



Toxicity footprint of fungicide use in Spanish viticulture: an LCA approach integrating USEtox™ and PestLCI-derived emission fractions

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Abstract

Purpose This study quantifies the pesticide-related chemical footprint in Spanish viticulture, linking national use data with USEtox™ through the PestLCI Consensus model, integrating emissions to air, soil, and water into a comprehensive life cycle impact assessment. We ask: (i) which active substances dominate chemical footprints, (ii) how applied mass versus intrinsic hazard drive their contributions, and (iii) how temporal portfolio changes influence overall impacts and management priorities.

Methods National pesticide-use data from the Spanish Ministry of Agriculture, Fisheries and Food (MAPA) for 2013 and 2019 were harmonized by active ingredient and linked with compartment emission fractions from PestLCI Consensus model. Characterization factors (CF) for ecotoxicological and human toxicity impacts were retrieved from USEtox™ v2.14 for emissions to continental air, freshwater, and agricultural and natural soils. Resulting Impact Scores (IS) combined emitted mass and compartmental CFs to quantify substance specific contributions. Uncertainty related to potential under- or over-reporting in official statistics was considered and implications. The analysis focuses on organic active substances with available USEtox™ characterisation factors, excluding copper- and sulfur-based compounds and other inorganic substances.

Results and discussion The results indicate that a few active substances dominate the chemical footprint of Spanish vineyards. Folpet and Mancozeb drive ecotoxicity impacts, while Mancozeb, Penconazole, Metalaxyl-M, Folpet, and Tebuconazole contribute most to human toxicity due to their high use and intrinsic hazard. Applied mass was decisive: substances with moderate CFs reached high IS under frequent or high-rate use, whereas highly toxic but restricted compounds (e.g., Chlorothalonil) contributed marginally. Regulatory and agronomic changes such as the withdrawal of Iprodione and Propineb, and the increased use of Dithianon and Fenbuconazole, reshaped the impact profile, leading to a noticeable increase in the overall footprint between 2013 and 2019 and a relatively stronger rise in human health impacts.

Conclusions Integrating national pesticide-use data with compartmental emission modelling (PestLCI Consensus) and impact characterization (USEtox™) enables a transparent and consistent estimation of chemical footprints. The framework provides actionable evidence for substance prioritization and policy design in sustainable pesticide management and can be transferred to other crops and regions for national-scale life cycle assessments.

Recommendations Future work should expand the assessment to more pesticide substances, particularly those currently lacking characterisation factors, while refining emission modelling by incorporating spatial and temporal variability. Updated national pesticide-use statistics will enable dynamic chemical-footprint modelling, supporting longitudinal assessment of toxicity-pressure trajectories and the evaluation of regulatory, agronomic, and policy-driven transitions in pesticide portfolios.

Keywords PestLCI Consensus · USEtox™ v2.14 · Chemical footprint · Human toxicity · Freshwater ecotoxicity · Vineyard fungicides

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1 Introduction

Pesticide use in viticulture plays a central role in farm productivity and economic performance, while simultaneously generating significant environmental and human-health

externalities. Empirical evidence links vineyard pesticide applications to impacts on soils, surface and ground waters, and biodiversity (Di Giovanni et al. 2024; Karimi et al. 2021; Steiner et al. 2024; Visconti et al. 2024), as well as to occupational and consumer health risks (Ahmad et al. 2024; Tucker et al., 2022; Tudi et al. 2022). Economic analyses further indicate that plant-protection products represent a substantial share of vineyard operating costs and that regulatory and agronomic pressures directly shape expenditure patterns and long-term economic sustainability in viticulture systems (Bourguet and Guillemaud 2016; Pretty and Bharucha 2015). In response, recent Common Agricultural Policy (CAP) reforms increasingly emphasize the reduction of pesticide dependence in viticulture while maintaining production viability (Homet et al. 2024). Field-based evidence also shows that reduced-pesticide strategies can preserve grape yield and quality when disease pressure is low and management practices are carefully integrated (Perria et al. 2022).

At European scale, fungicides constitute one of the most intensively marketed pesticide categories, with Spain consistently ranking among the highest-consuming Member States. Pesticide sales further exhibit marked interannual variability, with documented downturns linked to climatic anomalies such as drought events, demonstrating the sensitivity of pesticide demand to meteorological conditions (Carvalho et al. 2025). More broadly, viticultural pesticide use is strongly structured by climate-driven disease pressure. In wetter and more humid regions, higher fungal incidence (e.g. downy mildew, *Botrytis*) necessitates frequent fungicide applications, whereas drier Mediterranean climates may allow lower treatment intensity, albeit with emerging pressures linked to extreme heat and novel pests. This pattern is well documented in Spanish vineyards, where comparative studies between Atlantic (e.g. Galicia) and Mediterranean regions (e.g. La Rioja) report significantly higher fungicide residues in water bodies in humid climates, confirming that climatically driven disease pressure directly governs spray schedules and treatment intensity in Mediterranean viticulture (Fernández-Fernández et al. 2025).

Spain hosts approximately 964,000 Ha of vineyards, representing about 13% of global vineyard area and nearly 30% of the European Union total (Homet et al. 2024). In this context, national and regional strategies increasingly focus on eco-schemes and integrated management approaches aimed at reducing pesticide dependence in viticulture (Acebedo et al. 2022; Homet et al. 2024). Regional studies further highlight the importance of pesticide selection, soil management, biological control strategies and life cycle-based evaluation frameworks for guiding sustainable vineyard management (Lapierre et al. 2019; Vázquez-Blanco et al. 2023).

National pesticide-use statistics reported by MAPA indicate that vineyard fungicide programmes involve repeated applications each season, with most active substances showing average frequencies of one to two treatments per year and many vineyard plots being sprayed multiple times. As a result, the treated surface systematically exceeds the cultivated vineyard area, reflecting treatment intensity rather than land expansion. At national scale, total annual fungicide inputs to vineyards are of the same order of magnitude ($\approx 2 \times 10^7$ kg) in both reference years, while per-hectare application rates vary widely across substances, from very low doses for systemic fungicides to several tens of kilograms per hectare per year for contact compounds widely used in Spanish viticulture (Spanish Ministry of Agriculture, Fisheries and Food [MAPA], 2014, 2021). These patterns confirm the intensive and recurrent nature of fungicide use in Spanish vineyards and the dominant contribution of a limited number of active substances to the overall applied mass.

Accurate toxicity indicators and chemical-footprint metrics are therefore essential for supporting sustainable agricultural practices and policy design (El Afandi and Irfan 2024; Leclerc et al. 2023). In agricultural Life Cycle Assessment (LCA), pesticide emissions are estimated through emission models that allocate applied mass across environmental compartments (air, soil, freshwater), while USEtox™ characterization factors integrate fate, exposure and effect modelling to quantify potential human-health and freshwater-ecotoxicity impacts (Fantke et al. 2021). In viticulture, this has motivated the development of crop-specific emission modelling approaches, including adaptations of PestLCI that explicitly represent grapevine canopy structure and spraying conditions (Renaud-Gentié et al. 2015). Within this framework, USEtox™ provides a consensus life cycle impact assessment methodology consistent with European ILCD and Product Environmental Footprint (PEF) guidance for toxicity assessment in agri-food systems (Fantke et al. 2018; Peña et al. 2019; Roos et al. 2018), enabling harmonized comparisons across crops and regions (Mankong et al. 2022; Nemecek et al. 2022; Rosenbaum et al. 2008, 2011; Tang et al. 2022).

In this context, the present study advances the assessment of pesticide-related impacts in agriculture by integrating national pesticide-use statistics with crop-level emission modelling and life cycle impact assessment. Specifically, it couples the PestLCI Consensus model to estimate compartment-specific emission fractions of active substances to air, soil and freshwater (Nemecek et al. 2022) with USEtox™ v2.14 characterization factors for human toxicity and freshwater ecotoxicity based on harmonized fate, exposure and effect modelling (Rosenbaum et al. 2008). Applied to Spanish viticulture, this framework is extended to national

scale and across time, enabling a comprehensive chemical-footprint assessment and revealing how intrinsic hazard and applied mass jointly shape aggregate impacts in 2013 and 2019. These findings are context-specific and reflect the characteristics of Spanish viticulture and should therefore not be directly extrapolated to other cropping systems or regions without careful contextualization.

2 Methods

2.1 Study design and scope

We quantified the potential human toxicity and freshwater ecotoxicity associated with pesticide use in Spanish viticulture for two benchmark years (2013 and 2019). The analysis focused on the Spanish Ministry of Agriculture, Fisheries and Food category “fungicides and bactericides” (administrative category encompassing fungicides, some of which also show activity against bacterial diseases), excluding copper- and sulfur-based compounds as well as other inorganic substances (e.g., potassium phosphonates and potassium hydrogen carbonate), due to the higher uncertainty and limited comparability of their characterization within the USEtox™ framework. For both vintages, we combined nationally representative MAPA pesticide-use statistics—derived from harmonized farmer-reported consumption surveys—with compound-specific characterization factors from USEtox™ v2.14 at midpoint and endpoint levels.

The selection of 2013 and 2019 was based on two criteria: (i) they correspond to the only vintages for which MAPA provides vineyard-specific pesticide-use datasets compiled using comparable methodology, coverage and reporting structure, enabling a consistent national-scale assessment; and (ii) they exhibit relevant agro-climatic contrasts known to modulate fungal disease pressure and pesticide demand. However, these differences are not necessarily reflected in total fungicide mass at national scale, but rather in changes in treatment strategies, application frequency, and the selection of active substances.

According to Spanish State Meteorological Agency (AEMET), 2019 was significantly warmer than the long-term average and characterized by spatially heterogeneous rainfall and episodic high-humidity events, whereas 2013 presented more regionally variable conditions (Spanish State Meteorological Agency (AEMET), 2020; Cortiñas Rodríguez et al. 2020). Because temperature, rainfall distribution and humidity strongly influence the onset and severity of downy and powdery mildew, these differences provide essential context for interpreting variations in pesticide use and associated toxicity footprints between both study years.

USEtox™ structures toxicity characterization factors as the product of fate, exposure, and effect terms, establishing a transparent “source-to-effect” linkage that is particularly relevant when multiple active substances are applied episodically in agricultural systems (Peña et al. 2019). The chemical footprint concept further links these toxicity-based metrics to broader sustainability and policy frameworks, including planetary boundaries for chemical pollution (Sala and Goralczyk 2013; Zijp et al. 2014), offering a coherent basis to interpret pesticide-related pressures in viticulture within wider environmental objectives (Nordborg et al. 2014).

In this study, midpoint indicators included freshwater ecotoxicity PAF (potentially affected fraction of species)·m³·day·kg⁻¹ emitted and human toxicity (cases·kg⁻¹ emitted), while endpoint indicators comprised human health damage DALY (Disability-Adjusted Life Years)·kg⁻¹ emitted and freshwater ecosystem damage PDF (Potentially Disappeared Fraction of species)·m²·yr·kg⁻¹ emitted, following Fantke et al. (2018).

2.2 Data on pesticide use in Spanish vineyards

Annual vineyard-specific pesticide-use data were compiled from the MAPA for vintages 2013 and 2019. For each active ingredient (AI), we extracted: use mass (kg), product type (fungicide), and crop (grape/vineyard). Data processing steps were:

1. **Crop filter.** Records were filtered to vineyard uses only (Crop code: Vineyard (C2410)). Data on pesticide use in vineyards were obtained from official surveys conducted by the Spanish Ministry of Agriculture, Fisheries and Food (MAPA): *Tables on Pesticide Use 2013 (EUPF13)*. Ministry of Agriculture, Food and Environment. Available at: https://www.mapa.gob.es/dam/mapa/contenido/estadisticas/temas/estadisticas-agrarias/2.agricultura/7.-medios-de-produccion/fitosanitarios/tablas_datos_utilizacioneupf13.xlsx. *Tables on pesticide use 2019 (EUPF19)*. Ministry of Agriculture, Fisheries and Food. Available at: <https://www.mapa.gob.es/dam/mapa/contenido/estadisticas/temas/estadisticas-agrarias/2.agricultura/7.-medios-de-produccion/fitosanitarios/utilizacion-de-productos-fitosanitarios/tabladatosdeutilizacion2019eupf19.xlsx>.
2. **Active-ingredient harmonization.** AIs were mapped to CAS numbers and canonical names (USEtox_substance_data_organics.xlsx). Since MAPA datasets report pesticide use as mass of active substances (kg of active ingredient), all compounds were used directly as provided, without chemical normalization, conversion

between salt forms, or transformation to a common active moiety.

3. **Screening & inclusion.** We retained AIs with (i) non-zero vineyard use and (ii) available USEtox™ v2.14 characterization factors for at least one relevant emission compartment. Substances without CFs were excluded from the analytical dataset. This resulted in a working dataset composed exclusively of organic fungicides with robust USEtox™ CF coverage, enabling a consistent and methodologically reliable toxicity-based assessment across the two benchmark years. The representativeness of the selected substances in terms of national use mass is quantified based on national pesticide-use data, as described below, and further discussed in the Results section in relation to impact score interpretation.

At national scale, total fungicide and bactericide use reported by MAPA amounted to 2.35×10^7 kg in 2013 and 2.29×10^7 kg in 2019. These totals include sulfur- and copper-based compounds as well as other inorganic substances, which were excluded from the present assessment. After applying these exclusions, the remaining mass amounted to 6.99×10^5 kg in 2013 and 1.38×10^6 kg in 2019. The substances effectively assessed in this study represented 5.52×10^5 kg in 2013 and 8.75×10^5 kg in 2019, corresponding to approximately 79% and 63% of the non-inorganic pesticide mass, respectively. As both the composition and coverage of the assessed substances differ between years, comparisons between 2013 and 2019 reflect not only changes in application patterns but also differences in dataset coverage.

1. The calculation of compartment-specific emission fractions for each active substance was performed following the guidelines of Nemecek et al. (2022), applying the parameterisation proposed for grapes and assuming no buffer zone as defined in the PestLCI Consensus model. The considered emission scenarios included releases to air, agricultural soil, natural soil, surface water, and crop, as detailed in Supplementary Material ESM2.xlsx available at: https://static-content.springer.com/esm/art%3A10.1007%2Fs11367-022-02048-7/MediaObjects/11367_2022_2048_MOESM2_ESM.xlsx. Following Nemecek et al. (2022), the default emission scenario for grape production was applied, corresponding to the use of an air blast sprayer (SM1).
2. **Quality control.** Duplicates, unit mismatches and outliers were flagged (IQR-based rules) and resolved by cross-checking MAPA totals against crop-level subtotals.

Following the approach of Leclerc et al. (2023) and Peña et al. (2019), impact scores (IS) were calculated for each active substance (i) and emission compartment (x) by

multiplying the annual emitted or applied mass ($m_{i,x}$) by the $CF_{i,x}$ obtained from USEtox™ v2.14:

$$IS_{i,x} = m_{i,x} \times f_{i,x} \times CF_{i,x}$$

where $f_{i,x}$ represents the emission fraction to each compartment (air, soil, or water) as estimated by PestLCI Consensus.

The resulting compound level impact scores were expressed as comparative toxic units for freshwater ecotoxicity ($CTU_e \cdot \text{year}^{-1}$) and human toxicity ($CTU_h \cdot \text{year}^{-1}$). CTU_e represents the potentially affected fraction of freshwater species integrated over volume and time per unit emission, whereas CTU_h represents the estimated increase in human disease cases per unit emission, consistent with USEtox™ definitions. To obtain the total toxicity footprint for Spanish viticulture in each reference year (2013 and 2019), all compound-specific scores were summed across compartments and substances:

$$IS_Y^{total} = \sum_i \sum_x IS_{i,x,Y}$$

where Y denotes the reference year (2013 or 2019).

This aggregation approach—analogue to the calculation of national toxicity footprints in Leclerc et al. (2023)—provides a measure of the annual chemical burden associated with vineyard pesticide use, without normalization by surface area or production. The comparison of IS^{total} values between 2013 and 2019 allowed quantifying relative changes in the overall toxicity footprint ($\% \Delta$), while compound-level differences ($\Delta IS_i = IS_{i,2019} - IS_{i,2013}$) were used to identify the substances contributing most to the variation in total impacts.

For each impact category (CTU_e and CTU_h), the relative contribution of each active ingredient to the national increase in toxicity impacts was calculated as:

$$Share_i = \frac{\Delta IS_i}{\sum_{\Delta IS > 0} \Delta IS_i}$$

The denominator includes only positive values, meaning that $Share_i$ expresses the fraction of the total increase attributable to each substance, while substances whose impacts decreased are not allocated a share of the increase. This metric enables distinguishing whether trends are driven by a few dominant compounds or by more distributed changes across the pesticide portfolio.

Note on regionalization. USEtox™ fate factors (FF) are climate- and compartment-dependent; temperature, humidity and precipitation patterns can affect persistence and FFs in soils and air. We therefore used the continental-scale CF set for consistency with national inventories, noting that

spatiotemporal variation can influence FFs and associated IS.

2.3 Characterization with USEtox™ v2.14

USEtox™ v2.14 characterization factors for human toxicity and freshwater ecotoxicity were retrieved from the official USEtox™ database and applied without modification, ensuring consistency with harmonized fate–exposure–effect modelling. For human toxicity, both midpoint and endpoint CFs were used. Midpoint CFs were applied as the primary basis for ranking substances and comparing years, while endpoint CFs, expressed in DALY, were used for damage-oriented interpretation when required. For freshwater ecotoxicity, the recommended midpoint CFs were applied.

2.4 Selection of priority substances

To ensure methodological robustness, this study focused on organic fungicides for which USEtox™ provides consistent and well-established characterization factors. Inorganic compounds—particularly copper- and sulfur-based products—were excluded because their toxicity characterization in USEtox™ is associated with substantially higher uncertainty. For metal-based compounds, this is largely due to the strong dependence of metal toxicity on environmental speciation, pH, redox conditions, and bioavailability assumptions (Fantke et al. 2018; Rosenbaum et al. 2008, 2011), while for other inorganic substances, including sulfur-based products, limitations arise from the lack of consistently available and fully harmonized characterization factors and their limited comparability within the USEtox™ framework.

At the same time, these substances account for a large share of the total pesticide mass applied in Spanish viticulture as quantified in Methods. In particular, sulfur-based products dominate the mass balance, representing more than 90% of the total applied mass, while copper-based compounds account for approximately 1–2%. However, despite their high contribution in terms of mass, these inorganic substances are generally associated with lower toxicity characterization factors within USEtox™, whereas organic active substances tend to drive toxicity-related impacts despite their lower contribution in terms of mass.

Restricting the assessment to organic active substances enables a more reliable and internally consistent comparison of toxicity-based impact scores. Nonetheless, copper-based products remain environmentally relevant in Spanish viticulture, and their inclusion would warrant a dedicated assessment framework capable of explicitly addressing metal speciation and bioavailability.

2.5 Uncertainty considerations and data limitations

Uncertainty in this study arises from several sources, including potential under- or over-reporting and aggregation in national pesticide-use statistics. To address this, we quantified the percentage of national use mass and corresponding impact scores (IS) captured by substances with available characterization factors (CFs), following current practices in LCIA applications.

Additional uncertainty is associated with incomplete data coverage and the use of estimated physicochemical and toxicological input parameters. EC₅₀ values and bioaccumulation factors (BAFs) were derived from QSAR models (e.g., EPI Suite™) and should be interpreted with caution due to the inherent uncertainty of such approaches, particularly for less-studied compounds (Boethling and Mackay 2000). For parameters including molecular weight (MW), octanol–water partition coefficient (K_{ow}), organic carbon partition coefficient (K_{oc}), Henry's law constant (K_H), vapor pressure (P_{vap}), solubility (Sol), and BAF, experimental data from Epi Suite™ were used when available; otherwise, estimated values provided by the software were applied. No formal sensitivity analysis was conducted; rather, the study focuses on quantifying dataset coverage and identifying key sources of uncertainty affecting the interpretation of the results.

3 Results and discussion

3.1 Discussion of input data

Fungicides represented the dominant share of the total pesticide mass applied in Spanish vineyards in both study years, largely driven by the extensive use of sulfur- and copper-based products, and were therefore prioritised in the analysis. Within this group, 90 active substances were reported at national level, of which 36 were retained for detailed assessment based on their toxicological relevance and the availability of USEtox™ v2.14 characterisation factors. These selected substances account for a substantial share of the non-inorganic pesticide mass effectively characterised in this study and constitute the portion of the pesticide portfolio for which a robust toxicity-based characterisation is currently feasible. Comparable findings have been reported in vineyard systems from other European regions, where fungicides also dominate pesticide use patterns and a limited number of active substances accounts for most of the applied mass and potential impacts. For instance, regional vineyard assessments in France and Italy have highlighted similarly concentrated pesticide portfolios and substantial reliance on a few key fungicides, indicating that the Spanish profile is broadly consistent with patterns observed in other

European viticulture systems (Renaud-Gentié et al. 2015; Rugani et al. 2013).

Active substances lacking USEtox™ characterization factors were excluded from impact calculations; however, their application mass was retained to quantify the proportion of total national use actually covered by the assessment.

It should be noted that Eugenol, Geraniol and Thymol, although included in the MAPA administrative category “fungicides and bactericides”, are not conventional synthetic agrochemicals but plant-derived active substances commonly classified as botanical biocides. In this study, these substances were treated using exactly the same methodological framework as the other fungicides, applying identical emission modelling assumptions and USEtox™-based toxicity characterization. In the tables, they are identified with a specific symbol to denote their botanical origin.

This section provides a comprehensive description of the physicochemical and toxicological parameters of the fungicides included in the assessment. These parameters constitute the underlying input information used by the USEtox™ model to derive CFs for human toxicity and freshwater ecotoxicity. Table S1 summarizes the parameters compiled for the 36 prioritized fungicides, including molecular weight (MW), octanol–water partition coefficient (K_{ow}), partition coefficient between organic carbon and water (K_{oc}), Henry’s law constant at 25 °C (K_H), vapor pressure at 25 °C (P_{vap}), aqueous solubility at 25 °C (Sol), degradation rates in air (K_{degA}) and water (K_{degW}), bioaccumulation factor (BAF), freshwater ecotoxicity (expressed as HC50), and human toxicity effect factors ($ED50_{ing, Non-Cancer}$ and $ED50_{ing, Cancer}$).

In general, the fungicides under study present variable degrees of solubility, K_{oc} and K_{ow} . These parameters provide an estimate of the mobility of fungicides in water environments, soils, and sediments. Among the compounds assessed in this work, Metiram, Difenconazole, Penconazole, Tebuconazole, Prochloraz, Dinocap, Fludioxonil, Cyprodinil, and Kresoxim-Methyl show the highest values of K_{ow} and K_{oc} , and low solubility; therefore, these compounds will probably be located in soils or sediments, or bioaccumulated (Boethling and Mackay 2000; PPDB, 2024; Schwarzenbach et al. 2003).

Conversely, highly soluble compounds with low K_{oc} and K_{ow} values tend to remain in the aqueous phase, exhibiting higher mobility through aquatic ecosystems. For example, Propamocarb shows extremely high water solubility (900,000 mg·L⁻¹) and very low hydrophobicity (log $K_{ow} \approx 1.12$), while Metalaxyl and Metalaxyl-M display a comparable physicochemical pattern to Propamocarb, characterised by very high aqueous solubility (10³–10⁵ mg·L⁻¹ range), low hydrophobicity and low Henry’s constants, favouring retention in the aqueous phase and facilitating mobility within aquatic systems. These physicochemical

characteristics—well-documented in environmental fate literature (Boethling and Mackay 2000; PPDB, 2024) suggest a strong potential for transport within the water column, increasing the likelihood of exposure for aquatic organisms, even in the absence of significant bioaccumulation.

For most substances, degradation rates in water, soil and sediment remain within the same order of magnitude (10⁻⁷–10⁻⁶ s⁻¹ range). However, a few compounds, such as Cymoxanil, Captan and Folpet, exhibit clearly faster degradation in sediments compared with water and soil compartments. As expected, degradation in air is consistently higher than in any other compartment due to dominant oxidative and photochemical reactions (Huijbregts et al. 2005; Rosenbaum et al. 2008). Despite this, most of the compounds present low vapor pressure values ($P_{vap} < 1$ Pa) and low Henry’s law constants (K_H), which indicates that they are unlikely to be found in significant concentrations in the atmospheric compartment. However, a few compounds—such as Propamocarb, Eugenol, Geraniol and Propionic Acid, exhibit comparatively higher P_{vap} values ranging from (3 to 470 Pa), and K_H (1.5 × 10⁻⁴ to 1.16 Pa·m³·mol⁻¹), suggesting a partial volatilization potential and possible distribution into the air compartment (Rosenbaum et al. 2008; Schwarzenbach et al. 2003).

Among the compounds evaluated, Penconazole (3549 L·kg⁻¹) and Difenconazole (2027 L·kg⁻¹) exhibited the highest bioaccumulation factors (BAFs), with Penconazole clearly exceeding the European REACH threshold of 2000 L·kg⁻¹ used to identify substances as bioaccumulative (B), and Difenconazole lying very close to this regulatory criterion. Prochloraz (1949 L·kg⁻¹) also presented values approaching this threshold. According to the European Chemicals Agency (ECHA) PBT/vPvB guidance, substances with BCF/BAF values above 2000 L·kg⁻¹ are considered bioaccumulative in aquatic organisms. (European Chemicals Agency (ECHA), 2017) Although BAFs for Fludioxonil (888 L·kg⁻¹), Tebuconazole (439 L·kg⁻¹) and Iprodione (336 L·kg⁻¹) remain below this threshold, they still indicate moderate bioaccumulation potential. These results are consistent with current understanding of pesticide bioaccumulation behavior and align with internationally recognized assessment frameworks. These findings are consistent with the Arnot and Gobas (2006) model and the criteria used under international regulatory frameworks, such as those established by the ECHA, (2017).

Ecotoxicological hazard was quantified using the α parameter (-log HC₅₀), where higher α values indicate greater aquatic toxicity. The log HC₅₀ (α) values were calculated according to the USEtox™ methodology as the average of the log-transformed EC₅₀ values from at least three trophic levels, when available (Rosenbaum et al. 2008). Following the USEtox™ definitions and supported by Rosenbaum et

al. (2008), α values greater than 1.5 are classified as having very high ecotoxicity. Among the compounds evaluated in this study, Propionic acid ($\alpha \approx 1.90$, based on *Daphnia* $EC_{50} = 22.7$ mg/L) and Propamocarb ($\alpha \approx 1.76$) exhibit the highest ecotoxicity potential. This is further corroborated by empirical toxicity data from sources such as ECETOC TR 127 (2021) and the USGS Pesticide Toxicity Index (Munn et al. 2006), which support the low HC_{50} values for these substances. Metalaxyl also shows a relatively elevated value ($\alpha \approx 1.31$), suggesting moderate to high toxicity. These compounds thus significantly contribute to the aquatic effect factor (EFeco) in USEtox™. Overall, only a limited number of substances fall into the high ecotoxicity category, while the majority display α values below 1.0, indicating moderate to low aquatic toxicity.

Human toxicity characterization was based on ED_{50} values (kg/person), representing the daily lifetime dose required to cause a 50% probability of disease (either cancer or non-cancer) via ingestion. Among the 36 fungicides evaluated, Prochloraz exhibited the lowest ED_{50} values for both noncarcinogenic (5.12 kg/person) and carcinogenic (9.54 kg/person) effects, highlighting its significant potential for adverse health outcomes. Chlorothalonil and Captan also demonstrated comparatively low ED_{50} values—32.9 and 49.2 kg/person (non-cancer), and 990 and 517 kg/person (cancer), respectively. These results are consistent with published toxicological assessments and regulatory reviews provided by USEtox™ (Rosenbaum et al. 2008), U.S. Environmental Protection Agency (2023), EFSA Panel on Plant Protection Products and their Residues (PPR) (2012), and FAO/WHO Joint Meeting on Pesticide Residues (JMPR) (2004). Therefore, Prochloraz, along with Chlorothalonil and Captan, represents the most critical contributors to the human effect factor (EFhuman) in the USEtox™ model for this study.

Building upon this analysis of environmental fate, the next step in the assessment focuses on calculating ecotoxicological (EFeco) and human toxicity (EFhum) effect factors, which are essential components of the CFs in USEtox™. These indicators integrate fate, exposure, and effect data to quantify the potential impact of each substance on both ecosystems and human health. To provide a transparent basis for subsequent impact quantification, Table 1 reports the midpoint USEtox™ v2.14 characterization factors for human toxicity and freshwater ecotoxicity for the 36 prioritized fungicides, disaggregated by emission compartment. These CFs constitute the quantitative foundation for the impact scores (IS) calculated in the following sections.

3.2 Characterization factors for fungicides under study

Table 1 presents the compartment-specific USEtox™ v2.14 CF for human toxicity and freshwater ecotoxicity for all fungicides included in the study. These CFs, obtained directly from USEtox™, serve as the quantitative inputs for the impact scores calculated in the subsequent sections. For each substance, midpoint and endpoint CFs are provided for both ecotoxicity and human toxicity, considering emissions to continental rural air (ECRA), continental freshwater (ECFW), continental natural soil (ECNS), and continental agricultural soil (ECAS). These compartmentalized CFs enable more detailed comparisons of the relative environmental and health impacts of pesticide emissions, facilitating substance ranking and uncertainty assessment within the life cycle impact assessment framework. Midpoint and endpoint indicators follow standard USEtox™ definitions (Rosenbaum et al. 2008, 2011).

The CF variability identified in this study is consistent with patterns reported in other agricultural systems, including recent life cycle assessments in Thailand (Mankong et al. 2024) and multi-crop evaluations in 2025 (Paezi et al. 2025). Both studies reported substantial variability in toxicity-related results, with differences exceeding one order of magnitude across substances and emission compartments. While characterization factors themselves are independent of crop type and local practices, the resulting impacts vary significantly depending on these factors through their influence on emission patterns, environmental conditions, and exposure pathways. These converging findings reinforce the robustness of USEtox™-derived CFs while highlighting the critical role of context-specific parameterization.

3.2.1 Ecotoxicological CF

Ecotoxicological effects are a central component in the environmental assessment of fungicides, particularly within the USEtox™ model, which estimates freshwater ecotoxicity characterization factors for emissions across air, water, and soil compartments. Table 1 presents the compartment-specific characterization factor values for the fungicides applied in vineyards between 2013 and 2019, revealing considerable variability in their ecotoxicological impact.

Among the studied fungicides, Chlorothalonil and Folpet exhibit the highest compartment-specific ecotoxicity characterization factors, particularly for emissions to continental freshwater (ECFW), with midpoint CFs ($PAF \cdot m^3 \cdot day \cdot kg^{-1}$) of 3.44×10^6 and 1.72×10^6 , respectively. These values indicate an exceptional potential to affect aquatic species due to their high persistence and partitioning behavior. They are followed by Thiram, Prochloraz, Azoxystrobin, and Dinocap,

Table 1 USEtox™ Characterization Factors (CFs) by compartment for fungicides applied in vineyards in 2013 and 2019

Substance	Midpoint Ecotox. Charact. factor [PAF.m ³ .day/kg _{ginteed}]				Endpoint Ecotox. Charact. factor [PDF.m ³ .day/kg _{ginteed}]				Midpoint Human health characterization factor [cases.kg ⁻¹ .a]				Endpoint Human health characterization factor [DALY/kg _{ginteed} .a]			
	ECRA ^b		ECNS ^d		ECFW ^c		ECAS ^e		ECRA ^b		ECNS ^d		ECFW ^c		ECAS ^e	
	ECRA ^b	ECNS ^d	ECFW ^c	ECAS ^e	ECRA ^b	ECNS ^d	ECFW ^c	ECAS ^e	ECRA ^b	ECNS ^d	ECFW ^c	ECAS ^e	ECRA ^b	ECNS ^d	ECFW ^c	ECAS ^e
PROPAMOCARB	7.14E+00	1.72E-02	3.47E+02	1.73E-02	3.57E+00	1.74E+02	8.67E-03	8.67E-03	1.90E-08	1.35E-07	6.67E-12	1.53E-10	5.14E-08	3.64E-07	1.80E-11	4.13E-10
MANCOZEB	2.08E+03	7.03E+04	3.03E+03	3.15E+03	1.04E+03	3.52E+04	3.61E+02	1.57E+03	1.32E-07	3.64E-07	3.74E-09	3.90E-07	3.57E-07	9.84E-07	1.01E-08	1.05E-06
MANEB*	2.03E+03	9.21E+04	3.74E+03	1.72E+02	1.02E+03	4.60E+04	1.87E+02	8.62E+02	1.02E-07	4.50E-07	1.83E-09	2.00E-07	4.76E-07	2.10E-06	8.53E-09	9.33E-07
METIRAM	1.25E+02	8.55E+03	8.82E+02	8.82E-02	6.23E+01	4.27E+03	4.41E-02	4.41E-02	1.21E-06	9.59E-08	9.90E-13	1.62E-11	3.27E-06	2.59E-07	2.67E-12	4.38E-11
PROPINEB	1.73E+02	6.61E+03	4.25E+01	4.25E-01	8.66E+01	3.30E+03	2.12E+01	2.12E+01	5.38E-07	2.38E-06	1.53E-08	6.78E-07	1.45E-06	6.42E-06	4.13E-08	1.83E-06
THIRAM ^v	6.47E+02	7.93E+05	2.50E+03	2.50E+03	3.23E+02	3.97E+05	1.25E+03	1.25E+03	6.03E-08	7.46E-07	2.58E-09	7.34E-08	1.63E-07	2.02E-06	6.97E-09	1.98E-07
METHYL THIOPHANATE	2.34E+02	1.14E+04	4.75E+00	9.98E+00	1.17E+02	5.72E+03	2.38E+00	4.99E+00	7.77E-08	3.41E-07	1.42E-10	7.77E-09	2.10E-07	9.21E-07	3.83E-10	2.10E-08
CYPROCON- AZOLE ^v	3.29E+02	7.09E+03	2.05E+02	2.05E+02	1.65E+02	3.55E+03	1.03E+02	1.03E+02	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
DIFENOCON- AZOLE	8.21E+03	3.18E+05	2.00E+03	2.00E+03	4.11E+03	1.59E+05	9.98E+02	9.98E+02	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
FENBUCON- AZOLE	3.80E+03	1.82E+05	2.00E+03	2.00E+03	1.90E+03	9.12E+04	9.98E+02	9.98E+02	2.32E-06	1.25E-06	2.74E-08	1.16E-06	6.25E-06	3.38E-06	7.40E-08	3.13E-06
MYCLOBUTANIL	1.28E+03	4.02E+04	3.92E+02	3.92E+02	6.39E+02	2.01E+04	1.96E+02	1.96E+02	1.82E-07	2.81E-07	2.79E-09	2.65E-07	4.92E-07	7.57E-07	7.52E-09	7.15E-07
PENCONAZOLE	6.94E+02	2.66E+04	1.30E+02	1.30E+02	3.47E+02	1.33E+04	6.52E+01	6.52E+01	9.89E-07	2.97E-06	1.50E-08	2.08E-06	2.67E-06	8.02E-06	4.05E-08	5.61E-06
TEBUCON- AZOLE	3.12E+03	1.06E+05	6.44E+02	6.43E+02	1.56E+03	5.32E+04	3.22E+02	3.22E+02	2.46E-07	6.62E-07	4.01E-09	4.86E-07	6.63E-07	1.79E-06	1.08E-08	1.31E-06
TRIADIMENOL	3.12E+02	8.76E+03	1.55E+02	1.55E+02	1.56E+02	4.38E+03	7.75E+01	7.75E+01	8.05E-07	6.95E-07	1.23E-08	7.29E-07	2.17E-06	1.88E-06	3.32E-08	1.97E-06
DIMETHO- MORPH	1.63E+02	4.19E+03	1.27E+02	1.27E+02	8.15E+01	2.10E+03	6.34E+01	6.34E+01	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
EUGENOL* [®]	2.12E+00	8.71E+02	1.50E+01	1.51E+01	1.06E+00	4.35E+02	7.52E+00	7.52E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
GERANIOL* [®]	3.62E+00	5.22E+03	2.19E+01	2.19E+01	1.81E+00	2.61E+03	1.10E+01	1.10E+01	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
THYMOL* [®]	5.81E+00	3.15E+03	2.91E+00	2.91E+00	2.91E+00	1.57E+03	1.46E+00	1.46E+00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
CYMOXANIL	4.09E+02	1.46E+04	5.60E+01	5.60E+01	2.05E+02	7.29E+03	2.80E+01	2.98E+01	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
DODINE ^v	4.19E+02	2.08E+04	4.31E+00	4.31E+00	2.09E+02	1.04E+04	2.16E+00	2.16E+00	7.38E-09	2.49E-08	5.16E-12	3.20E-10	1.99E-08	6.72E-08	1.39E-11	8.64E-10
PROCHLORAZ ^v	1.15E+04	9.69E+05	1.34E+03	1.33E+03	5.74E+03	4.84E+05	6.71E+02	6.64E+02	2.40E-06	4.84E-05	6.73E-08	2.18E-06	1.39E-05	2.79E-04	3.89E-07	1.26E-05
METALAXYL-M	2.57E+02	2.88E+03	2.74E+02	2.74E+02	1.28E+02	1.44E+03	1.37E+02	1.37E+02	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
METALAXYL	1.25E+02	1.28E+03	1.37E+02	1.37E+02	6.24E+01	6.38E+02	6.86E+01	6.86E+01	1.61E-07	1.01E-07	1.12E-08	4.23E-07	4.36E-07	2.72E-07	3.02E-08	1.14E-06
CHLOROTHA- LONIL	8.96E+04	3.44E+06	1.44E+04	1.44E+04	4.48E+04	1.72E+06	7.19E+03	7.19E+03	1.32E-06	1.09E-06	4.33E-08	1.39E-07	3.93E-06	3.24E-06	1.29E-07	4.15E-07
IPRODIONE ^v	3.70E+03	9.58E+04	2.03E+03	2.03E+03	1.85E+03	4.79E+04	1.02E+03	1.02E+03	4.00E-07	8.16E-07	1.75E-08	8.11E-07	1.08E-06	2.20E-06	4.72E-08	2.19E-06
DINOCAP ^v	1.26E+04	6.07E+05	8.93E+00	8.93E+00	6.30E+03	3.03E+05	4.47E+00	4.47E+00	1.40E-06	7.20E-07	1.10E-11	2.63E-08	3.78E-06	1.94E-06	2.97E-11	7.11E-08
FLUDIOXONIL	3.53E+03	1.55E+05	2.15E+02	2.15E+02	1.76E+03	7.76E+04	1.08E+02	1.08E+02	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
CAPTAN	2.06E+03	1.30E+05	3.34E+02	3.34E+02	1.03E+03	6.49E+04	1.67E+02	1.67E+02	6.31E-08	2.94E-07	7.63E-10	3.86E-08	2.19E-07	1.02E-06	2.64E-09	1.34E-07
FOLPET	2.48E+04	1.72E+06	2.84E+03	2.84E+03	1.24E+04	8.61E+05	1.42E+03	1.42E+03	1.71E-07	1.48E-07	3.90E-10	1.40E-08	7.98E-07	6.91E-07	1.82E-09	6.55E-08
BUPIRIMATE	2.12E+02	2.27E+04	2.20E+02	2.15E+02	1.06E+02	1.13E+04	1.10E+02	1.08E+02	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Table 1 (continued)

Substance	Midpoint Ecotox. Charact. factor			Endpoint Ecotox. Charact. factor			Midpoint Human health characterization factor			Endpoint Human health characterization factor		
	[PAF·m ³ ·day/kg _{mineral}]	ECAS ^e	ECNS ^d	[PDF·m ³ ·day/kg _{mineral}]	ECRA ^b	ECFW ^c	ECNS ^d	ECAS ^e	ECRA ^b	ECFW ^c	ECNS ^d	ECAS ^e
CYPRODINIL	9,21E+01	1,65E+02	1,72E+02	4,61E+01	1,93E+04	8,59E+01	8,25E+01	n/a	n/a	n/a	n/a	n/a
PYRIMETH-ANIL ^v	2,13E+01	4,60E+03	3,49E+01	1,06E+01	2,30E+03	1,74E+01	1,69E+01	n/a	n/a	n/a	n/a	n/a
DITHIANON*	2,18E+03	5,69E+04	1,06E+03	1,09E+03	2,84E+04	5,30E+02	5,30E+02	6,44E-07	7,03E-07	1,31E-08	1,29E-06	3,48E-06
AZOXYSTROBIN ^{1,2}	1,18E+05	1,48E+04	1,48E+04	6,02E+03	5,88E+04	7,39E+03	7,39E+03	n/a	n/a	n/a	n/a	n/a
KRESOXIM-METHYL	5,10E+03	2,21E+05	7,06E+02	2,55E+03	1,10E+05	3,53E+02	3,53E+02	3,34E-08	5,67E-08	1,84E-10	3,65E-08	9,85E-08
PROPIONIC ACID ^v	4,77E+00	7,76E+01	4,31E+00	3,77E+00	3,88E+01	2,15E+00	1,88E+00	n/a	n/a	n/a	n/a	n/a

^v Application in crops only in 2013; * Application in crops only in 2019; ⓧ Botanical biocides
 Note: CFs marked as “n/a” indicate insufficient data availability to support USEtox™ calculation
^aTotal, for cancerous and non-cancerous effects, for those compounds that exhibit both effects
^bEmission into continental rural air
^cEmission into continental freshwater
^dEmission into continental natural soil
^eEmission into continental agricultural soil

all displaying midpoint CFs approaching 5.0×10^5 in at least one compartment, suggesting substantial ecotoxicological relevance. At the endpoint level (PDF·m³·day·kg⁻¹), the same compounds maintain the highest scores—exceeding 1.0×10^6 for Chlorothalonil and Folpet, and above 4.0×10^5 for Prochloraz and Thiram—indicating a strong contribution to potential biodiversity loss associated with pesticide emissions. In contrast, Propamocarb, Propionic acid, Thymol, Eugenol, and Geraniol show very low CFs across all compartments, with midpoint values below 1.0×10^3 and endpoint values below 5.0×10^2 , reflecting their limited persistence and lower ecotoxic potential. These findings highlight a marked variability in environmental toxicity among the evaluated compounds and emphasize the importance of considering compartmental emissions when interpreting the overall ecotoxicological burden of vineyard pesticide use.

This pattern of high CFs observed for Chlorothalonil, azoxystrobin, Mancozeb, and other fungicides aligns with previous studies. Notably, Nordborg et al. (2014) reported that Chlorothalonil alone contributed to 84% of the total CTU_e impacts in wheat production due to its marked toxicity to aquatic species. Moreover, Aggarwal (2024) offers updated ecotoxicological effect factors derived from a broader dataset and refined modelling assumptions, which substantiate and expand upon the elevated midpoint and endpoint CFs identified in this study.

These elevated CFs correlate strongly with the underlying physicochemical properties characterized in Sect. 3.1. Compounds such as Chlorothalonil, Azoxystrobin, Mancozeb, Prochloraz, Penconazole, Dithianon and Fenbuconazole all exhibit high log K_{ow} (ranging from ~3 to 5), low water solubility and substantial bioaccumulation factors (BAF > 1000 L·kg⁻¹), which predispose them to persist in sediments and biota, thereby increasing exposure and ecological hazard. Moreover, their low degradation rates in water and soil (K_{degW}, K_{degSl} < 10⁻⁷ s⁻¹) extend environmental residence times, thereby amplifying ecotoxicological fate and effect factors. Together, these physicochemical drivers—high hydrophobicity, persistence and bioaccumulation—underpin the elevated CFs identified in this study (Fantke et al. 2020; Fantke and Jolliet 2016; Komárek et al. 2010; Rosenbaum et al. 2008).

These relationships are further illustrated by compound-specific toxicological profiles. Azoxystrobin and Chlorothalonil stand out due to their acute and chronic toxicity across multiple aquatic species, including *Daphnia*, fish, and algae, combined with a high leaching potential and persistence in sediment-rich matrices. In addition to its aquatic effects, Azoxystrobin has been shown to induce oxidative stress and neurotoxicity in non-target terrestrial organisms, such as the land snail *Theba pisana*, even at low environmental concentrations (Radwan et al. 2024). Dithiocarbamates such as

Mancozeb, Maneb, and Thiram share a common profile of strong enzymatic toxicity in fish and amphibians, coupled with moderate environmental mobility that enhances aquatic exposure. Triazole fungicides, such as Fenbuconazole and Difenconazole, display chronic toxicity to aquatic invertebrates and birds, often linked to reproductive disruption, and exhibit strong sorption to particles that favors runoff-driven dispersion. Similarly, Prochloraz and Iprodione affect both vertebrates and invertebrates through endocrine and developmental toxicity, and present medium-to-high potential for particle-bound transport. By contrast, compounds such as Folpet, despite their slightly greater mobility, retain high acute toxicity in fish and invertebrates, contributing significantly to the overall ecotoxic burden (PPDB, 2024). These profiles illustrate how ecotoxic potency and environmental fate jointly determine USEtox™-derived CF values, reinforcing their relevance for compound-specific toxicological impact assessment within vineyard LCA frameworks.

This broad CF distribution—spanning over three orders of magnitude—is consistent with recent findings in global CF variability (Owsianiak et al. 2023), which observed similar ranges for freshwater ecotoxicity. Moreover, spatial studies using tools like WHAM 6.0 have reported CF variability across regions reaching up to 5–7 orders of magnitude (Viveros Santos et al. 2018).

3.2.2 Human health and toxicity CF

In the event of a focus on human health and toxicity, the sums of both carcinogenic and noncarcinogenic CFs have been added, under the assumption of equal weighting between carcinogenic and noncarcinogenic effects in those compounds where both effects were present. These aggregated results of the CFs were expressed as $\text{CTU}_h \cdot \text{kg}_{\text{emitted}}^{-1}$ (comparative toxic units) for the 36 fungicides investigated.

The use of the CF value as an index facilitates the prioritisation of substances under equivalent emission conditions. As shown in Table 1, the results indicate the relative importance of different fungicides, as well as their potential impact on human health. The CF values for toxicity and human health of the fungicides applied in vineyards between 2013 and 2019 range from 10^{-11} to 10^{-4} $\text{CTU}_h \cdot \text{kg}^{-1}$ revealing substantial variability among substances and emission compartments. In the context of human toxicity, several substances exhibit notably high characterization factors (CFs), expressed in disability-adjusted life years ($\text{DALY} \cdot \text{kg}^{-1}$), a metric that captures the potential chronic health burden associated with prolonged environmental exposure—particularly via inhalation and ingestion pathways (Huijbregts et al. 2005; Rosenbaum et al. 2011). Prochloraz shows the highest value ($2.1 \times 10^{-6} - 3 \times 10^{-4}$ $\text{DALY} \cdot \text{kg}^{-1}$), followed by Penconazole ($3 \times 10^{-6} - 6 \times 10^{-6}$),

Fenbuconazole ($3 \times 10^{-6} - 6 \times 10^{-6}$) Dithianon (3.48×10^{-6}), Triadimenol (1.97×10^{-6}), and Propineb (1.83×10^{-6}). Other relevant compounds include Tebuconazole (1.31×10^{-6}), Metalaxyl (1.14×10^{-6}), Mancozeb (1.05×10^{-6}), and Chlorothalonil (4.15×10^{-7}), all contributing substantially to the potential chronic health burden associated with pesticide emissions in vineyard systems. These values are consistent with the CF ranges previously reported in the literature using the USEtox™ model, such as those by Rosenbaum et al. (2011) and Huijbregts et al. (2005). In contrast, the majority of evaluated compounds have lower CFs (below 1×10^{-7} $\text{DALY} \cdot \text{kg}^{-1}$), indicating a comparatively reduced human toxicological potential.

Conversely, several of the substances with the lowest human-health endpoint CFs (e.g., Propamocarb, Thymol, Eugenol, Geraniol and Propionic acid) are compounds largely associated with low-toxicity profiles or with “natural/biopesticide-type” uses in viticulture rather than conventional synthetic fungicides. All of them exhibit USEtox™ human-health endpoint CFs below 1×10^{-7} $\text{DALY} \cdot \text{kg}^{-1}$. Their comparatively low values reflect, in most cases, lower intrinsic human-toxicity potential together with physicochemical and fate characteristics that limit persistence, exposure and bioaccumulation in USEtox™ modelling, rather than simply an absence of risk. These results highlight the different toxicological nature of pesticide groups used in Spanish vineyards and stress the relevance of distinguishing between conventional chemical fungicides and substances of biological or natural origin when interpreting toxicity footprints.

The elevated CFs observed for Prochloraz, Fenbuconazole, Penconazole, and Triadimenol correlate strongly with their physicochemical properties. These substances combine moderate-to-high hydrophobicity ($\log K_{ow} \approx 2-5$), low water solubility, and slow degradation rates ($K_{deg} < 10^{-7} \text{ s}^{-1}$), which favor persistence and bioaccumulation in environmental media and biota. In addition, their low ED₅₀ values for mammalian toxicity and endocrine-disrupting potential increase the likelihood of chronic exposure through inhalation and ingestion, leading to the higher DALY-based CFs.

For instance, Prochloraz stands out due to its dual endocrine-disrupting and reproductive toxicity, combined with a high potential for particle-bound transport. Fenbuconazole and Penconazole also exhibit endocrine-disrupting potential and, in the case of Fenbuconazole, notable chronic mammalian toxicity and strong environmental retention. Tebuconazole and Triadimenol share moderate persistence and developmental toxicity, aligning with their mid-to-high CFs (PPDB, 2024). By contrast, compounds like Mancozeb and Iprodione, though toxicologically relevant, display reduced environmental mobility, which may attenuate exposure and contribute to slightly lower CFs within the high range

(PPDB, 2024). Similar associations between physicochemical persistence, bioavailability, and chronic toxicity potential have been observed in prior toxicological modelling studies (Fantke et al. 2020; Fantke and Jolliet 2016).

Similar behaviour of triazoles and other systemic fungicides has also been observed in viticulture-focused toxicological and environmental fate studies, where persistence, hydrophobicity and chronic toxicity potential have been identified as key determinants of human and ecotoxicological concern. These findings are coherent with our CF-based ranking and further support the mechanistic plausibility of the substances identified here as major contributors to vineyard-related toxicity burdens (Marinho et al. 2020; Martín-García et al. 2024).

These data underscore the critical need for compound-specific evaluation in LCIA frameworks. Overall, the variability in CFs across substances highlights the importance of jointly assessing ecotoxicological and human health impacts to identify priority compounds for mitigation within vineyard pesticide management strategies.

3.3 Spanish impact score of fungicides applied on vineyard (2013–2019)

The increasing public awareness of the need to safeguard ecosystems and human health from pesticide-related risks has led to the implementation of a growing body of regulations in recent years, particularly in developed countries. However, national-scale evaluations of pesticide-related impacts can also benefit from complementary approaches based on Life Cycle Impact Assessment, which quantify potential human and ecotoxicological burdens beyond site-specific regulatory risk. Such approaches enable portfolio-level assessment of pesticide-related pressures across cropping systems and time. Accordingly, the present study quantifies the potential toxicity impacts of fungicides commonly used in Spanish vineyards using CFs provided by USEtox™.

3.3.1 Ecotoxicity impact score

The results of the impact score analysis for freshwater ecotoxicity for the years 2013 and 2019 are presented in Supplementary Table S2 and illustrated in Figs. 1 (2013), 2 (2019), and 3 (comparison of 2013–2019). These IS values were calculated by combining the emission mass of each compound ($\text{kg}\cdot\text{year}^{-1}$) with their respective midpoint ($\text{CTU}_e\cdot\text{kg}^{-1}$) and endpoint CF ($\text{CDU}_e\cdot\text{kg}^{-1}$), following the USEtox™ methodology.

In both years, Folpet and Mancozeb exhibit the highest ecotoxicity IS values, with IS₂₀₁₃ values of 1.00×10^9 and $4.08 \times 10^8 \text{CTU}_e\cdot\text{year}^{-1}$, respectively (Fig. 1), and increased

values of 1.67×10^9 and $5.88 \times 10^8 \text{CTU}_e\cdot\text{year}^{-1}$ in 2019 (Fig. 2). This increase is mainly attributed to a greater application mass of the assessed active substances in 2019. These substances are consistently the most impactful in terms of freshwater ecotoxicity, dominating the rankings in both years by at least one order of magnitude above the rest of the compounds. These ecotoxicological patterns are consistent with broader evidence from viticulture systems, where fungicides typically account for a large share of pesticide inputs and have been identified as major contributors to aquatic ecotoxicity risks due to their frequent application and transport to surface waters (Marinho et al. 2020; Zubrod et al. 2019).

Comparable dominance of fungicides in freshwater ecotoxicity has been reported in vineyard systems from France, Germany and Italy, where repeated seasonal applications and surface-water connectivity were found to strongly influence ecotoxicity outcomes (Foerster et al. 2024; Renaud-Gentié et al. 2015). These consistencies suggest that the Spanish toxicity footprint aligns with broader European viticulture dynamics rather than representing an isolated national case.

This alignment is further supported by recent comprehensive reviews on pesticides and winemaking, which underline the high reliance of grape and wine production on fungicides and the associated concerns regarding environmental dispersion and residue transfer along the production chain (Martín-García et al. 2024).

Interestingly, substances with the highest CFs do not always correspond to the highest IS values. For example, Azoxystrobin and Chlorothalonil exhibit extremely high CFs ($\sim 1.18 \times 10^5$ – $3.44 \times 10^6 \text{CTU}_e\cdot\text{kg}^{-1}$) but are less impactful in IS due to lower usage volumes—especially in 2013. Conversely, fungicides such as Metalaxyl, which exhibit moderate freshwater ecotoxicity CFs according to USEtox™, display significant IS values due to their large-scale application. This is consistent with the notion that ecotoxicological pressure in viticulture arises not only from intrinsically hazardous substances but also from moderately toxic compounds applied at large scale (Zubrod et al. 2019). This highlights the need for risk prioritization to integrate both intrinsic toxicity and actual usage patterns.

Several substances were not consistently applied in both years, influencing their contribution to IS. Specifically, Iprodione, Thiram, Dodine, Prochloraz, Dinocap, Pirimethanil, Ciproconazole, and Propineb were used only in 2013, whereas Dithianon, Eugenol, Geraniol, Thymol, and Maneb were used only in 2019. The disappearance of certain high-impact compounds between 2013 and 2019, such as Iprodione (IS₂₀₁₃: $8.81 \times 10^6 \text{CTU}_e\cdot\text{year}^{-1}$) and Thiram ($1.00 \times 10^7 \text{CTU}_e\cdot\text{year}^{-1}$), is consistent with major regulatory developments in the EU during this period, including several non-renewal decisions under Regulation (EC) No

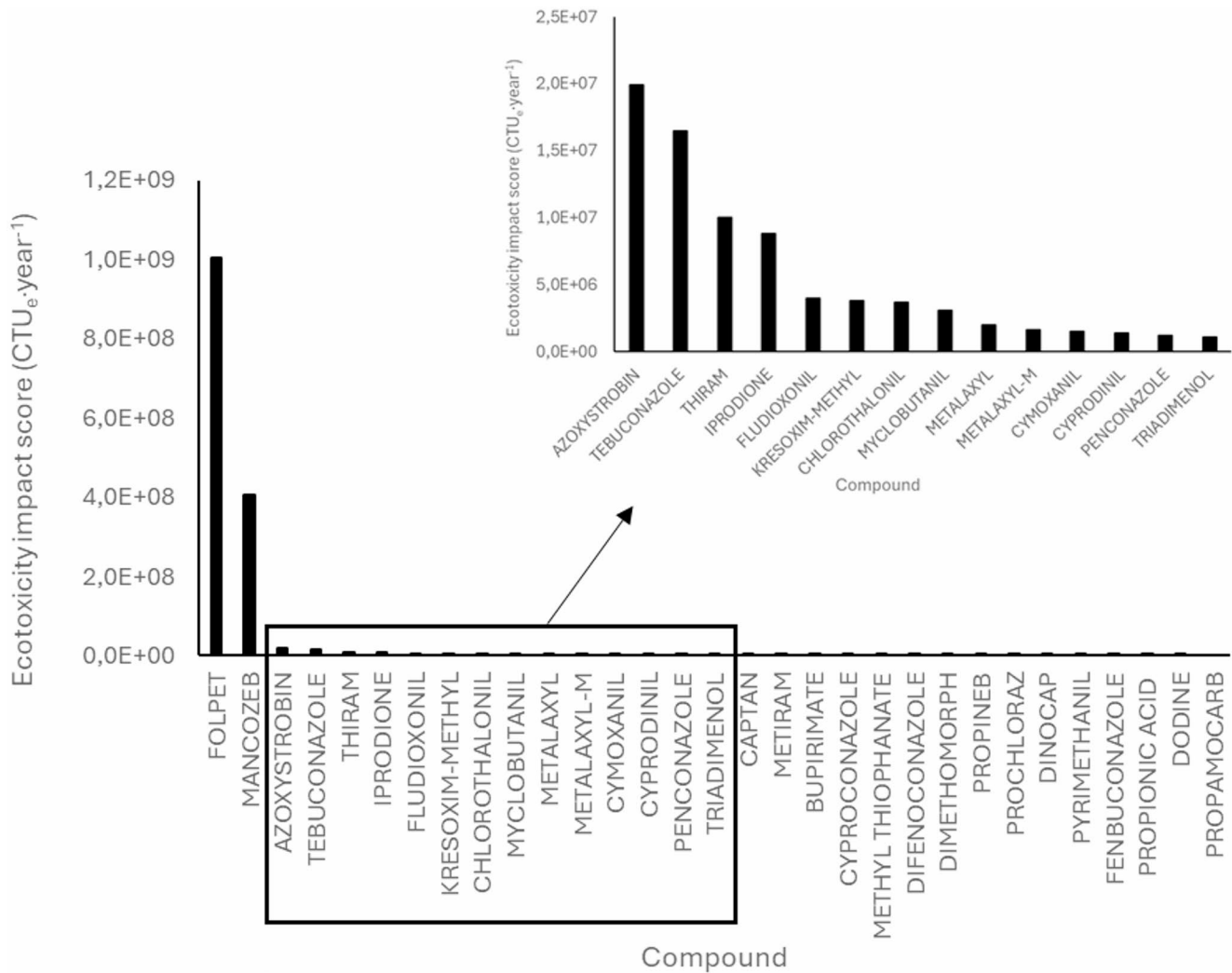


Fig. 1 Midpoint freshwater ecotoxicity impact score (CTU_e·year⁻¹) for vineyard-applied fungicides included in this study, Spain 2013

1107/2009 (e.g., non-renewal of Iprodione in 2017 and Thiram in 2018) (European Commission 2017, 2018), as well as broader tightening of approval conditions for certain fungicide classes. These regulatory restrictions, together with evolving vineyard pest-management strategies, likely contributed to their absence in 2019, which reduced their individual IS contributions. However, this reduction was partially compensated by the introduction of substances used only in 2019, particularly Dithianon (4.35×10^6 CTU_e·year⁻¹) and Maneb (2.52×10^5), among others.

Comparative evidence from vineyard ecosystems and regional monitoring studies reinforces the ecotoxicological risk profile derived from the Spanish vineyard data. The high ecotoxicity impact scores observed in this study for substances such as Folpet, Mancozeb, Azoxystrobin, Tebuconazole, and Metalaxyl are consistent with findings from both laboratory and field investigations. For example, the U.S. Environmental Protection Agency (EPA), (2005)

reports acute toxicity of Mancozeb to aquatic species, with LC₅₀ values as low as 460 ppb for fish and 580 ppb for *Daphnia magna*, underscoring its significant ecotoxicological potential even at environmentally relevant concentrations. Folpet has also demonstrated high toxicity to aquatic organisms. According to the U.S. Environmental Protection Agency (2012), Folpet exhibits acute toxicity with LC₅₀ values as low as approximately 15 µg/L for fish species such as *Oncorhynchus mykiss*, and EC₅₀ values near 20 µg/L for aquatic invertebrates like *Daphnia magna*. These data confirm the substantial ecotoxicological potential of Folpet, even at environmentally relevant concentrations, and underscore the need to consider its acute effects when assessing pesticide-related risks in freshwater ecosystems. Likewise, Tebuconazole and Metalaxyl have been frequently detected in vineyard runoff and surface waters, with concentrations exceeding the analytical limits of quantification (LOQ), indicating high persistence in soils and aquatic systems

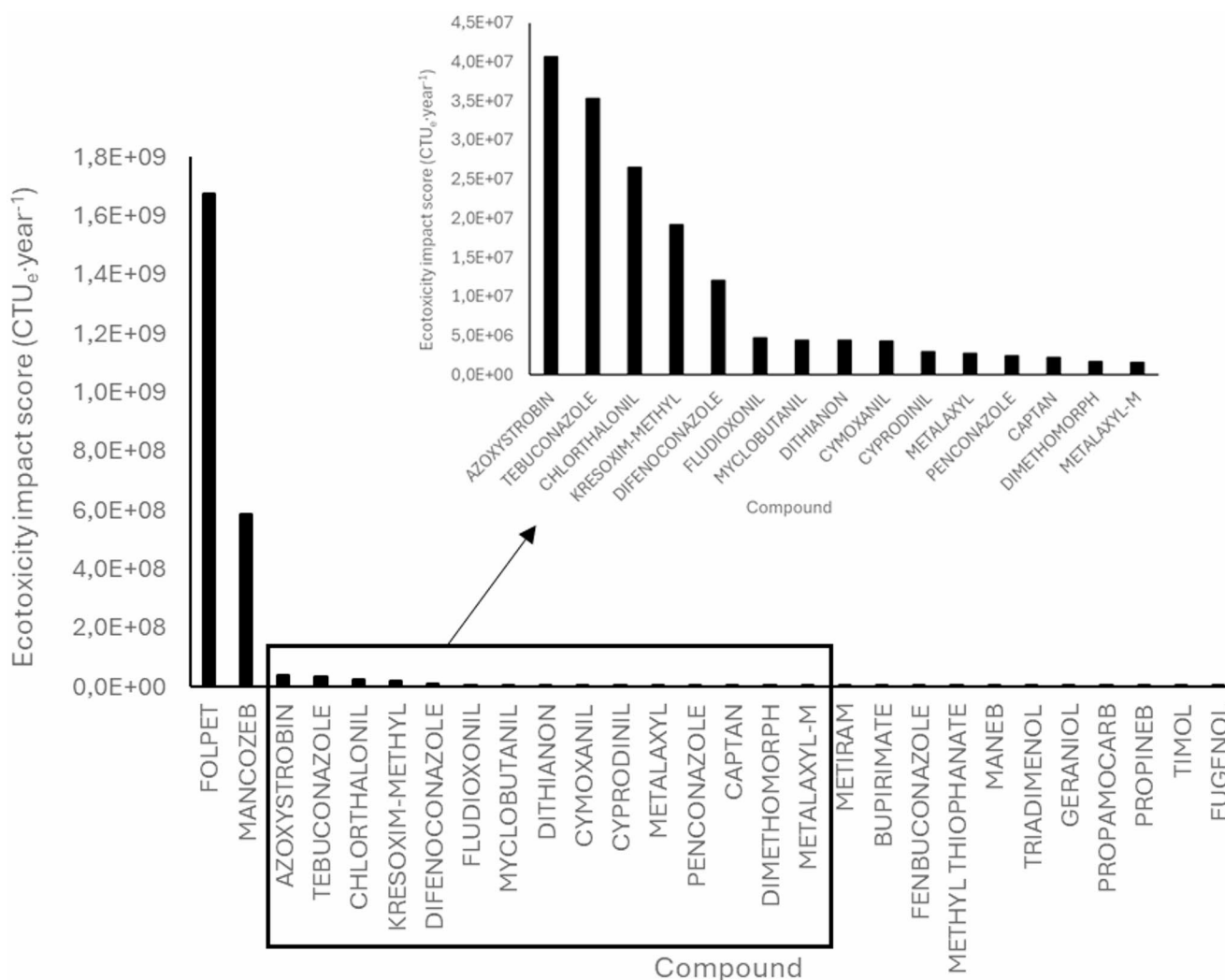


Fig. 2 Midpoint freshwater ecotoxicity impact score (CTU_e·year⁻¹) for vineyard-applied fungicides included in this study, Spain 2019

(Manjarres-López et al. 2021; Serpa et al. 2017). This pattern is also consistent with large-scale reviews reporting widespread environmental detection of triazoles, strobilurins and dithiocarbamates in vineyard regions and agricultural catchments worldwide (Zubrod et al. 2019).

Azoxystrobin, another key substance with elevated IS values, has been shown to induce physiological, biochemical, and histopathological effects in non-target terrestrial organisms such as land snails (*Theba pisana*), including oxidative stress, neurotoxicity, and growth inhibition, even at low environmental doses (Radwan et al. 2024). Furthermore, comprehensive reviews on vineyard soil contamination have highlighted the long-term accumulation, persistence, and ecological risk associated with fungicides in viticultural landscapes, emphasizing the importance of soil properties and climatic factors in modulating their fate and transport (Komárek et al. 2010; Peña et al. 2018).

In addition, the broad-scale review by Rondeau and Raine (2022) provides evidence of the widespread detection of fungicides such as Mancozeb, Azoxystrobin, and Tebuconazole in environmental matrices relevant to non-target organisms, reinforcing their toxicological significance across various cropping systems. This convergence of laboratory data, field evidence, and large-scale environmental reviews supports the prioritization of these active substances in pesticide life-cycle based toxicity impact modelling frameworks and calls for targeted mitigation strategies in viticulture.

When comparing the IS values for each of the studied substances between 2013 and 2019 (Fig. 3), it is evident that the total ecotoxicological impact was greater in 2019 than in 2013, as indicated by the cumulative IS values for most substances. This trend appears largely associated with an increase in the quantity of active substances applied, rather than with systematic shifts in their inherent toxicity profiles.

However, this interpretation should be viewed in the context of the aggregated nature of national pesticide-use statistics, where other factors such as climatic variability or changes in vineyard management strategies may also contribute to differences between years.

These findings underscore the importance of jointly considering emission magnitude and potential toxicity in impact-based evaluations, suggesting that limiting total application volumes—alongside the substitution of high-impact substances—may represent an effective strategy for reducing the toxic pressure of viticulture. Overall, the IS results reflect a dual dynamic: the ecotoxicological profile of each substance (as determined by CFs) and its actual agricultural use (application mass). The higher total IS in 2019 therefore reinforces the relevance of policies and practices aimed not only at promoting lower-toxicity substances but also at reducing total pesticide input where feasible. Beyond Spain, studies in France and Italy echo these trends. Previous LCA studies in viticulture have identified the vineyard stage as a major contributor to environmental impacts, with pesticide use playing a key role in several impact categories, particularly freshwater ecotoxicity, while other management practices may also contribute depending on the specific context (Baillet et al. 2025). Likewise, an Italian survey of vineyard inputs noted heavy reliance on fungicides and demonstrated that eliminating a highly toxic insecticide such as chlorpyrifos in an IPM scenario significantly reduced the human and ecotoxicity impacts (Russo et al. 2021). Our impact assessment aligns with these patterns, reinforcing the generalizability of our results. The magnitude of the impacts estimated in this study and the identity of pesticides as hotspot inputs are comparable to other Mediterranean viticulture LCA studies.

At the national scale, the total ecotoxicity impact score (CTU_e) for Spanish vineyards increased by 63% between 2013 and 2019, considering only the subset of active substances assessed in this study. This rise was mainly driven by a small number of fungicides, with Folpet contributing approximately 70% of the total increase and Mancozeb accounting for 19%. The remaining active substances each represented less than 2% of the total variation. These findings confirm that the observed rise in ecotoxicological impacts is strongly concentrated in a limited subset of compounds, rather than reflecting uniform changes across all applied substances.

3.3.2 Human toxicity impact score

To assess the potential human health burden associated with vineyard pesticide use, we present the Human Toxicity IS for 2013 and 2019, reported at both midpoint (disease incidence, CTU_h) and endpoint (disability-adjusted life years,

DALY) levels. These values are derived from the combination of the annual mass of active substances applied (M , $\text{kg} \cdot \text{year}^{-1}$) and their corresponding compartment-specific characterization factors (CFs) provided by USEtox™. The results are shown in Supplementary Table S3, which lists the IS values for all evaluated fungicides, and are further visualized in Figs. 4, 5 and 6. These figures highlight not only the most impactful substances but also those with lower scores, offering a comprehensive overview of year-to-year variations in human health impact contributions.

As presented in Table S3 and visualized in Figs. 4, 5 and 6, Mancozeb exhibited the highest IS in both years—rising from 4.35×10^{-2} to 6.29×10^{-2} CTU_h · year⁻¹—due to its extensive use and relatively low ED₅₀ values, underscoring its central role in the toxicity profile of vineyard treatments. Similarly, Penconazole, Tebuconazole, and Metalaxyl also maintained elevated IS values, reflecting their systemic activity and increasing application rates in 2019 (Figs. 4 and 5). These triazole and benzenoid fungicides are recognized for their systemic action and broad-spectrum efficacy, which likely contributes to their increasing use in vineyard management (Roman et al. 2021).

However, the relationship between CFs and resulting IS values is not always linear in practice, as actual agricultural use strongly conditions final contributions to human toxicity. For instance, Tebuconazole and Penconazole exhibit moderate CFs—between 1.00×10^{-9} – 1.00×10^{-6} CTU_h·kg⁻¹,—yet their IS values rose substantially in 2019 due to increased application masses: from 19,200 kg to 6200 kg in 2013 to 41,100 kg and 13,000 kg in 2019, respectively. In contrast, compounds such as Kresoxim-methyl and Chlorothalonil, with higher CFs (3.64×10^{-8} and 1.09×10^{-6} CTU_h·kg⁻¹), exhibited lower IS values because of limited usage—2,920 kg and 158 kg in 2013, and 14,800 kg and 1,140 kg in 2019, respectively. These findings illustrate that prioritisation cannot rely on intrinsic toxicity alone: real-world use intensity can shift impact dominance, elevating substances with moderate hazard but widespread application to leading contributors in national toxicity footprints.

Several substances were applied only in one of the two years—Iprodione, Thiram, Dodine, Prochloraz, Dinocap, Pyrimethanil, Cyproconazole, and Propionic acid in 2013; Dithianon, Eugenol, Geraniol, Thymol, Maneb, and Kresoxim-methyl in 2019—strongly influencing their IS contributions. The removal of Iprodione (2.28×10^{-3} CTU_h · year⁻¹) and Propineb (2.26×10^{-3} CTU_h · year⁻¹) likely reflects updated regulatory restrictions, while the introduction of Dithianon (3.25×10^{-3} CTU_h · year⁻¹) and Maneb (2.23×10^{-5} CTU_h · year⁻¹) contributed to the overall 2019 IS. These shifts in substance profiles between 2013 and 2019 suggest changes in pest management strategies, possibly driven by regulatory restrictions, the search for alternative

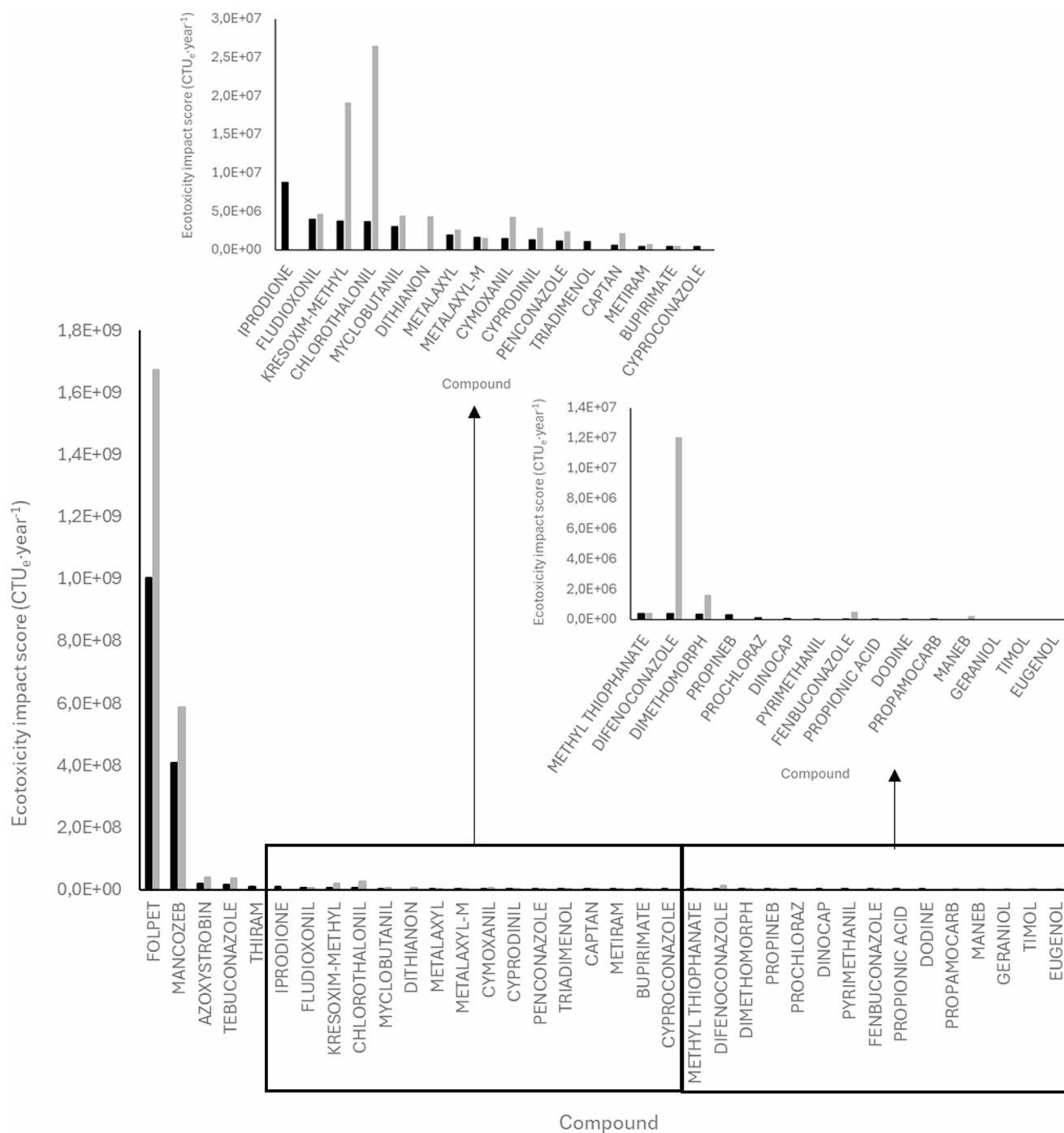


Fig. 3 Comparison of midpoint ecotoxicity impact scores (CTU_e·year⁻¹) associated with fungicide use in Spanish vineyards in 2013 (black bars) and 2019 (grey bars)

active ingredients, or adjustments to disease control programs in vineyards.

These observations align with the literature identifying Mancozeb as one of the most hazardous fungicides for human health—showing hepatotoxic, nephrotoxic, and genotoxic effects via its metabolite ETU (Corsini et al. 2005; Saber et al. 2019). Triazoles such as Tebuconazole

and Penconazole are linked to hepatic, neurological, immunological, and developmental toxicity (Marciano et al. 2024; EPA, 2015). Metalaxyl, though less potent individually, can disrupt steroidogenesis and act synergistically with Mancozeb and Tebuconazole (Atmaca et al. 2018). Collectively, these findings support the elevated IS values derived here and highlight the need to jointly consider intrinsic toxic

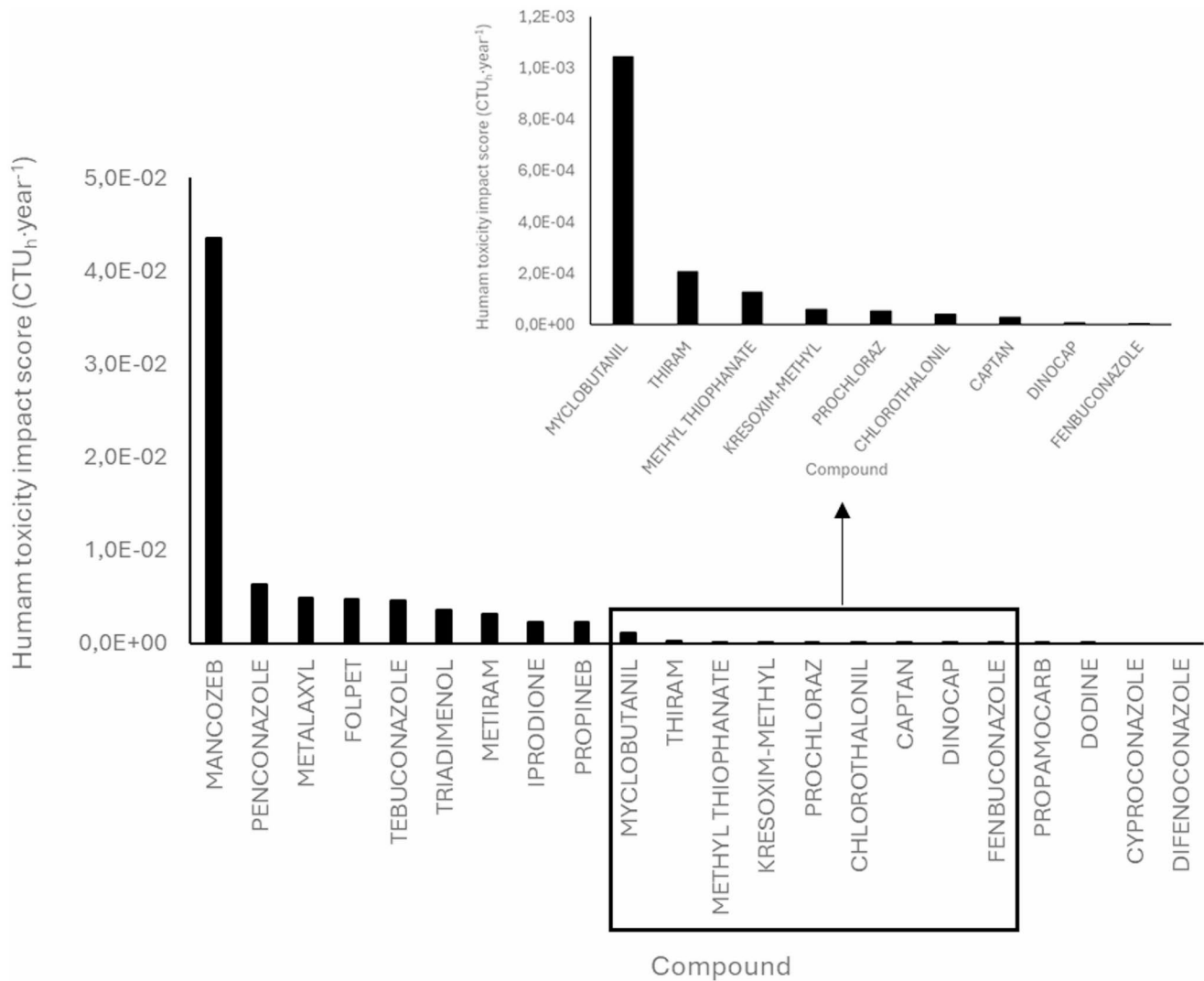


Fig. 4 Human toxicity impact scores (CTU_h·year⁻¹) for vineyard-applied fungicides included in this study, Spain 2013

potency and cumulative exposure when assessing pesticide-related health risks.

In the present study, botanical biocides showed marginal contributions to both freshwater ecotoxicity and human toxicity impact scores, reflecting their limited quantitative relevance within the assessed pesticide portfolio. However, this finding should be interpreted as a result of the specific substances and application patterns observed, rather than as an inherent advantage associated with their natural origin. Recent life cycle assessment evidence from viticulture systems indicates that substituting conventional agrochemicals with alternative or “natural” products does not necessarily lead to lower overall environmental impacts when assessed from a full life cycle perspective, due to potential trade-offs and burden shifting across impact categories (Tascione et al. 2024). Accordingly, botanical biocides were identified as a distinct subgroup for interpretative clarity, while being

evaluated using the same emission modelling and toxicity-based characterization framework as all other substances.

When comparing the human toxicity IS values for each of the evaluated substances between 2013 and 2019 (Fig. 6), it is evident that the cumulative impact was greater in 2019. This increase is mainly driven by the higher application masses recorded for key compounds, rather than by substantial changes in their inherent toxicity. For instance, Mancozeb, which already dominated the human toxicity profile in 2013, remained the most impactful substance in 2019, consolidating its central role in shaping the national human toxicity footprint. Likewise, Penconazole and Tebuconazole showed marked rises in IS, from 6.35×10^{-3} and 4.64×10^{-3} CTU_h·year⁻¹ in 2013 to 1.33×10^{-2} and 9.94×10^{-3} CTU_h·year⁻¹ in 2019, respectively, reflecting both their increasing usage and the persistence of their toxicological profiles.

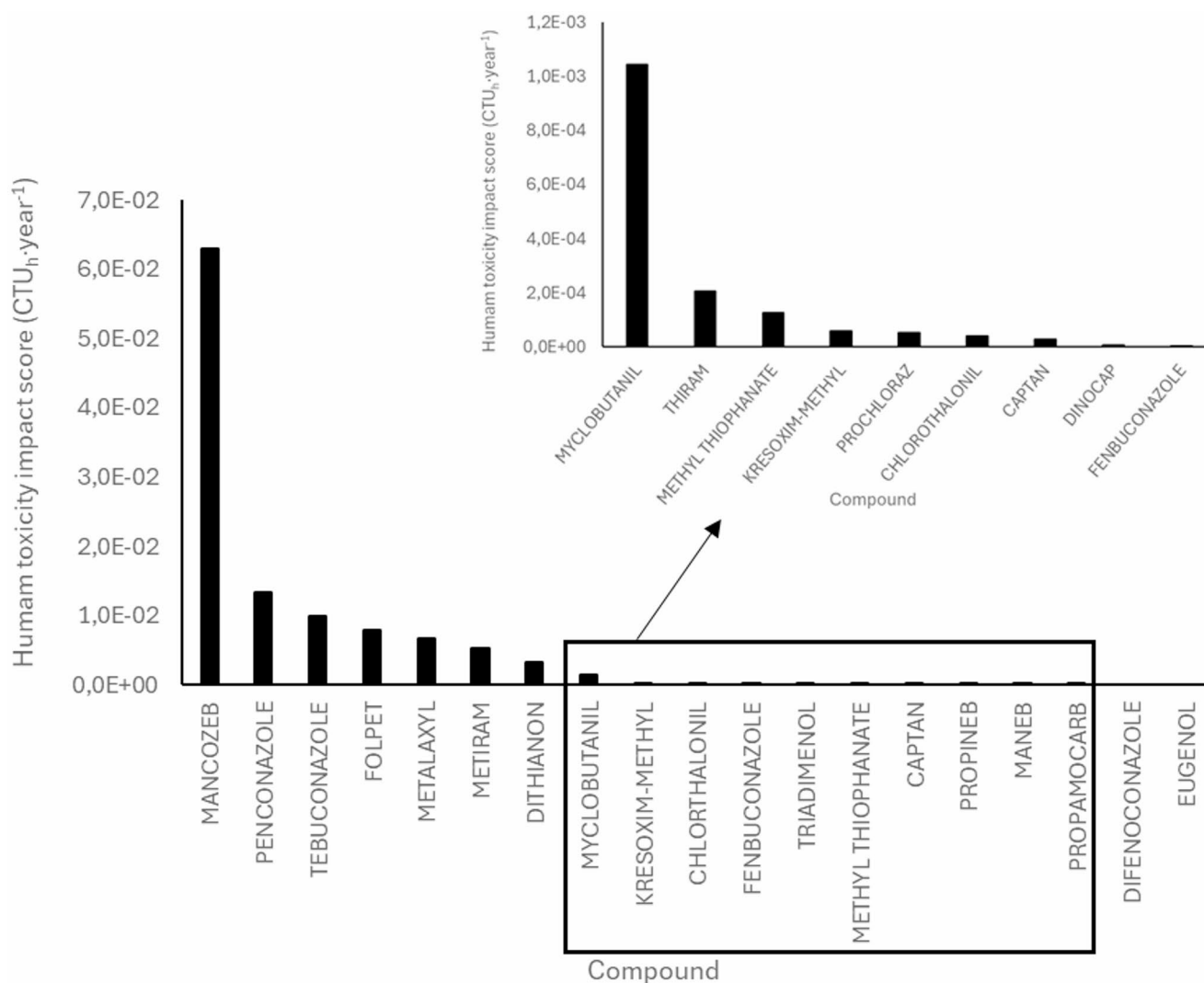


Fig. 5 Human toxicity impact scores (CTU_h·year⁻¹) for vineyard-applied fungicides included in this study, Spain 2019

In contrast, certain compounds, such as Iprodione (IS 2013: 2.28×10^{-3} CTU_h·year⁻¹) Dinocap (IS 2013: 7.08×10^{-6} CTU_h·year⁻¹), which were present only in 2013, were absent in 2019, thereby reducing their individual contributions to the total IS. However, this reduction was offset by the appearance in 2019 of substances like Dithianon (IS 2019: 3.25×10^{-3} CTU_h·year⁻¹) and Maneb (IS 2019: 2.23×10^{-5} CTU_h·year⁻¹), which added new sources of human health risk. Furthermore, Chlorothalonil, although applied in low quantities, maintained low IS values in both years.

Overall, the comparison reveals that the total human toxicity impact in 2019 was higher than in 2013, primarily due to increased application masses of the most widely used fungicides, including Mancozeb, Penconazole, and Tebuconazole. This outcome underscores the importance of considering both the magnitude of emissions and their toxic potency in risk-based assessments. Moreover, it suggests that reducing total pesticide inputs, alongside prioritizing

lower-toxicity substances, could be an effective strategy to mitigate the human health burden associated with pesticide use in vineyards.

In interpreting this increase, it is important to note that the higher national toxicity footprint observed in 2019 does not merely reflect changes in intrinsic toxicity but is plausibly linked to structural shifts in pesticide use patterns. MAPA vineyard-use statistics indicate a marked increase in the treated surface area between 2013 and 2019, together with a rise in treatment intensity, meaning that vineyards were sprayed more frequently in 2019 than in 2013 (MAPA, 2014; MAPA, 2021). These patterns are consistent with higher national application masses recorded for key fungicides such as Mancozeb, Penconazole, and Tebuconazole. In addition, meteorological conditions may have contributed to greater pesticide demand: although 2019 exhibited near-average precipitation at the national scale, it was significantly warmer than normal and characterized by spatially

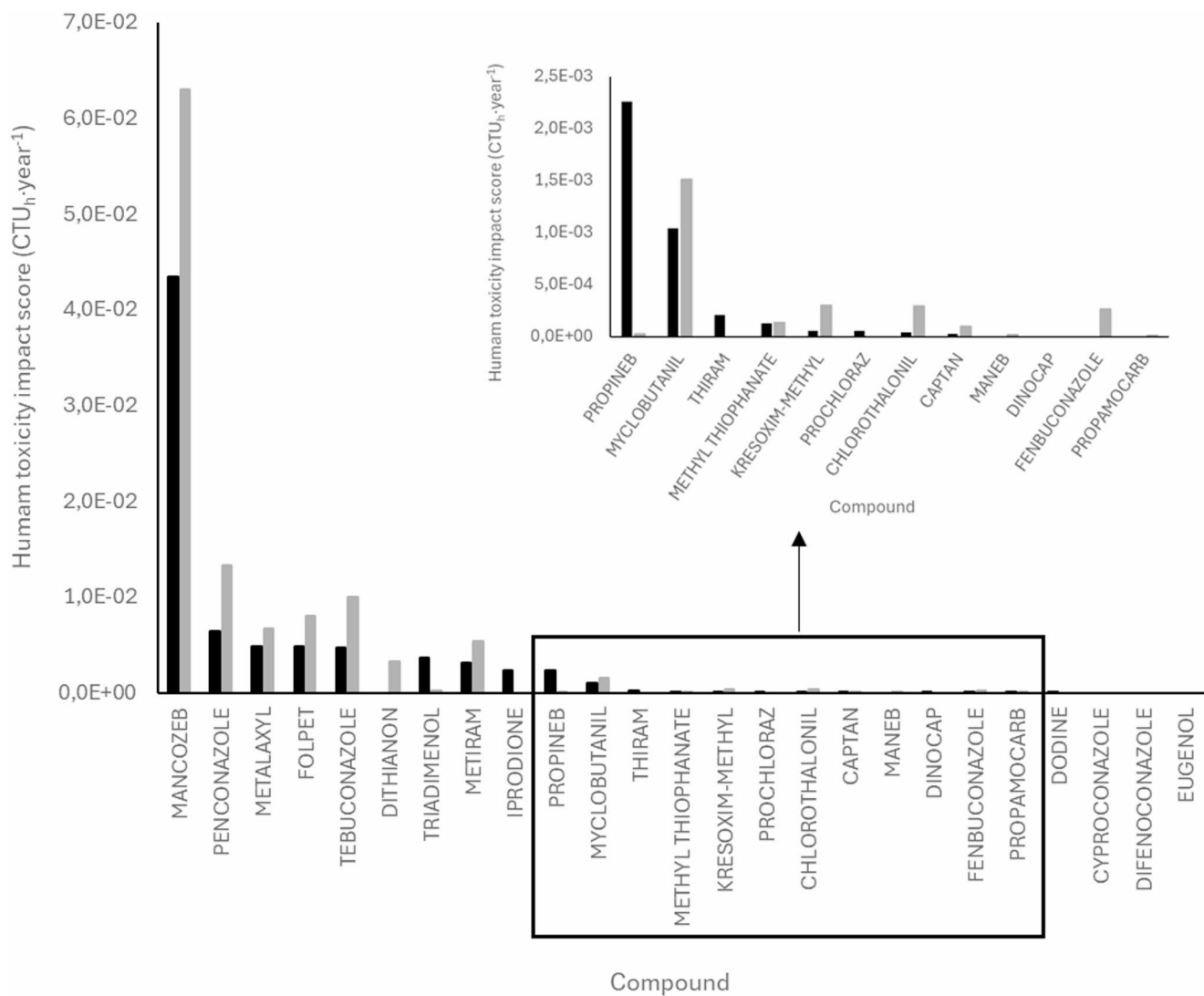


Fig. 6 Comparative human toxicity impact scores (CTU_h·year⁻¹) associated with fungicide use in Spanish vineyards in 2013 (black bars) and 2019 (grey bars)

heterogeneous rainfall and episodic high-humidity events, conditions known to influence fungal disease pressure in vineyards (AEMET, 2020; Cortiñas Rodríguez et al. 2020). Altogether, these factors provide a coherent explanation for the increased in the application mass of the assessed active substances in 2019—and consequently the higher aggregated human-toxicity impact scores— despite similar total pesticide use at national scale, reinforcing the interpretation that both usage volume and toxic potency jointly modulate national-scale health impact outcomes.

Regarding human toxicity (CTU_h), the total impact score increased by 46% over the same period. The variation was again dominated by a few key fungicides. Mancozeb accounted for 46% of the total increase, followed by Penconazole (16%), Tebuconazole (12%), Folpet (7%), and Dithianon (7%). These results indicate that human toxicity

impacts of Spanish vineyard fungal protection are largely driven by this subset of active substances, whose combined contribution explains the majority of the national footprint increase.

Beyond Spain, country-scale and regional LCIA studies in viticulture and other agricultural systems have also demonstrated that toxicity impacts tend to be driven by a restricted set of widely used active substances rather than evenly distributed across the pesticide portfolio. This has been shown for vineyard contexts as well as for other crops under intensive disease management regimes, reinforcing the policy relevance of targeting high-impact compounds first (Renaud-Gentié et al. 2015; Mankong et al. 2022).

Worthy to note, our results are consistent with vineyard LCA evidence indicating that plant protection treatments

dominate toxicity-related indicators in viticulture systems (Tascione et al. 2024).

Additionally, pesticide use intensity in vineyards is not only regulated by product availability and agronomic strategy; it is also conditioned by field microclimate, which influences disease development and therefore the quantity and frequency of plant-protection treatments (Tascione et al. 2024). In vineyard LCA case studies, on-site weather stations integrated with decision-support systems (DSS) are used to inform pest/disease management by monitoring wind, temperature, relative humidity, rainfall, soil moisture and leaf wetness—variables directly linked to disease pressure and spray decisions. Thus, because our inventory is based on national MAPA pesticide-use surveys, it does not provide farm-level meteorological conditions or disease incidence. Consequently, the differences observed between 2013 and 2019 should be interpreted as reflecting a combination of (i) regulatory and portfolio changes and (ii) unobserved inter-annual variability in field conditions that condition spray programs.

3.4 Discussion

3.4.1 Limitations and scope of the study

This study analyses fungicides and bactericides applied in Spanish vineyards in 2013 and 2019, which correspond to the most recent crop-specific national pesticide datasets currently available from MAPA, published on a five-year cycle. Within these inventories, 36 substances were selected because they jointly represent approximately 47–53% of the national fungicide mass applied and, critically, because robust midpoint and endpoint USEtox™ v2.14 characterization factors are available for them.

Nevertheless, several limitations should be acknowledged. First, a significant number of fungicides listed in MAPA statistics could not be included due to the absence of USEtox™ CFs, meaning that contributions from substances without CFs cannot be fully excluded. Second, insecticides and herbicides were not assessed, and copper-based fungicides—widely used in viticulture—were also excluded for methodological reasons, as USEtox™ provides CFs only for elemental copper and metal toxicity modelling still entails major uncertainties related to speciation, bioavailability and context-dependent toxicity processes. As a result, the ecotoxicity footprint reported here may be conservative. Third, the most recent dataset currently available corresponds to 2019, so substances subsequently withdrawn from the EU register still contribute to the footprint, while more recent shifts in pesticide portfolios cannot yet be reflected.

Additionally, USEtox™ indicators do not explicitly distinguish between cancer and non-cancer human toxicity

outcomes, which may mask differential health relevance among active substances. Moreover, emission fractions were estimated using the PestLCI consensus framework, which applies generalised assumptions that may not fully capture variability associated with specific spraying technologies, drift-control practices or local environmental conditions, as the default emission fractions proposed for grape production correspond to a single application technique (air blast sprayer, SM1) following Nemecek et al. (2022). While the PestLCI framework allows for a more refined selection of application techniques, this requires access to the full PestLCI platform, which is currently not available; therefore, the use of default emission fractions introduces additional uncertainty but also define clear opportunities for methodological refinement in future studies.

Rather than weaknesses, these aspects define a clear research agenda: progressively extending substance coverage as new CFs become available, integrating copper formulations through improved metal modelling, incorporating insecticides and herbicides, updating the analysis when the next MAPA dataset is released, and refining emission modelling with application- and site-specific information. Together, these developments will reduce uncertainty and further increase the policy relevance of toxicity-footprint assessments in viticulture.

It should be noted that the MAPA pesticide-use statistics used in this study are reported at national level and do not distinguish vineyard pesticide applications by farming system (e.g., conventional vs. organic). Therefore, differences between production systems could not be explicitly accounted for. In addition, potential inter-annual variability in climatic and agronomic conditions, which may influence pesticide demand (e.g., higher fungicide use in humid years), could not be formally assessed within the present dataset. Consequently, the comparison between 2013 and 2019 should be interpreted as a national-scale toxicity footprint contrast rather than a full causal attribution analysis of pesticide-use drivers.

In this context, while environmental risk assessment (ERA) remains the appropriate framework for regulatory authorisation and local risk evaluation, LCIA-based USEtox™ indicators provide valuable insight into the national-scale toxic pressure associated with pesticide use, complementing rather than replacing regulatory risk assessments (Gentil et al. 2020).

3.4.2 Regulatory status of assessed substances and policy relevance

The results of this study have direct implications for current regulatory frameworks governing pesticide use in the European Union. Under Regulation (EC) No. 1107/2009 (European Parliament and Council 2009), the approval and

renewal of active substances require a comprehensive risk assessment that considers their effects on human health and the environment. These regulatory risk assessments differ conceptually from the LCIA-based toxicity indicators applied in this study, which quantify potential impacts rather than site-specific risk. Recent EFSA guidance emphasizes the integration of context-specific exposure and effect data to refine these assessments, particularly for non-target species and vulnerable ecosystems (EFSA 2023; EFSA Panel on Plant Protection Products and their Residues (PPR Panel) 2012; Giacomelli et al. 2025; Peña et al. 2018; Rugani et al. 2013).

These findings also align with the EU's Farm to Fork Strategy, which aims to reduce the use and risk of chemical pesticides by 50% by 2030, prioritizing substances classified as "candidates for substitution" (European Commission 2024). Furthermore, the latest EFSA procedures emphasize the critical need for context-specific exposure assessments to enhance environmental risk evaluations, particularly for non-target organisms and vulnerable ecosystems (EFSA, 2025). The USEtoxTM-derived CFs and the vineyard-context IS generated in this study provide an additional layer of evidence to support prioritization processes during regulatory reviews (Foerster and Wagner 2025; Giacomelli et al. 2025).

Beyond regulatory decision-making, the results also have direct operational relevance for vineyard management systems. The identification of active substances with disproportionately high ecotoxicological and human toxicity profiles provides a scientific basis for selecting safer alternatives, optimizing pesticide application, and supporting the transition toward integrated pest management (IPM) practices. At farm and territorial scales, such impact-based indicators may complement existing risk-assessment tools by supporting portfolio-level prioritization rather than substance-by-substance regulation alone. Operational deployment of such metrics in digital decision-support systems would require periodic updating with the most recent pesticide-use datasets to reflect evolving product portfolios and application patterns. Nonetheless, the present work demonstrates the methodological feasibility and strategic value of this approach for guiding sustainability-oriented vineyard management.

The regulatory status of the active substances analysed is also highly relevant for interpreting these findings. Several active substances contributing substantially to ecotoxicity and human toxicity impacts have experienced differential regulatory outcomes in the EU over recent years. For example, mancozeb, a fungicide exerting major contributions in 2019, was not renewed under Regulation (EC) No 1107/2009 and its approval ceased on 4 January 2021, with Member States required to withdraw authorisations by mid-2021

(European Commission, 2025). Similarly, other dithiocarbamates such as thiram, maneb, propineb and zineb have been withdrawn or were never authorised, reflecting regulatory decisions prioritising human and environmental safety. Conversely, several key contributors in the 2019 toxicity footprint – including tebuconazole, metalaxyl / metalaxyl-M, kresoxim-methyl and dithianon – remain listed in the EU pesticides register, although subject to ongoing scrutiny and periodic renewal processes (European Commission, 2025).

This regulatory landscape illustrates how withdrawal decisions can effectively reduce contributions from particularly hazardous active ingredients, while underscoring the need for continuous reassessment of those substances that remain widely used and represent core contributors to national toxicity footprints. To further enhance policy relevance, future work could systematically integrate substance-specific authorisation statuses retrieved directly from the EU Pesticides Database (European Commission, 2025), thereby providing an up-to-date picture of which active ingredients remain permitted in viticulture and how this aligns with their toxicity profiles.

These regulatory patterns are strongly supported by evidence from the scientific literature. Our findings are consistent with previous viticulture LCA contributions reporting that fungicides dominate both ecotoxicity and human toxicity burdens in vineyard systems, largely due to their application frequency and total applied mass (Aoujil et al. 2024; Martín-García et al. 2024; Zubrod et al. 2019). Several studies have shown that a relatively small number of active substances accounts for the majority of toxicity impacts in grape production, reinforcing the need to prioritize substitution and reduction strategies for high-impact compounds (Aoujil et al. 2024; Foerster et al. 2024; Renaud-Gentié et al. 2015; Vázquez-Blanco et al. 2023).

In particular, Renaud-Gentié et al. (2015) demonstrated that viticulture-specific emission modelling frameworks (e.g., adapted PestLCI) identify patterns similar to those observed here, with frequently applied fungicides driving freshwater ecotoxicity. Likewise, multi-regional LCA assessments have highlighted that pesticide toxicity contributions can outweigh other environmental categories (Foerster et al. 2024) when vineyard management relies intensively on chemical disease control. Experimental evidence also shows that widely used vineyard fungicides can exert measurable toxic effects on non-target aquatic organisms at environmentally relevant concentrations, reinforcing the ecological relevance of the substances highlighted in this study (Marinho et al. 2020). More recent Spanish assessments also emphasize that pesticide decisions are a key determinant of vineyard sustainability performance (Vázquez-Blanco et al. 2023), which aligns with our national-scale toxicity footprint results for 2013 and 2019.

Altogether, these benchmarks support the robustness of our conclusions: toxicity outcomes in Spanish viticulture are primarily shaped by usage intensity and the toxicological profile of a subset of widely used fungicides. Therefore, mitigation should combine reduced total application volumes with the progressive replacement of substances with unfavourable impact profiles.

4 Conclusions

This study provides a national-scale, vineyard-specific chemical footprint assessment of fungicide use in Spanish viticulture by integrating official pesticide-use statistics with crop-level emission modelling (PestLCI Consensus) and compartment-specific toxicity characterization (USEtox™ v2.14). The proposed framework enables a consistent life cycle-based quantification of freshwater ecotoxicity and human toxicity pressures associated with real-world pesticide application patterns.

The analysis shows that toxicity footprints are structurally dominated by a limited subset of active substances and are shaped by the interaction between intrinsic toxic potency and application intensity rather than by hazard alone. This portfolio-level perspective demonstrates that use patterns transform chemical hazards into system-level impacts, providing a more realistic representation of national toxic pressure substance-based hazard classification approaches considered in isolation.

The temporal comparison between 2013 and 2019 further shows that regulatory substitution and portfolio restructuring modify toxicity profiles without necessarily reducing overall toxic pressure, illustrating how policy-driven changes may redistribute impacts rather than eliminate them.

Overall, these findings support the value of life cycle-based chemical footprint approaches as complementary tools to regulatory risk assessment frameworks. By enabling portfolio-level prioritization and substance ranking at national scale, this integrated perspective provides a robust scientific basis for targeting high-impact compounds and supporting strategic mitigation pathways in sustainable viticulture management. Such approaches offer a scalable and policy-relevant framework for aligning pesticide governance, regulatory prioritization and farm-level decision-making with long-term environmental and human-health protection objectives.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11367-026-02662-9>.

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Author contributions Conceptualization: J. I. López Sánchez, M. González García; R. González Combarros; Methodology: J. I. López Sánchez, M. González García, R. González Combarros; Data curation: R. González Combarros; Formal analysis: J. I. López Sánchez, M. González García; R. González Combarros; Validation: J. I. López Sánchez, M. González García; Visualization: R. González Combarros; Writing—original draft: J. I. López Sánchez, M. González García; R. González Combarros; Writing—review & editing: J. I. López Sánchez, M. González García; R. González Combarros; Supervision & project administration: J. I. López Sánchez, M. González García. All authors read and approved the final manuscript.

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Data availability All raw data used in this study are publicly available from the Spanish Ministry of Agriculture, Fisheries and Food (MAPA) vineyard pesticide-use surveys (as cited in the manuscript). Derived, curated datasets and analysis outputs used to calculate impact scores will be provided as Supplementary Material upon acceptance and are available from the corresponding author on reasonable request.

Code availability The scripts used to process MAPA datasets, interface with USEtox™ v2.14 characterization factors, and compute impact scores (midpoint and endpoint) can be found on the USEtox™ website (<https://usetox.org>).

Declarations

Ethical approval Not applicable. This study involves no experiments with human participants or animals; it analyzes publicly available national pesticide-use statistics and model outputs.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare that they have no competing interests.

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