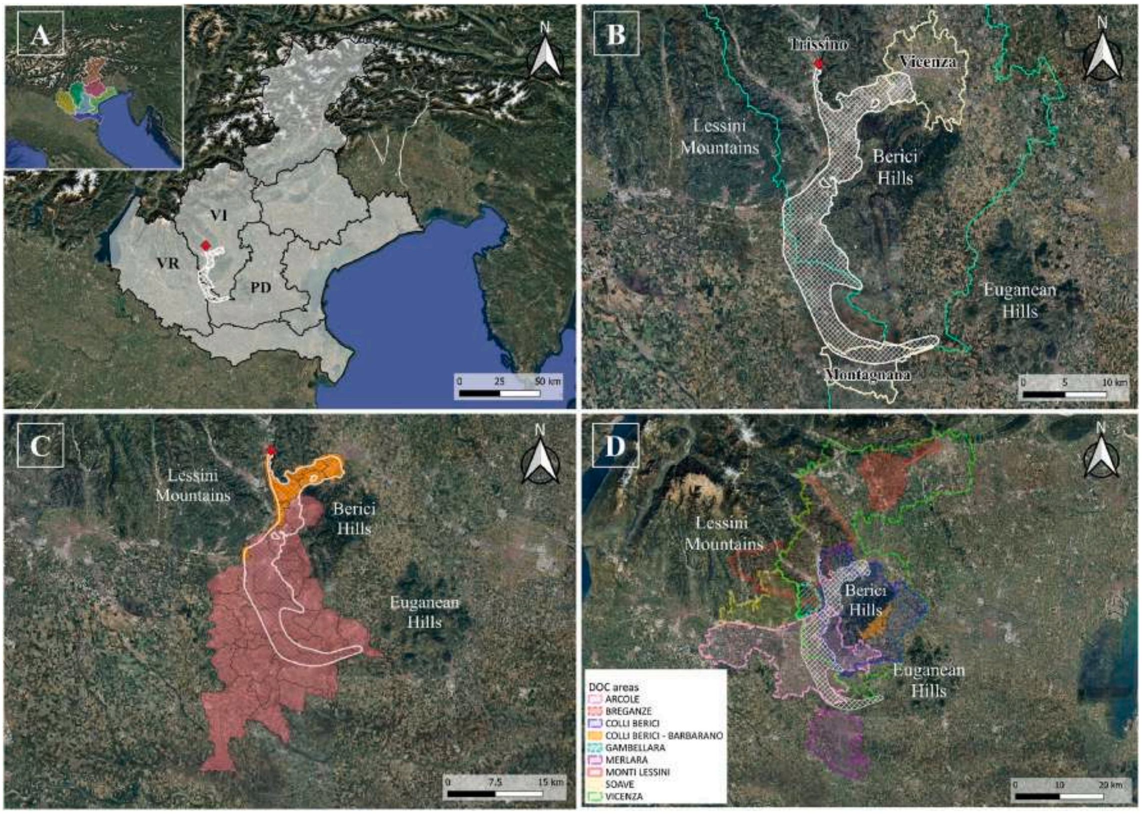

Fig. 1. A) The Veneto Region. The GW contamination plume (in white) as defined by ARPAV (2018) overlaps the provinces of Verona (VR), Vicenza (VI), and Padua (PD). The red dot represents the source of contamination; B) The contamination plume and the origin of the contamination with respect to the geological context and the provincial borders (light green strokes); C) The municipalities of the Orange and Red Areas, and the estimated GW contamination plume; D) Geographical extension of the DOCs in the study area. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

grown grapes by local winemakers and farmers, to geographically locate the grapes (i.e., the wines) in the territory. A total of 59 bottles were collected from 28 local winemakers and labelled from “1” to “59”. As a result, a higher percentage of Veneto IGT wines (n = 26, 44%) was sampled compared to the previous campaign, while the other wines belonged to DOCs (n = 27, 46%) and a limited set of wines (n = 6, 10%) didn't report any denomination. Red wines are the majority (n = 33, 56%) and the harvest year ranged between 2017 and 2023.

Based on the information collected in situ and on the winemakers' websites, we were able to identify the vineyard location associated with 44 wines. One wine was bought twice (ID 11 and 42). Therefore, we considered their average PFBA concentration in the spatial analysis, resulting in 43 statistically distinct spatial units (or simply: 43 distinct spatial units). Fig. 2 reports the masked location of the vineyards of the georeferenced wines. A geo-masking procedure was applied to the original coordinates by adding Gaussian noise with a standard deviation of 0.02° on latitude and longitude coordinates (approximately 1.5-2.2 km). No vineyard locations were excluded after geo-masking, as all perturbed coordinates remained within the study area and the original coordinates were used for statistical analyses. The bottles were stored in the dark at 5 °C until they were uncorked and analysed.

2.4. PFAS analysis

2.4.1. Chemicals and reagents

Standards and reference isotope-labelled standards were purchased from Wellington Laboratories (Guelph, Ontario, Canada) as a mix of 30 standards (PFAC30PAR) and 19 isotope-labelled standards (MPFAC-24ES), respectively. The native standard solution includes perfluorocarboxylates (C4–C14), perfluorosulfonates (C4–C10, linear and branched), fluorotelomer sulfonates (4:2 FTS, 6:2 FTS, and 8:2 FTS) FOSA, N-MeFOSAA, N-EtFOSAA, HFPO-DA, (N)ADONA, 9Cl-PF3ONS, and 11Cl-PF3OUdS. The list of labelled internal standards is provided in Table S7; 1000 ng/mL and 160 ng/mL stock solutions for the quantitative analysis were prepared from PFAC30PAR and MPFAC-24ES, respectively. Formic acid, ammonium acetate, and LC-MS grade solvents (ultrapure water, acetonitrile, and methanol) were purchased from Merck Chemicals (Darmstadt, Germany).

2.4.2. Sample preparation

After gentle shaking, the wines were uncorked, and 10 mL of each wine was transferred to a polypropylene conical tube and vortexed to degas the sample. Subsequently, 300 μL of each sample was filtered through a 0.2 μm regenerated cellulose Claristep® filter (Gottingen, Germany). An aliquot (30 μL) of each sample was transferred into a polypropylene vial and diluted 1:10 with a 4:1 v/v H_2O:MeOH + 0.1% formic acid solution, reaching a final volume of 300 μL. After addition of 20 μL of a 160 ng/L IS solution, 50 μL of each sample was used for the analysis. Each sample (i.e. each 10 mL aliquot) was analysed in triplicate and kept at 10 °C during the instrumental analysis. Replicate measurements showed a variability of 10–15%.

2.4.3. Instrumental analysis

Samples were analysed via direct injection into an Ultra Performance Liquid Chromatography Triple Quadrupole Mass Spectrometry (UPLC-TQ/MS) system.

An Acquity Premier liquid chromatography system (Waters™) was used. The chromatographic separation was achieved using a BEH C18 1.7 μm 2.1 × 50 mm column at 35 °C, with a flow rate of 0.3 mL/min. Ultrapure water (UPW) and a 1:1 MeOH:AcCN, both containing 2 mM ammonium formate, were used as elution solvents. The chromatographic gradient elution program is reported in Table S5. The mass

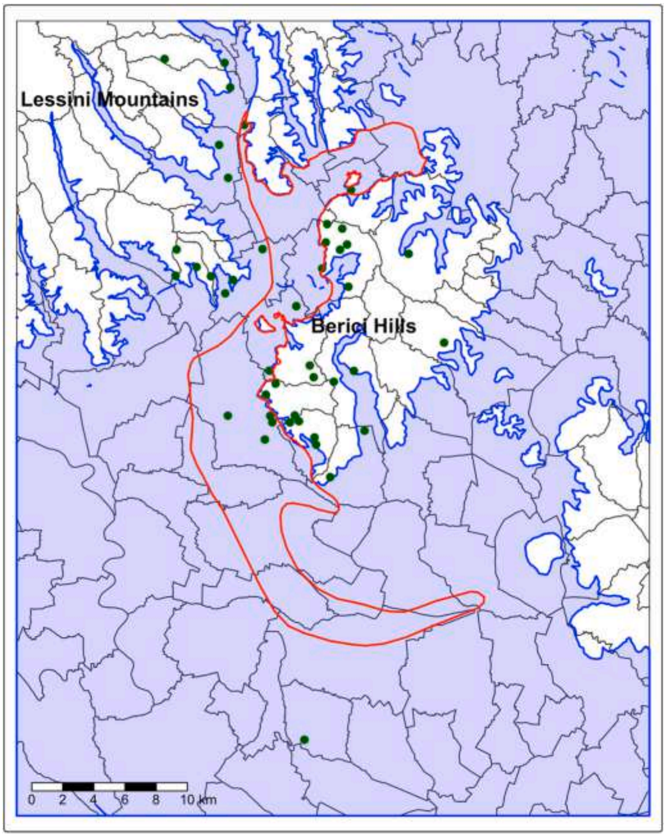

Fig. 2. Geo-masked location of the geolocalized vineyards and the related wines collected in the second campaign (green dots). The red contour indicates the GW contamination plume. The light blue area represents the aquifer basin. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

spectrometry analysis was performed by using an Xevo TQ Absolute spectrometer developed by Waters™ (Milford, MA, USA). Instrumental operative settings were as follows: ESI source temperature of 100 °C, desolvation temperature of 350 °C, desolvation flow rate of 900 L/h, and gas cone of 150 L/h. The spectrometer operated in negative ionization mode. The operative conditions of the mass spectrometer, including precursor and product ions of the analytes, retention time, cone voltage, and collision energy, are reported in Table S6.

Peak areas were integrated using the summation peak integration function, and quantification was performed using the 1/X weight type function on internal standard calibration curves. Quantitation and data processing were evaluated using the Waters Connect software (Milford, MA, USA).

2.4.4. Method validation

The quantification of the analytes was carried out by means of a 7-points external calibration curve (0.8-50 ng/L), correcting any instrumental drift with appropriate internal standards. Before performing the analysis on the real samples, the method was validated by calculating limit of detection (LOD), limit of quantification (LOQ), accuracy, and reproducibility on a wine fortified with 5 ng/L (for LOD and LOQ evaluation) and 10 ng/L (for accuracy and precision evaluation). The validation data is reported in Table S8. Precision was considered optimal if within ±20% of the % RSD (relative standard deviation), while accuracy was considered optimal if within ±30% of the percent recovery. LOD and LOQ were calculated according to the Eurachem guidelines (Cantwell, 2025) from ten wine replicates fortified at 5 ng/L, using the corrected standard deviation multiplied by 3 for LOD and by 10 for LOQ. For some PFAS, although detectable at 5 ng/L, the response at this level was not sufficiently reliable for quantification because of matrix effects and/or replicate variability; therefore, the final LOQ was set at a higher concentration. Method recovery was additionally evaluated at two fortification levels, yielding recoveries of 89-125% at 50 ng/L and 92-111% at 500 ng/L. The reported LOD and LOQ values have already been multiplied by the dilution factor of 10. Linearity was assessed for each analyte, and final linear ranges were determined by visual inspection and calculating the RSD of relative response factors ($R^2 > 0.99$ and RSD <20%).

2.5. Statistical and geostatistical analysis

Data characteristics were summarized using frequencies and percentages for categorical variables and means with standard deviations (SD) or medians with interquartile ranges (Q1–Q3) for continuous variables. Group comparisons were conducted using Pearson's chi-squared test for categorical variables, or Fisher's exact test when any expected cell count was fewer than 10. For continuous variables, non-parametric methods were applied: the Wilcoxon rank-sum test for comparisons between two groups and the Kruskal–Wallis test for comparisons involving more than two groups.

To predict PFBA concentrations in groundwater, a three-step geostatistical and regression-based approach was implemented (see Section S1). First, point-level measurements of PFAS concentrations in groundwater (GW) collected between 2017 and 2023, corresponding to the harvest years of the selected wines, were retrieved from the ARPAV database (ARPAV, 2025). Measurements within the study area (latitude 45.1°-45.8°; longitude 11.0°-11.9°) were used to generate a continuous spatial prediction of PFBA concentrations through generalized additive models and kriging procedures. Although robustness to alternative spatial prediction methods was not formally evaluated, the adopted approach was not a simple interpolation procedure, but a dedicated three-stage model-based geostatistical framework specifically designed for highly asymmetric, non-stationary, and left-censored spatial data. This approach was selected a priori because it allowed spatial prediction of PFBA concentrations in GW while appropriately accounting for heterogeneous sampling density, censoring below detection limits, and residual spatial dependence. These predictions were then used to assign PFBA concentration values to the GW points nearest to each vineyard location (see Supplementary Section S1 for further details). Because vineyards may be located either on plains, where GW is readily accessible, or in hilly areas, where direct access to GW is limited, the minimum Euclidean distance between each georeferenced vineyard and the nearest GW basin point was calculated. Vineyards situated directly above a GW basin were assigned a distance equal to zero. Then, to assess the potential association between the PFBA concentration in wine and the predicted concentration of the same PFAS in GW considering the distance of the vineyard from the nearest GW source, we applied a multiple linear regression model with an interaction term (equation (1)):

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 I(X_2 < d) + \beta_3 X_1 I(X_2 < d) + \varepsilon \quad (1)$$

where the outcome Y is the log-transformed concentration of PFBA measured in the wine, X_1 the log-transformed predicted concentration of PFBA in GW at the closest point, and $I(X_2 < d)$ is a binary variable structured by an indicator function $I(.)$ equal to one if the minimum distance between the vineyard and the GW is lower than d, and zero otherwise. Lastly, β_0 represents the intercept, while ε denotes the error term, assumed to be a white noise and normally distributed. The value of d was selected minimizing the Bayesian Information Criterion (BIC). This model was used to assess the relationship between PFBA concentrations in wine and in GW, while accounting for the potential modifying effect of vineyard distance from GW sources through an interaction term. A significant interaction term would indicate that the strength of the association between PFBA levels in GW and in wine varies according to the vineyard's proximity to GW availability and the value d denotes the threshold. The model results were presented by means of regression coefficients along with their 95% confidence intervals and associated p-values. Statistical significance of the coefficients and hypothesis testing was set to 5%. Statistical and geostatistical analyses were carried out via R software 4.3, with the *geoR* and *sp* packages for spatial analysis. Fig. 1A-D and S1B were prepared using QGIS version 3.34 with the Google Satellite basemap layer.

2.6. Estimation of weekly PFAS intake by wine consumption and comparison with health-based reference values

The Weekly Intake (WI) of PFAS was calculated for each wine and compared to the Tolerable Weekly Intake (TWI) proposed by EFSA (4.4 ng/kg b.w., as sum of PFOA, PFOS, PFNA, and PFHxS) assuming a body weight (BW) of 70 kg, by using the following equation (eq. (2)):

$$EWI = \frac{C_i * DI * 7\ days}{BW} \tag{2}$$

where EWI (Estimated Weekly Intake) for each PFAS was calculated based on the concentration of the selected PFAS in each wine (C_i) and on the daily intake of wine (*DI*) multiplied by 7.

Four different daily consumption scenarios were considered, i.e. the consumption of 1, 2, 3, and 4 alcoholic units of wine (i.e., 125 to 500 mL per day). According to the National Health Institute (ISS, Istituto Superiore di Sanità), 1 alcoholic unit corresponds to approx. 12 g of pure ethanol, or 125 mL of a 12% wine (or: wine at 12% alcohol) (ISS, 2022).

Relative potency factors (RPFs) are used to compare the toxicological strength of a group of similar chemicals. They can help overcome the difficulties and the pitfalls of assessing individual compounds, as substances like PFAS are usually found as mixtures in the environment and in the biota. RPFs are approximately equivalent to the toxic equivalency factors (TEFs) used to assess the toxicity of mixtures of dioxins and dioxin-like compounds (Backhaus, 2023). Bil et al. derived RPFs for 23 PFAS on the basis of available literature data of existing subchronic oral toxicity studies in male rats, taking absolute liver weight increase as an endpoint (Bil et al., 2021). The same RPFs are currently applied in the ongoing EU revision of PFAS water quality standards (EQS), where an RPF-based sum of 24 PFAS expressed as PFOA-equivalents is used for surface waters (Backhaus, 2023; Council of the European Union, 2026). As an alternative approach, the EWIs were recalculated by first applying RPFs to calculate PFOA-equivalent concentrations by multiplying the concentration of each PFAS (C_i) by the corresponding RPF of the quantified (>LOQ) analytes (Table S11). Their sum was considered as the PFOA-equivalent concentration as shown in equation (3):

$$PFOA_{eq} = \Sigma C_i \times RPF_i \tag{3}$$

To further contextualize the potential health implications of PFAS detected in wine, we compared the estimated daily intake (EDI) of each PFAS with the oral reference dose (RfD) proposed by the U.S. Environmental Protection Agency (EPA), if available. Table S12 reports available RfDs for noncancer chronic (C) and subchronic (SC) effects proposed by U.S. EPA with respect to PFAS quantified in this study (see Section 3). RfDs represent health-protective thresholds for non-cancer adverse effects, derived from critical endpoints observed in experimental or epidemiological studies, such as developmental toxicity, immune suppression, hepatic alterations, or thyroid hormone disruption. More in detail, an RfD represents estimates of a daily oral exposure to a chemical that is likely to be without appreciable risk of adverse health effects over a lifetime (IRIS glossary, 2025). For example, the RfD for PFOA (3×10^{-8} mg/kg bw/day) is based on reduced vaccine antibody response in children, while that for PFBS (3×10^{-4} mg/kg bw/day) is based on decreased serum T4 levels in neonatal mice. Each RfD incorporates uncertainty factors to account for interspecies variability, human sensitivity, and data limitations. By comparing the PFAS-specific daily intake values (referred to the hypothetical consumption of each wine) with these health-based benchmarks, we aimed to identify whether any consumption scenario may lead to doses approaching or exceeding toxicologically relevant thresholds. For every quantified analyte, the EDI was calculated according to equation (4), assuming a body weight of 70 kg:

$$EDI = \frac{C_i * DI}{BW} \tag{4}$$

3. Results

The evaluation of the results was based on the LOQ values that were taken as operational cutoff to ensure a conservative estimation of total PFAS occurrence and the geospatial and correlational analyses.

3.1. Occurrence of PFAS in wines

Table 1 summarizes the analytical results for the full set of 76 wines (i.e., bottles collected in both campaigns), and the complete dataset is provided in Table S9. Only PFAS that were both quantifiable and relevant for the GW contamination, i.e. PFAA C4-C8 and HFPO-DA, are reported and discussed. PFAS were detected (values > LOD) in 75 out of 76 wines, and at least one PFAS was quantified (values > LOQ) in 73 out of 76 wines. Total PFAS concentration (values > LOQ) ranged between 10.1 and 21,810 ng/L (average and median value of 1088 and 232 ng/L, respectively). In detail, 17 wines (22.4%) showed a total PFAS concentration ≤99 ng/L, 42 wines (55.3%) ranged between 100 and 999 ng/L, and 17 (22.4%) exceeded 1000 ng/L.

PFBA clearly dominates the PFAS profile, both in terms of quantification frequency and concentration levels. It exceeded the limit of quantification (LOQ) in approximately 94% of samples, with a maximum concentration of 18,067 ng/L and a median value of 196 ng/L. Other short-chain PFAA, namely PFPeA, PFHxA, and PFBS, were also widely detected. PFPeA was quantified in 61.5% of the wines, generally at lower concentrations than PFBA (median: 14.9 ng/L; maximum: 2750 ng/L). PFBS and PFHxA were quantified in 51.3% and 44.7% of samples, respectively. Although their overall concentrations were lower than those of PFBA and PFPeA, elevated values were observed in some cases (maximum: 291 ng/L for PFBS and 676 ng/L for PFHxA). HFPO-DA, PFOA, PFHpA, and PFHpS were quantified less frequently (<10% of samples), though some wines exhibited relatively high concentrations (maximum: 155 ng/L for PFOA and 105 ng/L for HFPO-DA). PFHxS and PFOS did not exceed the LOQ in any of the samples analysed. Among the georeferenced wines, samples 3, 4, 43 and 44 showed the highest overall concentrations (1861- 8133 ng/L).

Table 2 shows the concentrations of the most frequently quantified PFAS (PFBA, PFPeA, PFBS, and PFHxA - see Table 1) clustered by wine denomination (DOC, Veneto IGT, and wines without denomination). DOC wines were further categorized according to whether their production areas partially overlapped the PFAS GW plume ("DOC inside plume") or not ("DOC outside plume"). Wines produced in DOC areas partially overlapping the contamination plume (n = 29) showed significantly higher concentrations of all selected PFAS compared with DOC wines outside the plume, Veneto IGT wines, and wines without denomination. Wines from DOC areas within the plume had a median PFBA concentration of 539 ng/L, compared with 79.9 ng/L for DOCs outside the plume, 80.3 ng/L for Veneto IGT wines, and 148 ng/L for wines without denomination (Table 2; p = 0.009). Differences were even more pronounced when considering mean concentrations by denomination. A similar pattern was observed for PFPeA and PFHxA, with higher median (and mean) concentrations in DOC wines produced within the plume area compared with other denominations ($p < 0.05$). PFBS represented the only exception: although DOC wines outside the plume showed the lowest concentrations, the highest values were not exclusively associated with DOC wines within the plume area.

As shown by the marked difference between the mean and the

Table 1
Distribution of PFAS concentrations by analyte, including the % of measurements below the LOQ; N = number of samples.

PFAS	N	Min	5%	25%	50%	75%	95%	Max	%<LOQ
PFBA	76	<50	<50	89.7	196	793	5565	18,067	6.58
PFPeA	76	<11	<11	<11	14.9	71.6	679	2750	39.5
PFBS	76	<7	<7	<7	7.22	13.9	66.2	291	48.7
PFHxA	76	<5	<5	<5	<5	16.7	107	676	55.3
HFPO-DA	76	<18	<18	<18	<18	<18	26.2	105	94.4
PFOA	76	<20	<20	<20	<20	<20	<20	155	96.1
PFHpA	76	<11	<11	<11	<11	<11	<11	13	98.7
PFHpS	76	<44	<44	<44	<44	<44	<44	47.5	98.7
PFHxS	76	<8	<8	<8	<8	<8	<8	<8	100
PFPeS	76	<8	<8	<8	<8	<8	<8	<8	100
PFOS	76	<19	<19	<19	<19	<19	<19	<19	100

Table 2
Summary statistics of the analysed PFAS with at least 40% of measurements above the LOQ, clustered by wine denomination. Values below or equal the LOQ were imputed as LOQ/$\sqrt{2}$.

PFAS	**DOC inside plume** N = 29	**DOC outside plume** N = 10	**No denomination** N = 8	**Veneto IGT** N = 29	**p-value**[1]
PFBA					0.009
Mean (SD)	1613 (3542)	227 (329)	511 (643)	576 (1303)	
Median (Min, Max)	539 (35.4, 18,067)	79.7 (29.0, 1037)	80.3 (35.4, 1570)	148 (51.6, 6365)	
PFPeA					0.025
Mean (SD)	226 (540)	24.0 (36.5)	58.2 (78.3)	82.4 (266)	
Median (Min, Max)	56.2 (7.8, 2750)	7.8 (7.8, 122)	12.5 (7.8, 204)	14.3 (7.8, 1415)	
PFHxA					0.033
Mean (SD)	46.7 (125)	8.7 (10.1)	12.5 (14.1)	17.6 (50.9)	
Median (Min, Max)	13.8 (3.5, 676)	3.5 (3.5, 31.8)	5.3 (3.5, 39.3)	3.5 (3.5, 265)	
PFBS					0.054
Mean (SD)	22.8 (52.3)	8.6 (3.97)	27.8 (35.7)	12.4 (20.9)	
Median (Min, Max)	11.8 (4.9, 291)	8.0 (4.9, 14.0)	12.6 (4.9, 106)	4.9 (4.9, 103)	

[1] Kruskal-Wallis rank sum test.

median value, the distribution of the considered PFAS is highly skewed. A correlation analysis was conducted to examine the relationships among the same PFAS with the highest quantification frequency in wine samples, after log transformation (Fig. 3). Because most analytes exhibited a high proportion of <LOQ results, the analysis was restricted to the four PFAS with the highest quantification frequency. The results indicated several significant positive correlations between PFAS compounds.

Notably, log-PFBA, log-PFHxA, and log-PFPeA showed a strong positive pairwise correlations (Spearman's $r > 0.75$, $p < 0.001$). Moderate correlations were observed between log-PFBA, log-PFHxA, and log-PFPeA with log-PFBS (Spearman's r, $p < 0.001$).

3.2. Statistical and geostatistical analysis results

Under the hypothesis of the use of GW for agricultural irrigation, we compared the PFAS concentration and composition in GW from the ARPAV database (ARPAV, 2025) with those found in the analysed wines. The ARPAV database constitutes an exceptionally large dataset and includes approximately 5000 determinations per analyte over the 2017-2024 period (Table 3).

The concentration profiles of the same analytes measured in GW between 2017 and 2023 within the selected area (see Section 2.5) indicate that PFOA, PFBA, and PFBS were the most abundant PFAS (Table 3). In detail, PFOA showed the highest median and upper percentile concentrations, followed by PFBA and PFBS. PFHxA and PFPeA were quantified in most of the examined GW samples, and notable concentrations of PFOS and PFHpA were also recorded. Overall, the distribution and relative abundance of PFAS in GW differ markedly from those observed in wine samples, where long-chain PFAS were rarely quantified.

Fig. S2 reports the distribution of log-transformed PFAS compound in the GW samples, the pairwise scatterplot and Spearman's correlation with relative p-value. The pairwise scatterplot matrix reveals strong and statistically significant positive associations among most of the log-transformed PFAS compounds in GW. Short- and long-chain PFCA (e. g., PFHxA, PFPeA, PFOA) and PFBS display very high correlations (Spearman's $r > 0.85–0.95$; $p < 0.001$), consistent with a common contamination source or pathway within the study area. PFOS and PFHpA also exhibit moderate-to-strong correlations with several compounds, although these associations are generally weaker than those observed among the carboxylic acids. In contrast, HFPO-DA and PFHpS show comparatively lower correlation coefficients with the other PFAS. The density plots further indicate that the distributions remain right-skewed even after log transformation.

Consistently with the results, PFBA emerged as the most informative proxy of the site-specific PFAS contamination profile, combining major occurrence in groundwater, strong correlation with the other PFAS in groundwater, and the highest detection frequency and concentration levels in wine. The three-step geostatistical model (see details in Supplementary Section S1) allowed the estimation of the log-transformed PFBA concentration in the area where the aquifer underlies, which basically covers the plain part of the study area (see Figure S1.1). Twelve vineyards are located on the plain part of the study area, while the other 31 vineyards are located on a hilly area and they are located at a variable distance from the aquifer (between 37 and 1490 m; average 519 m). The log-PFBA concentration in the wine significantly decreases with the increasing distance of the related vineyards from the aquifer based on the estimated log-PFBA value in the GW at the closest point to the vineyard (Spearman's r: -0.468 $p < 0.01$), and at the same time the correlation between the log-PFBA in the wine and in the closest GW points is weakly positive, but not statistically significant (Fig. 4).

In order to choose the value of the distance from the GW that minimizes the BIC value, we estimated a series of models obtaining an estimate for d equal to 75 m. The results of the linear regression analysis are reported in Table S10. The interaction term ($\beta_3 = 0.44$, 95% CI: 0.18 to 0.70) is positively and highly statistically significant ($p = 0.001$), indicating that the log-PFBA concentration in wines from vineyards within 75 m from the GW positively correlates with the log-PFBA concentration estimated at the closest GW point. Based on the regression coefficient, a 1% increase in PFBA concentration in GW corresponds to an estimated 0.48% increase in PFBA concentration in wine. Fig. 5

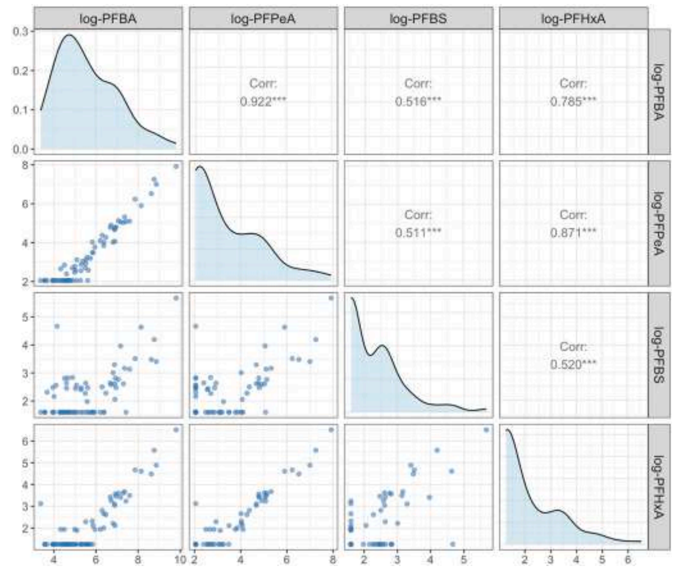

Fig. 3. Distribution of log-transformed PFAS compound in the wines, pairwise scatterplot and Spearman's correlation with relative p-value (*p < 0.05, **p < 0.01, ***p < 0.001). Values below or equal the LOQ were imputed as $LOQ/\sqrt{2}$.

Table 3
PFAS concentrations (ng/L) in groundwater samples; N = number of samples.

PFAS	N	Min	5%	25%	50%	75%	95%	Max	%<LOQ
PFBA	4937	<5	<5	<5	20	125	1210	11,900	36.3
PFOA	4937	<4	<10	<10	21	253	2803	32,523	36.6
PFBS	4933	<2	<5	<5	15	90	663	9315	37.1
PFHxA	4937	<2	<5	<5	9	51	536	7230	43.0
PFPeA	4936	<5	<5	<5	7	50	541	7540	45.6
PFOS	4935	<4	<10	<10	<10	27	140	1901	57.3
PFHpA	4937	<2	<5	<5	<5	13	144	3540	57.9
PFHxS	4936	<2	<5	<5	<5	8	39	443	68.7
HFPO-DA	3997	<2	<2	<5	<5	<25	12	6461	93.6
PFHpS	4017	<2	<2	<5	<5	<10	<25	98	96.2

illustrates the estimated relationship between log-transformed PFBA concentrations in wine and the corresponding predicted log-PFBA concentrations in GW, accounting for the distance between each vineyard and the nearest GW point. For vineyards located within 75 m of GW, PFBA concentrations in GW are positively associated with those measured in wine (blue line). In contrast, this association is weaker and not statistically significant for vineyards located farther from GW (red line). Although the regression model includes only two main predictors and their interaction term, it explains a substantial proportion of the variance (65.2%), highlighting the strong spatial and environmental influence of GW contamination, modulated by vineyard proximity to GW, on PFBA accumulation in wine. The model residuals approximate the normal distribution and fitting appears adequate (Fig. S3).

3.3. Estimation of weekly PFAS intake from wine consumption

As far as the EFSA TWI is concerned, PFNA, PFOS and PFHxS were not quantified, and only PFOA contributed to the calculated WI. Only for three wines (samples 43, 44, W8) concentrations of one or more of the four PFAS included in the EFSA TWI were quantified, resulting in a WI > 0. Table 4 summarizes the number of wines exceeding the considered health-based benchmarks under each consumption scenario, including the EFSA TWI approach, the RPF-adjusted approach, and the compound-specific RfD.

The TWI (EFSA Contam Panel et al., 2020) was exceeded only for one wine (sample 43) under the hypothesis of consumption of 375 or 500 mL/day (corresponding to 5.8 and 7.8 ng/kg b.w., respectively), while WIs of the other 2 wines resulted in a total intake far below the reference threshold (1.1 - 1.3 ng/kg b.w.) under the 500 mL/day scenario. The exceedance is mainly attributable to the presence of PFOA in that specific wine (155 ng/L).

When applying PFOA-equivalent RPFs as described in section 2.6, the potency-adjusted TWI benchmark was exceeded for 3, 5, 6, and 8 wines in the 125 to 500 mL consumption scenarios, respectively.

The U.S. EPA carried out comprehensive evaluations to derive RfDs of selected PFAS, including PFBA, although evidence from animal studies (mammals) was necessarily integrated to epidemiological evidence to provide sufficient insight into potential effects on the thyroid, liver, reproductive system, or developmental effects (U.S. EPA, 2022). RfDs for PFOA and PFOS are based on human epidemiological studies, hence the higher confidence level with respect to the other compounds (Table S12). Although no explicit confidence level was assigned, the U.S. EPA RfDs for HFPO-DA is based on robust animal studies, and the main study from which chronic and sub-chronic RfDs were derived was classified as “high quality” (U.S. EPA, 2021). According to the estimated daily intakes and under the same consumption scenarios, none of the detected PFAS exceeded their respective reference doses (RfDs), with the exception of PFOA. In detail, wines W8, 43 and 44 were associated with PFOA intake levels exceeding its RfD across all consumption scenarios. Notably, under the lowest consumption scenario (125 mL/day), the estimated daily intake for these wines were 4.7×10^{-8}, 2.8×10^{-7} and 4.0×10^{-8} mg/kg/day (i.e., 1.6, 9.3 and 1.3 times higher than the RfD), respectively, while under the highest consumption scenario (500 mL/day), the associated EDI were 1.9×10^{-7}, 1.1×10^{-6} and 1.6×10^{-7} mg/kg/day (i.e., 6.3, 37 and 5.4 times higher than the RfD), respectively.

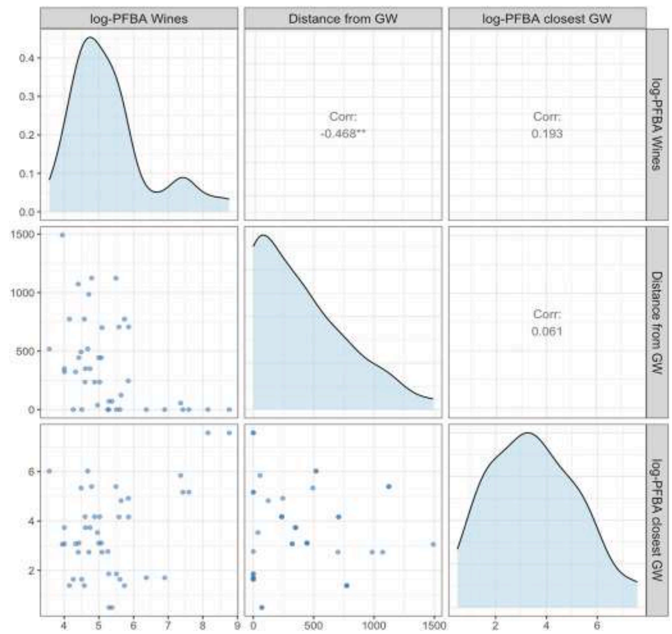

Fig. 4. Distribution of log-transformed PFBA concentrations in wines, distance of vineyards from groundwater (GW), and log-transformed predicted PFBA concentrations at the closest GW point, together with pairwise scatterplots and Spearman's correlation coefficients. Values below or equal to the LOQ were imputed as LOQ/$\sqrt{2}$.

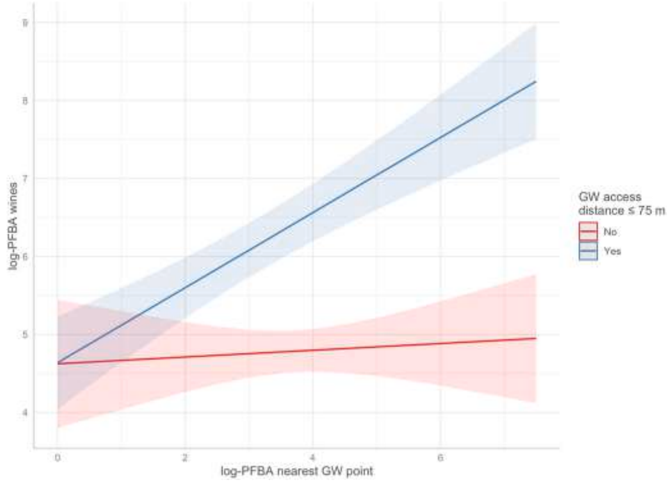

Fig. 5. Predicted log-PFBA concentration in the wine in relationship to log-PFBA closest GW point and the distance from the GW. Shaded regions represent pointwise 95% confidence band.

Table 4
Summary of exceedances of health-based benchmarks across the four hypothetical wine consumption scenarios.

Benchmark	N° of samples exceeding benchmark for each consumption scenario				Samples ID exceeding threshold
	125 mL	250 mL	375 mL	500 mL	
EFSA TWI	0	0	1	1	43
EFSA TWI (RPF-adjusted)	3	5	6	8	W8, W9, 3, 4, 29, 30, 43, 44
RfD	3	3	3	3	W8, 43, 44

4. Discussion

4.1. Occurrence of PFAS in wine

To date and to the authors' knowledge, this is the first peer-reviewed study to systematically assess the concentration of a broad set of PFAS in wine from a contaminated area, and to explore the relationship between the occurrence of PFAS in wine and underlying GW.

All the analytes quantified in the wine samples were produced by the company responsible for the contamination. Among them, PFOA and PFOS were the PFAS produced over the longest time span (end of 60s-2013), whereas the perfluoroether carboxylic acid HFPO-DA (a novel substitute for PFOA) was more recently introduced and processed (2014-2018) (ARPAV, 2019; Italian Parliamentary Commission of Inquiry, 2022). The presence of this compound in the GW of the contaminated area has been confirmed by ARPAV starting from 2018 (ARPAV, 2025; 2019). Despite being more recently introduced, HFPO-DA was detected in 4 out of 59 wines analysed.

Only a few studies reported the presence of C $\geq$ 3 PFAS in grapes or wine. Van Leeuw et al. (2024) investigated PFAS occurrence in different food products from the Belgian market and reported PFBA concentrations of 62-130 ng/L in three wine samples. Li et al. (2019) examined PFAS occurrence in different matrices collected downstream of a fluorochemical industrial park. Among the analysed food items, grapes contained eight detected PFAS (Σ_8PFAS = 2.2 ng/g ww, n = 16), with main contributions of PFBA (~50%), followed by PFOA and PFPeS. Assuming a grape-to-wine conversion of 1.0-2.5 kg/L (Tsalidis et al., 2022) and 100% transfer to wine, this would correspond to a PFBA concentration of approx. 1100-2750 ng/L in wine. Despite the rough extrapolation, these values are broadly consistent with the background-to-upper range of concentrations observed in the wines analysed in the present study.

Upon literature research, it emerged that no peer-reviewed study has explored the relationship between the properties of specific PFAAs and the underlying bioaccumulation mechanisms in *Vitis vinifera* L. or other grapevine species. Nevertheless, the predominance of short-chain PFAS in the analysed wines is consistent with the broader literature on plant uptake, which generally reports greater mobility and transfer of short-chain PFAAs to aboveground plant compartments, whereas longer-chain compounds tend to be more strongly retained in soils and roots (Ghisi et al., 2019; Felizeter et al., 2014, 2012; Lesmeister et al., 2021; Zhang et al., 2020). The same literature also indicates generally lower transfer of PFSAs than the corresponding carboxylic acids of similar chain length (Lesmeister et al., 2021).

Among on-field research, two studies are particularly valuable for interpreting our findings. Gredelj et al. (2020) investigated the uptake of PFAAs in red chicory using both irrigation water and soil enriched with PFAS to reach concentrations comparable to those measured in the PFAS-contaminated areas of the Veneto Region. They observed a clear chain-length-dependent accumulation pattern, with PFBA, PFPeA, PFHxA, and PFBS occurring at comparatively high levels in edible tissues. Similarly, Battisti et al. (2024) reported that grafted tomato plants cultivated in the same PFAS-affected area investigated here and irrigated with contaminated GW showed preferential occurrence of short-chain carboxylic acids such as PFBA, PFPeA, and PFHxA in fruits, whereas longer-chain PFAS and sulfonates were much less represented in the edible fraction. Both studies also highlighted the role of the soil as a barrier for the bioavailability of long-chain PFAS, as these compounds were often detected in the soil but not in the plant tissues.

Overall, these studies provide a useful context for interpreting the PFAS concentration patterns observed in wine vs GW: the decrease of plant uptake efficiency with increasing carbon chain length suggests a plant-mediated fractionation during transfer and, relatively, the enrichment and accumulation of highly mobile short-chain PFAS in grape-derived products. However, since no soil or grapevine tissues were analysed here, the current dataset does not allow direct assessment of the intermediate processes governing PFAS transfer from groundwater to the final wine matrix.

The strong positive correlations observed among most PFAS in GW indicate a common contamination source or shared transport pathway within the aquifer. Such correlation structures are typical of point-source industrial contamination, where multiple PFAS are co-released in relatively stable compositional ratios (Hu et al., 2016; Sunderland et al., 2019). The high correlation between PFOA and shorter-chain carboxylates may reflect historical emissions combined with environmental redistribution processes, including differential mobility along GW flow paths.

By comparing the PFAS profiles of the samples, it emerges that wines with PFBA concentration below 100 ng/L are either unlabelled, labelled as 'Veneto IGT', or belong to DOCs located far from (Breganze DOC) or not overlapping (Soave DOC) the contamination plume. Given that the non-DOC denomination allows for the blending of grapes sourced from different areas within the Veneto Region, the measured concentrations of PFBA, regarded here as a possible marker of local PFAS contamination in the grapes, may be influenced in both directions: diluted by the addition of grapes from less impacted zones, or elevated by those originating from areas with higher contamination levels. Nevertheless, the regression findings indicate that PFBA levels in wine increase both with proximity to the contamination plume and with GW PFBA concentrations, consistent with the use of GW for irrigation and winemaking in the region. This confirms the potential of PFBA as a key environmental marker for PFAS contamination, with geographic proximity to the contaminated area acting as a primary driver of its transfer from GW to wine. Notably, other PFAS detected in GW, such as PFOA, were not transferred to wine to the same measurable extent as PFBA. However, the positive association between PFBA in wine and GW suggests that groundwater is effectively being used in the agricultural system. In this context, PFBA in wine may act not only as a marker of direct transfer to the final product, but also as an indicator of the broader upward mobilization of the PFAS mixture present in GW, including compounds that may be less efficiently transferred to grapes and wine but may still accumulate in soils, biota, or other food matrices within the surrounding agricultural environment.

4.2. Considerations on human exposure to PFAS by wine consumption

PFBA was by far the most frequently quantified analyte and occurred at the highest concentrations, thus deserving particular consideration. Among PFCA homologues, it has gained increasing attention in the context of the global-level shift toward short-chain PFAS that increased its environmental relevance. Despite the significantly shorter serum half-lives (Fenton et al., 2021), short-chain PFAS are considered very persistent and very mobile substances, and experts proposed the phasing-out of their non-essential uses (Cousins et al., 2020). Although toxicological information is vastly limited to the long-chain PFAA (Fenton et al., 2021), PFBA has been associated with adverse effects on the biota, such as reproductive toxicity, endocrine disruption, and hepatotoxicity (Crebelli et al., 2019; Ivantsova et al., 2024; Liu et al., 2025; Sana et al., 2023; Weatherly et al., 2021; Zhang et al., 2025). In the abovementioned toxicological review, the U.S. EPA concluded that PFBA is likely associated with liver, thyroid, and developmental effects in humans, while also concluding that the epidemiological data is limited, often of low-confidence, and insufficient to inform on exposure towards sensitive subpopulations or life stages (U.S. EPA, 2022). Recent in-vitro evidence in human neuronal cells showed that PFBA induced oxidative stress and metabolic disruption as possible mechanisms of toxicity (Obiako et al., 2024).

4.2.1. Application of RPFs and RfDs

Even if a proper risk assessment should consider the general diet of the exposed population, the results of this study indicate the possible exceedance of health-based reference values (TWI) by solely drinking wine for a very limited number of samples, overall suggesting that wine may contribute non-negligibly to PFAS exposure under specific scenarios, depending on the benchmark applied.

At the same time, the use of RPFs and RfDs for PFAS remains subject to scientific debate and methodological limitations, which should be considered when interpreting the observed benchmark exceedances.

Concerning the RPFs proposed by Bil et al. (2021), some authors (Backhaus, 2023; Rietjens et al., 2022) pointed out: i) the discrepancy between the toxicological endpoints proposed and those used for other reference thresholds (the TWI established by EFSA is derived from immunotoxic effects in humans, and not hepatotoxicity); ii) the different relative toxic potency of specific compounds with respect to different endpoints (e.g. PFNA is reported to be 17-fold more toxic than PFHxS, while EFSA's TWI assumes their equal potency); iii) the use of data from studies conducted in different laboratories, with varying rat strains, exposure durations, and administration routes (e.g. PFOA); iv) the high sensitivity of the RPFs to modelling approaches. Nevertheless, subsequent work by the same authors (Bil et al., 2023) showed broadly consistent and similar PFAS potency rankings for immunological endpoints (rat lymphoid organ weights). While further work is necessary with regard to human relevance, their results support the use of RPFs as a reasonable tool for estimating aggregate exposure to PFAS mixtures.

RfDs, and more generally health-based guidance values for PFAS, have changed substantially in the last decade. This is particularly true for the legacy compounds (PFOA, PFOS), for which the lowering of safety doses is primarily driven by the increase of human epidemiological data along with more precautionary regulatory approaches, therefore affecting the points of departure (PoDs) and uncertainty factors (UFs) applied when calculating such thresholds (Dong et al., 2017).

For example, the medium-to-high confidence level of EPA's RfD for PFOA (3×10^{-8} mg/kg bw/day) is justified by robust human epidemiological evidence (reduced antibody response in children), model-based dose extrapolation, and robust uncertainty factors, whereas the toxicological basis for PFBA is less consolidated. Alternative PFOA RfDs (Burgoon et al., 2023) are substantially higher (1×10^{-5} to 7×10^{-5} mg/kg-day), mainly because of differences in the selected critical endpoint, the evidence base (human vs. animal data), and the uncertainty factors applied. Overall, the EPA value is more precautionary, as it prioritizes human epidemiological evidence and includes a 10-fold uncertainty factor to account for human variability.

4.2.2. Considerations on the exposure of the population to PFAS in wine

Exposure to PFAS through wine consumption may vary significantly with respect to demographic characteristics and drinking habits.

National and regional ISTAT-based data (see Supplementary section 2) indicate that wine consumption is more prevalent among adults and older individuals than among younger groups, in whom beer and alcoholic aperitifs are more common, and that the Veneto Region shows wine consumption levels above the national average, particularly among males (ISTAT, 2024a; 2024b; Scafato et al., 2025). Overall, these data suggest that wine-related PFAS exposure may be more relevant in specific subgroups, particularly males and older adults.

The estimation of the exposure of the local population to PFAS by wine ingestion on the basis of national and regional data of wine consumers is not possible, mainly because i) the non-stochastic sampling of wines and ii) the weak assumption that local residents (of the Red and Orange areas) coincide with consumers. The potential contribution of wine consumption to PFAS exposure in the local population is supported by previous epidemiological evidence from the same contaminated area. Ingelido et al. (2018) reported a significant positive association between serum PFAS concentrations and alcohol intake, particularly wine consumption, in the contaminated area. After stratification by sex, the association with beer and total alcohol intake lost statistical significance, whereas the correlation with wine consumption remained significant, although weaker and involving a reduced number of PFAS analytes. Furthermore, Ingelido et al. (2020) reported significantly higher serum concentrations of several PFAS among local farmers living in the contaminated area, compared to the exposed and non-exposed general population. Contaminated public drinking water remained the predominant source, while private well water and consumption of self-produced food further contributed to internal exposure. This finding underscores a specific risk for agricultural workers, whose dietary habits may increase their exposure.

In the context of this work, this suggests that wine may represent a non-negligible dietary exposure pathway in the studied area, and that local winemakers, especially male subjects, may be more exposed to PFAS ingestion by wine consumption than the local general population.

5. Conclusions

The monitoring of PFAS in local agricultural products is essential in areas with a known contamination history. In this study, we provide the first evidence of a PFAS contamination of wines produced in one of Europe's most impacted PFAS settings. The contamination mainly involves short-chain PFAS, especially PFBA. The different PFAA distribution profiles in groundwater and wines are consistent with a chain length-dependent uptake and bioconcentration mechanism from groundwater to roots and fruits, as suggested by available peer-reviewed literature on PFAS uptake by vegetable species.

The geospatial data analysis on wines from georeferenced vineyards highlighted a correlation between the occurrence levels of PFAS in wine and in groundwater, confirming the possibility to trace the potential environmental contamination by using wines as a bioindicator, although with limitations. The statistical evidence supports the initial hypothesis that contaminated groundwater contributed to the presence of PFAS in wines. However, contributions of other sources, such as surface water, cannot be ruled out.

Estimated weekly intakes of PFAS based on specific wine consumption scenarios indicated how high consumers can ingest a dose of PFAS higher than the EFSA-recommended TWI by solely drinking wine. The exceedance is more pronounced when taking into account specific relative potency factors. Moreover, under the hypothesis of daily consumption of some wines, daily intake of specific compounds was higher than recently proposed human health reference doses. These results suggest that wine, as a widely consumed local agricultural product, may represent a non-negligible pathway of human exposure to PFAS. Attention should be given to health risks for specific population subgroups who may continue to experience higher exposure levels over time.

These findings should nevertheless be interpreted cautiously, as health-based benchmarks for short-chain PFAS such as PFBA remain less established than those for legacy compounds such as PFOA and PFOS.

The results of this study call for both a more tailored investigation and for the development of practical measures capable of protecting human health as well as traditional agricultural activities that are intertwined with territorial identity and economic interests. It would be advisable to plan implementable solutions that allow the exploitation of alternative, cost-effective treated water.

CRediT authorship contribution statement

Francesco Calore: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Paolo Girardi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Alessandro Bonetto:** Validation, Methodology, Investigation, Formal analysis, Data curation. **Laura Pagnin:** Writing – original draft, Validation, Investigation, Formal analysis, Data curation. **Antonio Marcomini:** Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2026.128482.

Data availability

Data will be made available on request.

References

Affricano, A., Asteggiano, A., Di Bernardo, A., Apirakkan, O., Khachonwongwattana, A., Sinaviwat, S., Medana, C., 2026. Case study: targeted HPLC-MS/MS analysis of TFA and other USC-PFAS in beverages and waters from Italy and Asia. Food Control 181, 111779. https://doi.org/10.1016/j.foodcont.2025.111779.

Altissimo, L., Bertoldo, S., Campagnolo, F., Gusmaroli, G., Muraro, T., Sottani, A., 2014. Esperienze di MAR con sistemi disperdenti a largo diametro: primo bilancio di attività sperimentali nell'alta pianura vicentina (Italia Settentrionale) (Managed aquifer recharge experiences with shallow wells: first analysis of the experimental activities in the high Vicenza plain (Northern Italy))- in italian. Acque Sotterranee - Italian Journal of Groundwater 3. https://doi.org/10.7343/as-082-14-0108.

ARPAV, 2025. Concentrazione di sostanze perfluoroalchiliche (PFAS) nelle acque prelevate da ARPAV - PFAS concentrations in waters analyzed by ARPAV - in italian [WWW Document]. URL. https://www.arpa.veneto.it/dati-ambientali/open-data/idrosfera/concentrazione-di-sostanze-perfluoroalchiliche-pfas-nelle-acque-prelevate-da-arpav (accessed 3.30.26).

ARPAV, 2024. Monitoraggio delle sostanze per- e polifluoroalchiliche (PFAS) nella rete di sorveglianza delle acque sotterranee (Monitoring campaign relative to the groundwater surveillance network) - in italian. URL. https://www.arpa.veneto.it/temi-ambientali/acque-interne/acque-interne/pfas/20250102_monitoraggio_pfas_rete_sorveglianza.pdf (accessed 3.30.26).

ARPAV, 2022. Gestione delle risorse idriche nella Regione Veneto (water resource management in the Veneto Region) - in italian [WWW Document]. URL. https://www.arpa.veneto.it/temi-ambientali/acque-interne/acque-potabili/gestione-delle-risorse-idriche (accessed 3.30.26).

ARPAV, 2019. Contaminazione da PFAS: azioni ARPAV - periodo di riferimento: 14 Giugno 2013- 31 Dicembre 2018. Riassunto delle attività (PFAS Contamination: ARPAV Actions - Reference period: 14 June 2013 to 31 December 2018. Summary of activities) - in italian. URL. https://www.arpa.veneto.it/dati-ambientali/open-data/dati-ambientali/open-data/fitosanitari/resolveuid/dfb88c5c26c4254cc14fc49cf5af2247.

Backhaus, T., 2023. Commentary on the EU commission's proposal for amending the water framework directive, the groundwater directive, and the directive on

environmental quality standards. Environ. Sci. Eur. 35, 1–7. https://doi.org/10.1186/s12302-023-00726-3.
Bartolomé, M., Gallego-Picó, A., Cutanda, F., Huetos, O., Esteban, M., Pérez-Gómez, B., Castaño, A., 2017. Perfluorinated alkyl substances in Spanish adults: geographical distribution and determinants of exposure. Sci. Total Environ. 603–604, 352–360. https://doi.org/10.1016/j.scitotenv.2017.06.031.
Battisti, I., Trentin, A.R., Franzolin, E., Nicoletto, C., Masi, A., Renella, G., 2024. Uptake and distribution of perfluoroalkyl substances by grafted tomato plants cultivated in a contaminated site in northern Italy. Sci. Total Environ. 915, 170032. https://doi.org/10.1016/j.scitotenv.2024.170032.
Biggeri, A., Stoppa, G., Facciolo, L., Fin, G., Mancini, S., Manno, V., Minelli, G., Zamagni, F., Zamboni, M., Catelan, D., Bucchi, L., 2024. All-cause, cardiovascular disease and cancer mortality in the population of a large Italian area contaminated by perfluoroalkyl and polyfluoroalkyl substances (1980–2018). Environ. Health 23, 42. https://doi.org/10.1186/s12940-024-01074-2.
Bil, W., Ehrlich, V., Chen, G., Vandebriel, R., Zeilmaker, M., Luijten, M., Uhl, M., Marx-Stoelting, P., Halldorsson, T.I., Bokkers, B., 2023. Internal relative potency factors based on immunotoxicity for the risk assessment of mixtures of per- and polyfluoroalkyl substances (PFAS) in human biomonitoring. Environ. Int. 171, 107727. https://doi.org/10.1016/j.envint.2022.107727.
Bil, W., Zeilmaker, M., Fragki, S., Lijzen, J., Verbruggen, E., Bokkers, B., 2021. Risk assessment of Per- and Polyfluoroalkyl Substance mixtures: a relative potency factor approach. Environ. Toxicol. Chem. 40, 859–870. https://doi.org/10.1002/ETC.4835.
Blaine, A.C., Rich, C.D., Sedlacko, E.M., Hundal, L.S., Kumar, K., Lau, C., Mills, M.A., Harris, K.M., Higgins, C.P., 2014. Perfluoroalkyl acid distribution in various plant compartments of edible crops grown in biosolids-amended soils. Environ. Sci. Technol. 48, 7858–7865. https://doi.org/10.1021/es500016s.
Bonato, T., Pal, T., Benna, C., Di Maria, F., 2025. Contamination of the terrestrial food chain by per- and polyfluoroalkyl substances (PFAS) and related human health risks: a systematic review. Sci. Total Environ. 961, 178337. https://doi.org/10.1016/j.scitotenv.2024.178337.
Burgoon, L.D., Clewell, H.J., Cox, T., Dekant, W., Dell, L.D., Deyo, J.A., Dourson, M.L., Gadagbui, B.K., Goodrum, P., Green, L.C., Vijayavel, K., Kline, T.R., House-Knight, T., Luster, M.I., Manning, T., Nathanail, P., Pagone, F., Richardson, K., Severo-Peixe, T., Sharma, A., Smith, J.S., Verma, N., Wright, J., 2023. Range of the perfluorooctanoate (PFOA) safe dose for human health: an international collaboration. Regul. Toxicol. Pharmacol. 145, 105502. https://doi.org/10.1016/j.yrtph.2023.105502.
Burtscher-Schaden, H., Langemann, S., Lyssimachou, A., Roynel, S., 2025. Message from the bottle- the rapid rise of TFA contamination across the EU. GLOBAL 2000 – Friends of the Earth Austria; Pesticide Action Network Europe (PAN Europe).
Cantwell, H. (Ed.), 2025. Eurachem Guide: the Fitness for Purpose of Analytical Methods - a Laboratory Guide to Method Validation and Related Topics, third ed. Available from: www.eurachem.org
Chaves, M.M., Zarrouk, O., Francisco, R., Costa, J.M., Santos, T., Regalado, A.P., Rodrigues, M.L., Lopes, C.M., 2010. Grapevine under deficit irrigation: hints from physiological and molecular data. Ann. Bot. 105, 661–676. https://doi.org/10.1093/aob/mcq030.
Cheng, W., Doering, J.A., LaLone, C., Ng, C., 2021. Integrative computational approaches to inform relative bioaccumulation potential of Per- and Polyfluoroalkyl substances across species. Toxicol. Sci. 180, 212–223. https://doi.org/10.1093/toxsci/kfab004.
Chopin, E.I.B., Marin, B., Mkoungafoko, R., Rigaux, A., Hopgood, M.J., Delannoy, E., Cancès, B., Laurain, M., 2008. Factors affecting distribution and mobility of trace elements (Cu, Pb, Zn) in a perennial grapevine (Vitis vinifera L.) in the Champagne region of France. Environmental Pollution 156, 1092–1098. https://doi.org/10.1016/j.envpol.2008.04.015.
Council of the European Union, 2026. Position of the Council at first reading with a view to the adoption of a directive of the European Parliament and of the Council amending directive 2000/60/EC establishing a framework for Community action in the field of water policy. Directive 2006/118/EC on the Protection of Groundwater Against Pollution and Deterioration and Directive 2008/105/EC on Environmental Quality Standards in the Field of Water policy- Adopted by the Council on 17 February 2026. Eur-Lex. Brussels. ST 14144 2025 REV 1.
Cousins, I.T., Dewitt, J.C., Glüge, J., Goldenman, G., Herzke, D., Lohmann, R., Ng, C.A., Scheringer, M., Wang, Z., 2020. The high persistence of PFAS is sufficient for their management as a chemical class. Environ. Sci. Process. Impacts 22, 2307–2312. https://doi.org/10.1039/D0EM00355G.
Crebelli, R., Caiola, S., Conti, L., Cordelli, E., De Luca, G., Dellatte, E., Eleuteri, P., Iacovella, N., Leopardi, P., Marcon, F., Sanchez, M., Sestili, P., Siniscalchi, E., Villani, P., 2019. Can sustained exposure to PFAS trigger a genotoxic response? A comprehensive genotoxicity assessment in mice after subacute oral administration of PFOA and PFBA. Regul. Toxicol. Pharmacol. 106, 169–177. https://doi.org/10.1016/j.yrtph.2019.05.005.
Dong, Z., Bahar, M.M., Jit, J., Kennedy, B., Priestly, B., Ng, J., Lamb, D., Liu, Y., Duan, L., Naidu, R., 2017. Issues raised by the reference doses for perfluorooctane sulfonate and perfluorooctanoic acid. Environ. Int. 105, 86–94. https://doi.org/10.1016/j.envint.2017.05.006.
Dorosh, O., Fernandes, V.C., Moreira, M.M., Delerue-Matos, C., 2021. Occurrence of pesticides and environmental contaminants in vineyards: case study of Portuguese grapevine canes. Sci. Total Environ. 791, 148395. https://doi.org/10.1016/j.scitotenv.2021.148395.
Dumitriu (Gabur), G.-D., Teodosiu, C., Morosanu, I., Plavan, O., Gabur, I., Cotea, V.V., 2021. Heavy metals assessment in the major stages of winemaking: chemometric analysis and impacts on human health and environment. J. Food Compos. Anal. 100, 103935. https://doi.org/10.1016/j.jfca.2021.103935.
EFSA, Contam Panel, Dieter, S., Bignami, M., Bodin, L., Chipman, J.K., del Mazo, J., Grasl-Kraupp, B., Hogstrand, C., Hoogenboom, L., Leblanc, J.C., Nebbia, C.S., Nielsen, E., Ntzani, E., Petersen, A., Sand, S., Vleminckx, C., Wallace, H., Barregård, L., Ceccatelli, S., Cravedi, J.P., Halldorsson, T.I., Haug, L.S., Johansson, N., Knutsen, H.K., Rose, M., Roudot, A.C., Van Loveren, H., Vollmer, G., Mackay, K., Riolo, F., Schwerdtle, T., 2020. Risk to human health related to the presence of perfluoroalkyl substances in food. EFSA J. 18, e06223. https://doi.org/10.2903/J.EFSA.2020.6223.
European Parliament and Council of the European Union, 2013. Regulation (EU) no 1308/2013 of the European Parliament and of the Council of 17 December 2013 establishing a common organisation of the markets in agricultural products and repealing Council Regulations (EEC) no 922/72, (EEC) no 234/79, (EC) no 1037/2001 and (EC) no 1234/2007. Off. J. Eur. Union L347, 671–854. http://data.europa.eu/eli/reg/2013/1308/oj.
European Parliament and Council of the European Union, 2024. Regulation (EU) 2024/1143 of the European Parliament and of the Council of 11 April 2024 on geographical indications for wine, spirit drinks and agricultural products, as well as traditional specialities guaranteed and optional quality terms for agricultural products, amending Regulations (EU) no 1308/2013, (EU) 2019/787 and (EU) 2019/1753 and repealing Regulation (EU) no 1151/2012. Off. J. Eur. Union 2024/1143, 1–76. http://data.europa.eu/eli/reg/2024/1143/oj.
Evich, M.G., Davis, M.J.B., McCord, J.P., Acrey, B., Awkerman, J.A., Knappe, D.R.U., Lindstrom, A.B., Speth, T.F., Tebes-Stevens, C., Strynar, M.J., Wang, Z., Weber, E.J., Henderson, W.M., Washington, J.W., 2022. Per- and polyfluoroalkyl substances in the environment. Science 375, 6580. https://doi.org/10.1126/science.abg9065.
Felizeter, S., McLachlan, M.S., De Voogt, P., 2014. Root uptake and translocation of perfluorinated alkyl acids by three hydroponically grown crops. J. Agric. Food Chem. 62, 3334–3342. https://doi.org/10.1021/jf500674j.
Felizeter, S., McLachlan, M.S., De Voogt, P., 2012. Uptake of perfluorinated alkyl acids by hydroponically grown lettuce (Lactuca sativa). Environ. Sci. Technol. 46, 11735–11743. https://doi.org/10.1021/es302398u.
Fenton, S.E., Ducatman, A., Boobis, A., DeWitt, J.C., Lau, C., Ng, C., Smith, J.S., Roberts, S.M., 2021. Per- and Polyfluoroalkyl substance toxicity and human health review: current State of knowledge and strategies for informing future research. Environ. Toxicol. Chem. 40, 606–630. https://doi.org/10.1002/etc.4890.
Freeling, F., Mira de Orduña Heidinger, R., 2025. Tracking trifluoroacetate (TFA) through time: a 78-Year record from archived wines. Environ. Sci. Technol. 59, 26762–26769. https://doi.org/10.1021/acs.est.5c10868.
Gallocchio, F., Mancin, M., Belluco, S., Moressa, A., Angeletti, R., Lorenzetto, M., Arcangeli, G., Ferrè, N., Ricci, A., Russo, F., 2022. Investigation of levels of perfluoroalkyl substances in freshwater fishes collected in a contaminated area of Veneto Region, Italy. Environ. Sci. Pollut. Res. 29, 20996–21011. https://doi.org/10.1007/s11356-021-17236-5.
Ghisi, R., Vamerali, T., Manzetti, S., 2019. Accumulation of perfluorinated alkyl substances (PFAS) in agricultural plants: a review. Environ. Res. 169, 326–341. https://doi.org/10.1016/j.envres.2018.10.023.
Girardi, P., Merler, E., 2019. A mortality study on male subjects exposed to polyfluoroalkyl acids with high internal dose of perfluorooctanoic acid. Environ. Res. 179, 108743. https://doi.org/10.1016/J.ENVRES.2019.108743.
Gredelj, A., Nicoletto, C., Polesello, S., Ferrario, C., Valsecchi, S., Lava, R., Barausse, A., Zanon, F., Palmeri, L., Guidolin, L., Bonato, M., 2020. Uptake and translocation of perfluoroalkyl acids (PFAAs) in hydroponically grown red chicory (Cichorium intybus L.): growth and developmental toxicity, comparison with growth in soil and bioavailability implications. Sci. Total Environ. 720, 137333. https://doi.org/10.1016/j.scitotenv.2020.137333.
Hu, X.C., Andrews, D.Q., Lindstrom, A.B., Bruton, T.A., Schaider, L.A., Grandjean, P., Lohmann, R., Carignan, C.C., Blum, A., Balan, S.A., Higgins, C.P., Sunderland, E.M., 2016. Detection of Poly- and Perfluoroalkyl Substances (PFASs) in U.S. Drinking Water Linked to Industrial Sites, Military Fire Training Areas, and Wastewater Treatment Plants. Environ. Sci. Technol. Lett. 3, 344–350. https://doi.org/10.1021/acs.estlett.6b00260.
Ingelido, A.M., Abballe, A., Gemma, S., Dellatte, E., Iacovella, N., De Angelis, G., Marra, V., Russo, F., Vazzoler, M., Testai, E., De Felip, E., 2020. Serum concentrations of perfluorinated alkyl substances in farmers living in areas affected by water contamination in the Veneto Region (Northern Italy). Environ. Int. 136, 105435. https://doi.org/10.1016/j.envint.2019.105435.
Ingelido, A.M., Abballe, A., Gemma, S., Dellatte, E., Iacovella, N., De Angelis, G., Zampaglioni, F., Marra, V., Miniero, R., Valentini, S., Russo, F., Vazzoler, M., Testai, E., De Felip, E., 2018. Biomonitoring of perfluorinated compounds in adults exposed to contaminated drinking water in the Veneto Region, Italy. Environ. Int. 110, 149–159. https://doi.org/10.1016/j.envint.2017.10.026.
IRIS glossary, 2025 [WWW Document]. https://www.epa.gov/iris/iris-glossary (accessed 3.30.26).
ISS, 2022. Definizioni operative relative alla Sorveglianza Sanitaria PASSI (operative definitions related to the PASSI sanitary surveillance) - in italian [WWW Document]. URL. https://www.epicentro.iss.it/passi/indicatori/alcol (accessed 3.30.26).
ISTAT, 2024a. ISTAT data on Drinking habits of the Italian population according to age [WWW Document]. URL. https://esploradati.istat.it/databrowser/#/en/dw/categories/IT1,Z0810HEA,1.0/HEA_STYLE/HEA_STYLE_DRINK/IT1,83_85_DF_DCCV_AVQ_PERSONE1_215,1.0 (accessed 3.27.26).
ISTAT, 2024b. ISTAT data on Drinking habits of the Italian population according to Region and type of Municipality [WWW Document]. URL. https://esploradati.istat.it/databrowser/#/en/dw/categories/IT1,Z0810HEA,1.0/HEA_STYLE/HEA_STYLE_DRINK/IT1,83_85_DF_DCCV_AVQ_PERSONE1_218,1.0 (accessed 3.27.26).

ISTAT, 2020. Seventh national agricultural census database [WWW Document]. URL. https://esploradati.istat.it/databrowser/#/it/censimentoagricoltura (accessed 1.3.26).
Italian Parliamentary Commission of Inquiry, 2022. Relazione Sulla Diffusione Delle Sostanze Perfluoroalchiliche (Doc. XXIII, No. 18) (Report on the Diffusion of Perfluoroalkyl Substances (Doc. XXIII, No. 18)) - in Italian. Chamber of Deputies, Rome, Italy. URL. https://documenti.camera.it/_dati/leg18/lavori/documentiparlamentari/indiceetesti/023/018/intero.htm (accessed 3.27.26).
Ivantsova, E., Lu, A., Martyniuk, C.J., 2024. Occurrence and toxicity mechanisms of perfluorobutanoic acid (PFBA) and perfluorobutane sulfonic acid (PFBS) in fish. Chemosphere 349, 140815. https://doi.org/10.1016/j.chemosphere.2023.140815.
Lava, R., Calore, F., Mazzola, M., Moretto, C.G., Pretto, U., Salmaso, P., Bizzotto, A., Carvutto, R., Acerbi, M., Tommasi, J., Marcomini, A., 2021. Groundwater contamination by fluorinated aromatics: benzotrifluoride and its derivatives. Chemosphere 265, 129029. https://doi.org/10.1016/j.chemosphere.2020.129029.
Lesmeister, L., Lange, F.T., Breuer, J., Biegel-Engler, A., Giese, E., Scheurer, M., 2021. Extending the knowledge about PFAS bioaccumulation factors for agricultural plants – a review. Sci. Total Environ. 766, 142640. https://doi.org/10.1016/J.SCITOTENV.2020.142640.
Li, P., Oyang, X., Zhao, Yule, Tu, T., Tian, X., Li, L., Zhao, Yuan, Li, J., Xiao, Z., 2019. Occurrence of perfluorinated compounds in agricultural environment, vegetables, and fruits in regions influenced by a fluorine-chemical industrial park in China. Chemosphere 225, 659–667. https://doi.org/10.1016/j.chemosphere.2019.03.045.
Liu, Z., Cao, X., Wu, M., Huang, W., Dong, X., Chen, X., Zhang, C., 2025. Mechanisms of PFBA toxicity in Chlorella vulgaris: Photosynthesis, oxidative stress, and antioxidant impairment. Environ. Res. 273, 121228. https://doi.org/10.1016/j.envres.2025.121228.
Liviz, C. do A.M., Maciel, G.M., Pinheiro, D.F., Lima, N.F., Ribeiro, I.S., Haminiuk, C.W.I., 2025. Pesticide residues in grapes and wine: an overview on detection, health risks, and regulatory challenges. Food Res. Int. 203, 115771. https://doi.org/10.1016/j.foodres.2025.115771.
Menegatto, M., Zamperini, A., Menegatto, M., Zamperini, A., 2023. Health and psychological concerns of communities affected by Per- and poly-fluoroalkyl substances: the case of residents living in the Orange Area of the Veneto Region. Int. J. Environ. Res. Publ. Health 20. https://doi.org/10.3390/ijerph20227056.
Mirás-Avalos, J.M., Araujo, E.S., Mirás-Avalos, J.M., Araujo, E.S., 2021. Optimization of vineyard water management: challenges, strategies, and perspectives. Water 13. https://doi.org/10.3390/w13060746.
Obiako, P.C., Ayisire, S.O., Sayes, C.M., 2024. Impact of perfluorooctanoic acid (PFOA) and perfluorobutanoic acid (PFBA) on oxidative stress and metabolic biomarkers in human neuronal cells (SH-SY5Y). Environ. Int. 190, 108864. https://doi.org/10.1016/j.envint.2024.108864.
Palma, M., Maggio, S., Cappello, C., Congedi, A., De Iaco, S., 2023. Spatio-temporal modeling of groundwater quality deterioration and resource depletion. Hydrogeol. J. 31, 1443–1461. https://doi.org/10.1007/s10040-023-02692-9.
Pisciotta, A., Di Lorenzo, R., Santalucia, G., Barbagallo, M.G., 2018. Response of grapevine (Cabernet Sauvignon cv) to above ground and subsurface drip irrigation under arid conditions. Agric. Water Manag. 197, 122–131. https://doi.org/10.1016/j.agwat.2017.11.013.
Pitter, G., Da Re, F., Canova, C., Barbieri, G., Jeddi, M.Z., Daprà, F., Manea, F., Zolin, R., Bettega, A.M., Stopazzolo, G., Vittorii, S., Zambelli, L., Martuzzi, M., Mantoan, D., Russo, F., 2020a. Serum levels of perfluoroalkyl substances (PFAS) in adolescents and young adults exposed to contaminated drinking water in the Veneto region, Italy: a cross-sectional study based on a health surveillance program. Environmental Health Perspectives 128, 2. https://doi.org/10.1289/EHP5337.
Pitter, G., Zare Jeddi, M., Barbieri, G., Gion, M., Fabricio, A.S.C., Daprà, F., Russo, F., Fletcher, T., Canova, C., 2020b. Perfluoroalkyl substances are associated with elevated blood pressure and hypertension in highly exposed young adults. Environ. Health 19, 102. https://doi.org/10.1186/s12940-020-00656-0.
Rietjens, I.M.C.M., Schriks, M., Houtman, C.J., Dingemans, M.M.L., Van Wezel, A.P., 2022. Letter to the Editor on Bil et al. 2021 "Risk Assessment of Per- and Polyfluoroalkyl Substance Mixtures: a Relative Potency Factor Approach.". Environ. Toxicol. Chem. 41, 7–12. https://doi.org/10.1002/etc.5232.
Sana, T., Chowdhury, M.I., Logeshwaran, P., Megharaj, M., 2023. Behavioural, developmental and reproductive toxicological impacts of perfluorobutanoic acid (PFBA) in Caenorhabditis elegans. Environ. Chall. 10, 100662. https://doi.org/10.1016/j.envc.2022.100662.
Scafato, E., Ghirini, S., Gandin, C., Matone, A., Manno, V., Vichi, M., CSDA (Centro Servizi Documentazione Alcol) Working Group, 2025. Epidemiologia e monitoraggio alcol-correlato in Italia e nelle Regioni. In: (Epidemiology and alcohol-related Monitoring in Italy and in the Regions. Evaluation of the National Observatory on Alcohol on the Impact of the Alcohol Consumption in Support for the Implementation of the Activities of the National Alcohol and Health Plan and of the National Prevention Plan. Report 2025.) - in Italian, Rapporti ISTISAN. Istituto Superiore Di Sanità, Roma. Valutazione dell'Osservatorio Nazionale Alcol sull'impatto del consumo di alcol ai fini dell'implementazione delle attività del Piano Nazionale Alcol e Salute e del Piano Nazionale della Prevenzione. Rapporto 2025.
Schiavo, M., 2024. Spatial modeling of the water table and its historical variations in Northeastern Italy via a geostatistical approach. Groundw. Sustain. Dev. 25, 101186. https://doi.org/10.1016/j.gsd.2024.101186.
Schusterova, D., Hajslova, J., Kocourek, V., Pulkrabova, J., Schusterova, D., Hajslova, J., Kocourek, V., Pulkrabova, J., 2021. Pesticide residues and their metabolites in grapes and wines from conventional and organic farming System. Foods 10. https://doi.org/10.3390/foods10020307.
Sunderland, E.M., Hu, X.C., Dassuncao, C., Tokranov, A.K., Wagner, C.C., Allen, J.G., 2019. A review of the pathways of human exposure to poly- and perfluoroalkyl substances (PFASs) and present understanding of health effects. J. Expo. Sci. Environ. Epidemiol. 29, 131–147. https://doi.org/10.1038/s41370-018-0094-1.
Tsalidis, G.A., Kryona, Z.-P., Tsirliganis, N., 2022. Selecting south European wine based on carbon footprint. Resources, Environment and Sustainability 9, 100066. https://doi.org/10.1016/j.resenv.2022.100066.
U.S. EPA, 2022. IRIS toxicological review of perfluorobutanoic acid (PFBA, CASRN 375-22-4) and related salts. EPA IRIS Assessments. URL. https://iris.epa.gov/static/pdfs/0701tr.pdf (accessed 04.03.26).
U.S. EPA, 2021. Human health toxicity values for hexafluoropropylene oxide (HFPO) dimer acid and its ammonium salt (CASRN 13252-13-6 and CASRN 62037-80-3) also known as "GenX Chemicals" (No. 822R-21– 010). URL. https://www.epa.gov/system/files/documents/2021-10/genx-chemicals-toxicity-assessment_tech-edited_oct-21-508.pdf (accessed 04.03.26).
Van Leeuw, V., Malysheva, S.V., Fosseprez, G., Murphy, A., El Amraoui Aarab, C., Andjelkovic, M., Waegeneers, N., Van Hoeck, E., Joly, L., 2024. Per- and polyfluoroalkyl substances in food and beverages: determination by LC-HRMS and occurrence in products from the Belgian market. Chemosphere 366, 143543. https://doi.org/10.1016/j.chemosphere.2024.143543.
Veneto Region, 2019. Veneto Region statement n° 1319 (in italian) [WWW Document]. URL. https://www.regione.veneto.it/article-detail?articleId=3336172 (accessed 3.31.26).
Veneto Region, 2018. Deliberazione della Giunta Regionale n. 691 del 21 Maggio 2018. Modifica del "Piano di sorveglianza sulla popolazione esposta alle sostanze perfluoroalchiliche", di cui all'Allegato A alla D.G.R. n. 2133 del 23/12/2016 [Deliberation of the Regional Executive Council No. 691 of 21 May 2018 Amendment to the "Surveillance plan for the population exposed to per- and polyfluoroalkyl substances (PFAS)", as set out in Annex A to Regional Executive Council Deliberation No. 2133 of 23 December 2016 - In Italian [WWW Document]. URL. https://bur.regione.veneto.it/BurvServices/pubblica/DettaglioDgr.aspx?id=370611 (accessed 04.14.26).
Vicenza Province, 2019. Statistics on agricultural production of the Vicenza Province (Veneto Region, Italy) based on ISTAT data - in Italian [WWW Document]. URL. https://www.provincia.vicenza.it/ente/la-struttura-della-provincia/servizi/statistica/dati-statistici/agricoltura-1 (accessed 04.14.26).
Weatherly, L.M., Shane, H.L., Lukomska, E., Baur, R., Anderson, S.E., 2021. Systemic toxicity induced by topical application of heptafluorobutyric acid (PFBA) in a murine model. Food Chem. Toxicol. https://doi.org/10.1016/j.fct.2021.112528.
Wen, B., Li, L., Zhang, H., Ma, Y., Shan, X.-Q., Zhang, S., 2014. Field study on the uptake and translocation of perfluoroalkyl acids (PFAAs) by wheat (Triticum aestivum L.) grown in biosolids-amended soils. Environmental Pollution 184, 547–554. https://doi.org/10.1016/j.envpol.2013.09.040.
Zamboni, M., Fin, G., Scatton, N., Facciolo, L., Stoppa, G., Catelan, D., Ungherese, G., Biggeri, A., 2021. [Perfluoroalchilic food contamination in the PFAS high-risk area of the Veneto Region (Northern Italy)]. Epidemiol. Prev. 45, 387–394. https://doi.org/10.19191/EP21.5.P387.105.
Zhang, J., Zhang, S., Lu, C., Wang, X., Du, Z., Wang, Jinhua, Li, B., Wang, Jun, Zhu, L., 2025. Comparison of the combined toxicity of PFOA and emerging alternatives: a comprehensive evaluation of oxidative damage, apoptosis and immunotoxicity in embryonic and adult zebrafish. Water Res. 273, 123028. https://doi.org/10.1016/j.watres.2024.123028.
Zhang, M., Wang, P., Lu, Y., Lu, X., Zhang, A., Liu, Z., Zhang, Y., Khan, K., Sarvajayakesavalu, S., 2020. Bioaccumulation and human exposure of perfluoroalkyl acids (PFAAs) in vegetables from the largest vegetable production base of China. Environ. Int. 135, 105347. https://doi.org/10.1016/j.envint.2019.105347.