

Pulsed light treatment of pesticides induces high compound degradation and toxicity decrease

François Clavero, Jérôme Cachot, Christelle Clérandeau, Laure Sandoval, Fanny Meytraud, Warren Albertin, Gilles de Revel, Rémy Ghidossi, Céline Franc

▶ **To cite this version:**

François Clavero, Jérôme Cachot, Christelle Clérandeau, Laure Sandoval, Fanny Meytraud, et al.. Pulsed light treatment of pesticides induces high compound degradation and toxicity decrease. Ecotoxicology and Environmental Safety, 2025, 305, pp.119232. ⟨10.1016/j.ecoenv.2025.119232⟩. ⟨hal-05575307⟩

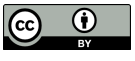
HAL Id: hal-05575307

https://hal.inrae.fr/hal-05575307v1

Submitted on 1 Apr 2026

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY 4.0 - Attribution - International License

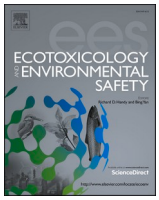
Ecotoxicology and Environmental Safety 305 (2025) 119232



Contents lists available at ScienceDirect

Ecotoxicology and Environmental Safety

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





Pulsed light treatment of pesticides induces high compound degradation and toxicity decrease

François Clavero [a,b,*], Jérôme Cachot [c], Christelle Clérandeau [c], Laure Sandoval [b], Fanny Meytraud [b], Warren Albertin [a], Gilles de Revel [a], Rémy Ghidossi [a], Céline Franc [a,**]

[a] Univ. Bordeaux, INRAE, Bordeaux INP, Bordeaux Sciences Agro, UMR 1366, ŒNO, ISVV, Villenave d'Ornon, F-33140, France
[b] SANODEV, Limoges, F-87000, France
[c] Univ. Bordeaux, CNRS, INP Bordeaux laboratoire EPOC, UMR 5805, Pessac, F-33600, France

ARTICLE INFO

Edited by Jianbo Shi.

Keywords:
Phytosanitary products
Fish
Algae
Bacteria
HPLC-MS/MS, photoproducts, ecotoxicity

ABSTRACT

Pulsed light (PL) is a technology using high-intensity pulses of polychromatic light enabling the photolysis of various organic compounds. This study examined the photodegradation by PL of 18 pesticides commonly used in viticulture using both chemical and ecotoxicological approaches. Pesticide concentrations were monitored in treated and untreated samples, along with the formation of degradation products using HPLC-MS/MS. PL successfully degraded the 18 pesticides from initial concentrations between 304 and 561 μg/L to < 30 μg/L after a treatment at 91 J/cm^2 for 8.53 min duration. The concentrations of 14 pesticides were even reduced below their limit of quantification, and for 10 of them, below their limit of detection. Dimethomorph was the least degraded compound, with a 93.5 % reduction. Besides, 42 degradation products were observed. The study also showed that PL can degrade the degradation products themselves. The ecotoxicological approach assessed the acute toxicity of the pesticide mix before and after PL on three levels of the aquatic trophic chain: the bacteria *Aliivibrio fischeri*, the microalgae *Raphidocelis subcapitata*, and the fish *Oryzias latipes*. Acute toxicity was reduced two-fold for *A. fischeri* and 24-fold for *R. subcapitata*. For *O. latipes*, a mortality rate of 6.6 % was observed in treated samples, whereas it was 100 % in untreated samples. However, some sublethal effects, such as axial skeleton deformations appeared in 22.2 % of *O. latipes*, likely due to residual pesticides and degradation products. These results demonstrate that PL is a promising process to significantly lower both pesticide concentrations and acute toxicity.

1. Introduction

The world population is constantly increasing. Indeed, according to the projections of the United Nations (United Nations, 2022), the world population is set to grow by a further 25 %, reaching 10.3 billion by the mid-2080s, up from 8.2 billion in 2024. Faced with growing demand, feeding the world population is a major challenge that agriculture has to overcome. Mineral fertilization is one of the primary tools for increasing crop yields (Antonkiewicz and Łabętowicz, 2016). Next, the use of pesticides ensures the quality and the quantity of the production. According to the FAO (Food and Agriculture Organization) (World Health Organization, 2019), the total import and export value of pesticides has increased in the past two decades by more than two times compared to the 1990s in Europe. These compounds can contaminate air, soil, water bodies or agricultural wastewater (Chowdhury et al., 2012; Hildebrandt et al., 2008; Massot et al., 2012; Manjarres-López et al., 2021; Pose-Juan et al., 2015) as a result of spraying methods, leaching phenomena or accidental contaminations. It is therefore essential to develop water remediation techniques using new and efficient methods.

There is a growing interest in the degradation of phytosanitary products using advanced oxidation processes (AOPs), such as cold plasma (Abedi-Firoozjah et al., 2021), photocatalysis (Varma et al., 2020) and ozonation (Ikehata and Gamal El-Din, 2005). These methods are low-priced and have proven effective in removing pesticides from fresh products and water.

During the degradation of organic pollutants, photodegradation processes generate transformation products (TP) which may be more toxic than their parent compound, and this needs to be assessed.

* Corresponding author at: Univ. Bordeaux, INRAE, Bordeaux INP, Bordeaux Sciences Agro, UMR 1366, ŒNO, ISVV, Villenave d'Ornon, F-33140, France.
** Corresponding author.
E-mail addresses: francois.clavero@u-bordeaux.fr (F. Clavero), celine.franc@u-bordeaux.fr (C. Franc).

https://doi.org/10.1016/j.ecoenv.2025.119232
Received 16 June 2025; Received in revised form 19 September 2025; Accepted 5 October 2025
Available online 19 October 2025
0147-6513/© 2025 The Authors. Published by Elsevier Inc. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

Moreover, a single compound can give rise to numerous transformation products. In recent years, photodegradation processes and in particular pulsed light (PL), have demonstrated significant efficiency in degrading organic pollutants such as chlorophenol (Hadi et al., 2021), bisphenol A (Fadaei et al., 2022) and dyes (Martínez-López et al., 2019). PL is a non-thermal technology that utilizes a capacitor to accumulate high discharge voltage. The stored electrical energy is then delivered as intermittent short pulses through a light source filled with xenon gas. This technology operates over a wide wavelength range, from 200 to 1000 nm, providing a greater probability of interactions with organic molecules. For comparison, continuous UV lamps only irradiates at a few specific wavelengths, such as 254 nm and 365 nm (Wekhof, 2000). Furthermore, the UV irradiance of flash lamps is about three or four orders of magnitude higher than standard mercury lamps (Schaefer et al., 2007). Continuous UV lamp degradation of pesticides has already been widely described in the literature (Lassalle et al., 2014; Skanes et al., 2021; Hong et al., 2021). Although these studies show the formation of at least ten photoproducts for each studied pesticide, they focused only on the degradation of 1–3 pesticides simultaneously and they required long exposure times ranging 40–150 min. In addition, these works rarely study toxicity through *in vivo* bioassay, as the possible toxicity of TPs is generally predicted using QSAR models.

In the literature, only five studies have explored the degradation of pesticides by PL (Baranda et al., 2012, 2014, 2017; Clavero et al., 2025a, 2025b) to our knowledge. Baranda et al. (2014) showed significant concentration reductions, above 80 % for 5 pesticides in a cocktail of 7 (simazine, atrazine, phosmet, azinphos-methyl, parathion-methyl, pirimiphos-methyl, and chlorpyrifos-ethyl) with short treatment times (15 pulses of 325 μs). However, there is still a lot of work to be done, given the large number of existing pesticides. Additionally, the impact of PL treatment on toxicity of pesticide solutions through bioassays was not examined. In a previous work (Clavero et al., 2025a), we examined the acute toxicity on the bacteria *Aliivibrio fischeri* of water contaminated with pesticides after PL treatments. A significant reduction in acute toxicity was observed for 10 out of 18 individual pesticides, while the acute toxicity was unchanged for the remaining seven. For a cocktail solution, the acute toxicity decreased by 7.25-fold between the untreated and the most treated solution.

To comprehensively assess the suitability of PL treatment for pesticide-contaminated viticultural effluents, it is essential to evaluate acute toxicity across multiple taxa representative of different trophic levels in aquatic ecosystems as toxicity may differ depending on the species considered. This is particularly important given that some transformation products may exhibit greater toxicity, persistence, or mobility than their parent compounds (Sinclair and Boxall, 2009). Although screening acute toxicity assays offer a relatively rapid approach to assessing water treatment efficacy, relying on a single test provides only a partial view of the overall toxicological impact. The toxicity bioassays across multiple taxa remain underutilized, largely due to the requirement for specialized equipment and their associated time and cost constraints. Nevertheless, they are critical for detecting effects of contaminants at environmentally relevant concentrations. In a recent review (Lashuk and Yargeau, 2021), it was highlighted that the results could be inconsistent across bioassays due to a heterogeneity of the sensitivity of the various biological models. This variability underscores the need to implement a battery of complementary bioassays to obtain a robust and comprehensive toxicity profile.

Therefore, the aim of the present study was to investigate the efficiency of PL technology as a new remediation process for pesticides in reducing acute toxicity on various taxa. To achieve this goal, chemical and ecotoxicological analyses were carried out on pesticide-spiked water samples. Firstly, the impact of PL on a cocktail solution of 18 pesticides was studied by HPLC-MS/MS quantitative analysis. The degradation of pesticides and the formation of photoproducts were monitored. Secondly, the impact of pesticides-contaminated water samples treated by PL on acute toxicity was evaluated. Three aquatic species belonging to three trophic levels were tested: the bioluminescent marine bacteria *Aliivibrio fischeri* using Microtox® bioassays, the freshwater algae *Raphidocelis subcapitata*, and the freshwater fish *Oryzias latipes*. Acute toxicity of PL treated and untreated solutions of pesticides were compared, providing information on toxicity level of pesticides relatively to their photoproducts.

2. Materials and methods

2.1. Chemicals

Azoxystrobin, benalaxyl, boscalid, cyprodinil, difenoconazole, dimethomorph, fenbuconazole, fenhexamid, fludioxonil, iprovalicarb, kresoxim-methyl, mandipropamid, metrafenone, pyraclostrobin, pyrimethanil, tebuconazole, tebufenozide, and tetraconazole, along with triphenylphosphate (TPP) used as the internal standard (IS), were purchased from Sigma-Aldrich Chimie (St Quentin Fallavier, France).

These 18 pesticides were selected based on their relevance in viticulture, with all chemical standards having a purity above 96.6 %. Difenoconazole-d_6 (99.4 % isotopic purity), fenbuconazole-d_5 (98.8 % isotopic purity), metrafenone-d_9 (99.9 % isotopic purity), pyraclostrobin-d_6 (99.8 % isotopic purity), tebuconazole-d_6 (97.5 % isotopic purity), and tebufenozide-d_9 (98.9 % isotopic purity) used as IS were acquired from CLUZEAU INFO LABO (Sainte Foy la Grande, France).

HPLC-grade acetonitrile was from VWR International SAS (Rosny-sous-Bois, France) and LC-MS grade acetonitrile (Optima®, 100 % purity), used for chromatographic separation was provided by Fisher chemical (Illkirch, France). Ultrapure water was obtained using a Milli-Q Reference system (Merck Millipore, Fontenay-sous-Bois, France). The mobile phases employed for HPLC separation were acidified with 0.1 % of formic acid (CAS RN: [64–18–6], high purity grade, 100 %) from Amresco Inc. (Solon, Ohio, USA).

2.2. Pulsed light

The LPBox, manufactured by Sanodev (Limoges, France), was utilized for pulsed light treatments. The light pulses were generated by storing electric energy in a capacitor, which was then rapidly discharged through a xenon lamp, resulting in the emission of pulses. The LPBox was operated at 4 kV and 3 Hz, as optimized in our previous study (Clavero et al., 2025a). The emission spectrum of polychromatic light ranged from 200 to 1000 nm. The spectral distribution at 4 kV is as follows: UV-C 3.2 %, UV-B 6.2 %, and UV-A 19 %. This spectrum was recorded in a rectangular delimited area (10 × 20 cm) located 32 cm from the lamp using an Ardop Qwave spectrometer (Pessac, France).

The LPBox delivers a fluence of 0.05723 J/cm^2 per flash at 4 kV within the delimited area. This value was measured using a sensor and a monitor from Thorlabs Inc. (Newton, USA). The total fluence (H) for each sample was calculated by multiplying the number of flashes by the fluence per flash.

2.3. Sample preparation

A concentrated cocktail solution containing azoxystrobin, benalaxyl, boscalid, cyprodinil, difenoconazole, dimethomorph, fenbuconazole, fenhexamid, fludioxonil, iprovalicarb, kresoxim-methyl, mandipropamid, metrafenone, pyraclostrobin, pyrimethanil, tebuconazole, tebufenozide, and tetraconazole at approximately 3.0-5.6 g/L for each compound was prepared in acetonitrile (ACN). The concentrated solution was then diluted with ultrapure water to obtain a 0.01 % ACN aqueous solution, with concentrations ranging from 304 to 561 μg/L depending on the pesticide.

A sample (10 mL of the aqueous cocktail solution (test sample) or 10 mL of the 0.01 % ACN aqueous solution (control sample)) was placed in a glass Petri dish in the centre of the delimited area of the LPBox. The diameter of the Petri dish was 60 mm and the thickness of the liquid film

was 5 mm. PL treatment was operated with voltage set at 4 kV and fluence of 91 J/cm^2 as these parameters were previously shown to be optimum for pesticide degradation (Clavero et al., 2025a). Any evaporation caused by high UV treatments was compensated for by adding ultrapure water, with a maximum evaporation of 8 %, the maximum temperature after treatment was 42°C. Each PL-treatment was performed in triplicate.

2.4. LC-MS analysis

LC-MS analyses were performed in multiple reaction monitoring (MRM) mode as described in Clavero et al., 2025a). PL-treated and untreated samples were filtered on 0.2 μm PTFE membrane and 1 mL of filtered sample was precisely withdrawn and transferred to an HPLC vial. Ten μL of IS solution was added and the vial vortexed before LC injection of 10 μL of the sample. Pesticides were quantified through calibration lines established in water in the range 1–300 μg/L with duplicate preparation. Regarding photoproducts, the quantification was relative (comparison of peak areas) due to unavailability of analytical standards. Simultaneously, 18 pesticides and their 81 photoproducts were monitored (Table S1). Limits of detection (LODs) and quantification (LOQs) for parent pesticides are reported in Table S2.

2.5. Toxicity bioassay

For all acute toxicity analyses, the toxicity was corrected with the one of a 0.01 % ACN aqueous solution for untreated samples and with the one of a PL-treated 0.01 % ACN aqueous solution for treated samples. This percentage of ACN was previously determined to have toxicity effects below 10 % for all aquatic species studied.

For all toxicity analyses the pH of the solutions analysed were measured between 6.4 and 6.8.

2.5.1. Acute toxicity assay on bacteria (A. fischeri)

The marine bacteria, *Aliivibrio fischeri*, known for its bioluminescent properties, was used as the reference organism in the Microtox® assay. The Microtox® test kits were supplied by Modern Water Inc. (New Castle, Delaware, USA). The assays were conducted according to the NF EF ISO 11348–3 guidelines (ISO, 2007). The Microtox® reagents were stored at −20 °C. The analyses were performed subsequently to the rehydration of lyophilized bacteria with 1 mL of ultrapure water at 5°C in test cuvettes for luminescence measurements. PL-treated and untreated cocktail solutions of pesticides were diluted at 0 %, 50 % and 75 % with a 20 g/L NaCl solution (2 %), in order to determine the EC20 (effective concentration 20 %) (Domínguez et al., 2023), i.e. the concentration inducing 20 % of bioluminescence inhibition for the bacterial culture. The positive control solutions were prepared with $K_2Cr_2O_7$ at 25, 50, 100, and 200 mg/L in 2 % NaCl aqueous solution. Negative controls consisted of an aqueous solution containing 0.01 % of ACN either treated or untreated with PL depending on the sample analyzed. The bacteria were exposed to the various test solutions for a duration of 30 min at 15°C. The bioluminescence emitted by the bacterial culture was quantified at 5°C using Modern Water's M500 Toxicity Analyzer luminometer. To ensure the reliability of the results, each analysis was carried out in triplicate within a maximum of 2 h following rehydration, in accordance with the protocol outlined by Gómez et al. (2023) and Laranjeiro et al. (2024).

2.5.2. Acute toxicity assay on microalgae (R. subcapitata)

The freshwater green microalgae *Raphidocelis subcapitata* was used as reference organism. These algae were obtained from the AlgalToxkit F supplied by Microbiotest (Gent, Belgium). The protocol implemented was in compliance with ISO 8692 (EN ISO, 8692, 2012) and OECD 201 (OECD, 2011) and adapted for 96-well microplates (Blaise et al., 2018). The algae culture (2.10^5 cells/mL) was diluted at $1/10^{th}$ in the cocktail pesticide solutions in 96-well microplates (Figure S1). The microplates were then covered with cling film and cultured for 96 h in a climatic chamber (Snijders Scientific, Tilburg, The Netherlands). The culture conditions in the chamber were 24 ± 1 °C with an agitation of 120 rpm on an orbital shaker. The algae were illuminated continuously during the experiment with a white LED (SF Retroled Bright T8/JT5 and Fluorescent Lamp Sylvania F36W/2084 BriteGro, Sylvania Lighting France, Gennevilliers, France). The light intensity was equalized for each microplate by measuring the light intensity with a luxmeter (LUTRON RS232 LX105, Coopersburg, PA, USA). The mean light intensity was 680 lux. Additionally, every 12 h the position of each microplate was moved randomly, with the aim of limiting the impact of the position of each microplate on the growth of algae. Negative controls consisted of an aqueous solution containing 0.01 % of ACN either treated or untreated with PL depending on the sample analyzed. PL-treated and untreated cocktail solutions of pesticides were diluted at 10, 65, 77, 89, 94 and 97 %, in order to draw the dose-response curve and then determine the EC20. Positive control solutions consisted of an aqueous solution of $K_2Cr_2O_7$ at 10, 1.8, 1, 0.56, 0.32, 0.18, and 0.1 mg/L. The microalgae culture growth was monitored every day with a reverse microscope and Malassez counting cell. Finally, at 96 h, cell count was made in each well in order to quantify the cellular growth for each modality. Algae cell concentrations at 96 h are available in Table S3. The growth inhibition for each modality was deduced from the growth observed in the negative control. A growth rate greater than 16 was observed for all the negative controls. Each modality was analysed in triplicate.

2.5.3. Acute toxicity assay on fish pro-larvae (O. latipes)

The freshwater fish *Oryzias latipes* was used as reference organism for the acute toxicity bioassay for the trophic level fish (Figure S2 and S3). Eggs of Japanese medaka (*O. latipes)* were supplied by INRAE (Rennes, France). Upon receipt, fish embryos at 24 h-post-fertilization (hpf) were placed in a Petri dish containing ERS (Egg Rearing Solution). The composition of the ERS was: 17.11 mM NaCl, 0.4 mM KCl, 0.36 mM $CaCl_2$, 1.36 mM $MgSO_4$, with the pH set between 7 and 7.5. The ERS was supplemented with 4 g/L of NaCl to ensure proper embryonic development and to prevent bacterial contamination. Each Petri dish contained a maximum of 100 eggs. The Petri dishes were placed in a climatic chamber (Snijders Scientific) with conditions set at 28 ± 1°C and an agitation of 34 rpm on an orbital shaker. The eggs were illuminated with a photoperiod of 12 h light / 12 h dark until they hatched (8–9 days at 28°C). The development of the embryos was monitored daily under stereomicroscope. Any embryos with developmental defects, or that were dead or unfertilized, were discarded. Once the hatching peak was reached, 15 freshly hatched larvae were incubated for 48 h in 30 mL of the different solutions tested with an agitation of 34 rpm and a temperature of 26°C and a 12 h/12 h light/dark cycle. Exposure solution was renewed by half after 24 h. For this experiment, only the acute toxicity of the undiluted treated or untreated cocktail solution was studied, as a study of a range of dilutions would have required too many larvae. The oxygen saturation was measured daily and was always higher than 88 %. For this acute toxicity analysis, both lethal and sublethal effects (immobility and deformations of the axial skeleton) were recorded. All samples were analysed in triplicates.

2.6. Data analysis

Data of each experiment were analyzed by *t*-test, two samples were considered as different for a $p\text{-value} < 0.05$.

3. Results

3.1. Chemical analysis

3.1.1. Pesticide degradation

An aqueous cocktail solution of 18 pesticides with concentrations

ranging from 304 to 561 μg/L was subjected to PL treatment at 4 kV with a fluence of 91 J/cm^2. These parameters were selected for pesticide degradation as Clavero et al. (2025a). previously demonstrated that the highest voltage and highest fluence enabled the highest degradation rate. PL proved once again significantly efficient in decreasing pesticide concentrations (*t*-test, n = 3, p-value < 0.05, Fig. 1), in accordance with our previous study. The concentration of 14 compounds was reduced to levels below their LOQs, and for 10 compounds, the concentrations were even below their LODs (Table S2) in the treated samples. Only 4 compounds remained at concentrations higher than their LOQ (boscalid, dimethomorph, iprovalicarb, and pyrimethanil). They have, however, been significantly degraded. Indeed, post-treatment degradation rates reached 94.7 %, 93.5 %, 97.7 %, and 97.5 %, respectively.

These results are in agreement with the classification proposed in Clavero et al. (2025a) in which these compounds were among the 5 least sensitive compounds to PL with half fluences ($H_{1/2}$) above 30.8 J/cm^2. Tebufenozide completed this shortlist. However, due to its higher LOQ (20 μg/L) compared to the other compounds it reached a concentration below its LOQ. These results confirm that the ranking previously established using $H_{1/2}$ effectively determine the sensitivity of a compound. The poor sensitivity, in other words the higher resistance, of these compounds to photodegradation may be attributed to their large number of conjugated bonds and phenyl groups (Clavero et al., 2025a). The wide variety of wavelengths produced by the continuous spectrum of the LPBox, especially in the UV part of the spectrum (UV-C 3.2 %, UV-B 6.2 %, and UV-A 19 %), allows a significant impact on the concentrations of all the compounds studied (>93.5 % reduction).

3.1.2. Photoproduct formation

LC-MS analyses of the treated samples revealed 42 out of the 81 photoproducts investigated in MRM mode (Fig. 2). These compounds were observed with small peak areas for the majority of them. This is likely due to the high voltage and fluence applied to the samples. The degradation products that were not observed were probably formed and then degraded, as reported in Clavero et al. (2025a). Indeed, in the present work, intermediate fluences (11, 22, and 45 J/cm^2) were not studied due to the high cost and time involved in the toxicity analyses. It is also important to note that for all the pesticides whose degradation products are monitored in the method, at least one degradation product was observed, except for mandipropamid. In this experiment, 24 additional photoproducts were detected compared to the previous study, which found only 18 compounds stable at 91 J/cm^2. This may be due to the fact that the initial concentrations of the parent pesticides are higher, leading to the observation of a greater number of TPs. Indeed, TPs formed in smaller quantities in our previous study could not be observed due to low initial concentration of parent pesticides.

The different photoproducts are listed in (Clavero et al., 2025a). As described in our previous study, the hypothetical structures proposed suggest different photodegradation pathways for the halogenated compounds, with dehalogenation and hydroxylation (boscalid, difenoconazole, fenbuconazole, fenhexamid, metrafenone, pyraclostrobin, tebuconazole, and tetraconazole) being the most common. For the non-halogenated pesticides, breaking bonds were observed (benalaxyl, pyrimethanil) as well as hydroxylation (iprovalicarb, pyrimethanil). Numerous photoisomerizations were also observed for the compounds without halogen atoms (azoxystrobin, cyprodinil).

3.2. Acute toxicity on 3 aquatic species

3.2.1. Acute toxicity test on the bacteria A. fischeri

The acute toxicity of the PL-treated (T) and untreated (UT) cocktail solutions of pesticides was measured on the bacteria *Aliivibrio fischeri* following the Microtox® protocol. The assays were validated using a positive control ($K_2Cr_2O_7$) and a negative control (NaCl 2 %).

The results indicate that the bioluminescence of the bacteria culture exposed to the treated sample was much higher than that exposed to the untreated one, indicating a reduction of the acute toxicity of the pesticide cocktail after the PL treatment. This result is illustrated by the EC20 (effective concentrations at 20 %) values (Fig. 3), which increased by a factor of 2 after PL treatment of the pesticide cocktail. The 2-fold increase of the EC20 implies a division by 2 of the acute toxicity, as EC20 is inversely correlated with toxicity. These results are consistent with those of (Clavero et al., 2025a), in which a significant reduction in acute toxicity for *A. fischeri* was observed for PL-treated pesticide cocktail samples. However, the acute toxicity reduction is moderate for the present study, since a 7.25-fold reduction in acute toxicity was previously noted.

This difference could be explained by the fact that initial pesticide concentrations are higher in the present experiment, leading to higher residual pesticide concentrations under the same treatment conditions. Indeed, in the previous study, only three pesticides had concentrations above their LOQ: boscalid, dimethomorph and pyrimethanil at 6.9, 7.2 and 6.0 μg/L respectively, i.e. 2.0 %, 2.1 % and 2.2 % of their initial concentrations. In the present study, boscalid, dimethomorph, iprovalicarb and pyrimethanil had concentrations of 28, 30, 9 and 14 μg/L respectively i.e. 5.3 %, 6.5 %, 2.3 % and 2.5 % of their initial concentrations. These higher concentrations could therefore explain the difference in acute toxicity observed. On the other hand, the higher pesticide concentrations also led to the detection of 24 additional TPs compared to the previous study. It is therefore possible that these 24 TPs

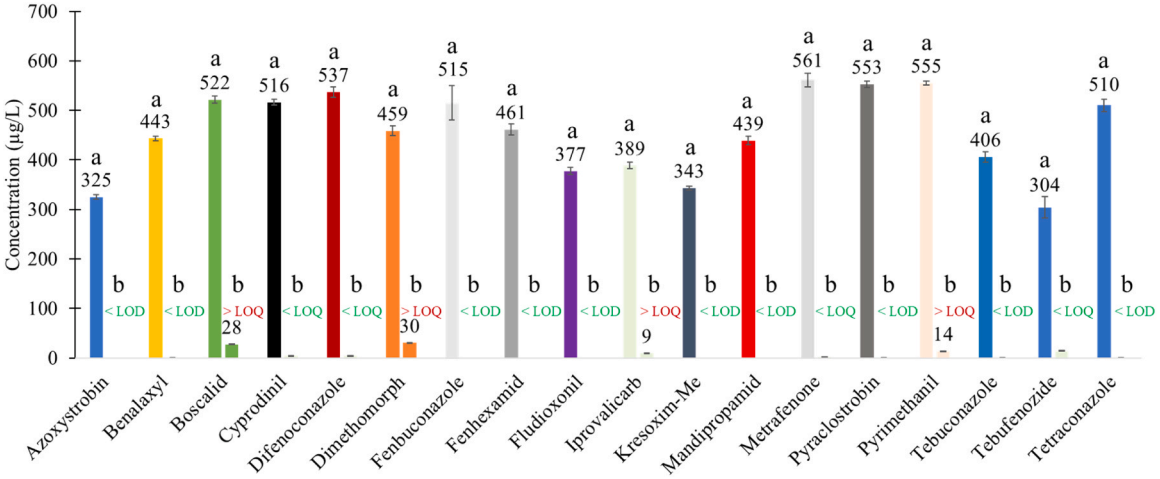


Fig. 1. Pesticide concentrations of the treated and untreated cocktail solution (*t*-test, n = 3, p-value < 0.05).

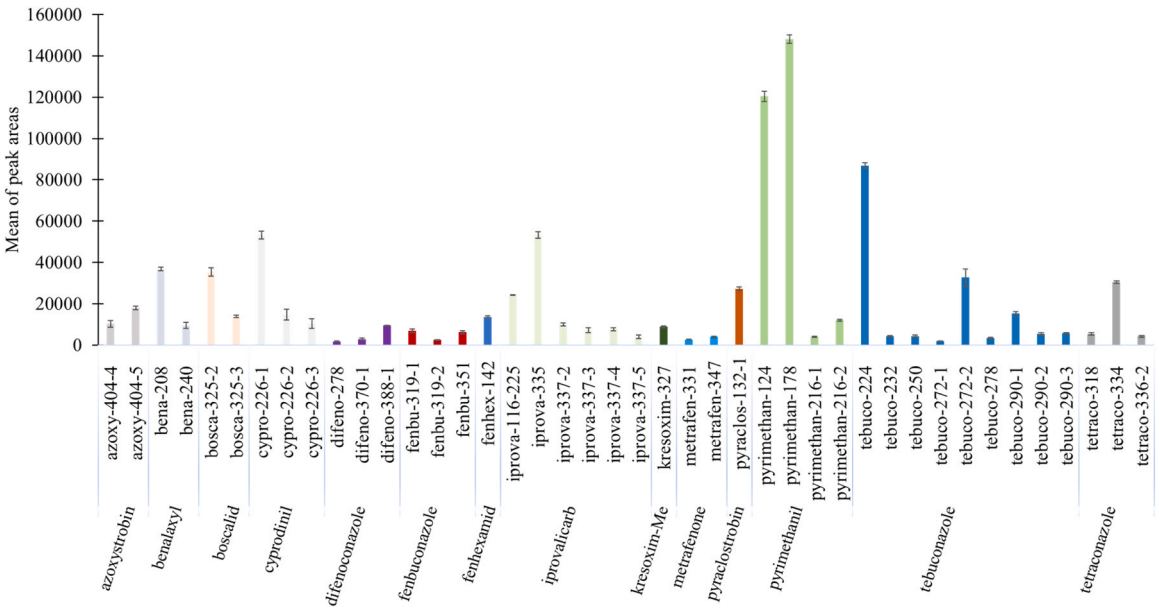


Fig. 2. Mean of peak areas (n = 3) of the photoproducts of the different pesticides tested.

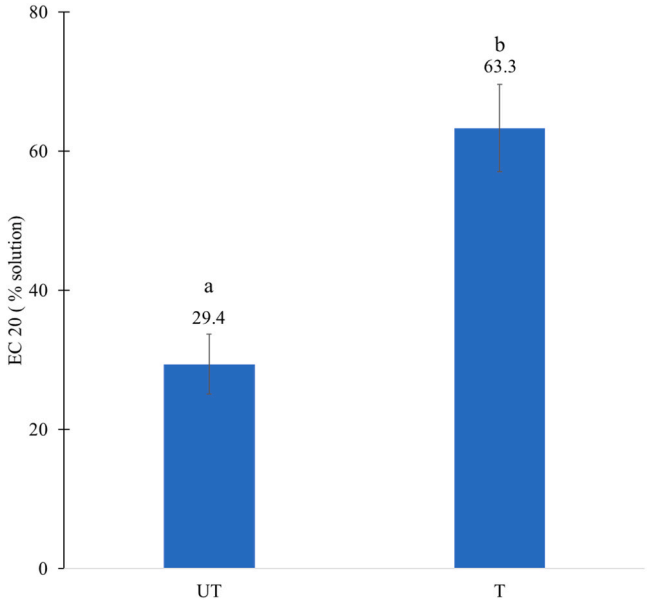


Fig. 3. EC20 of PL-treated (T) and untreated (UT) pesticide cocktail samples on the bacteria *A. fischeri* (Mean ± Standard Deviation, *t*-test, n = 3, p-value < 0.05).

induced higher acute toxicity which could have been at the origin of this discrepancy.

3.2.2. Acute toxicity test on the microalgae R. subcapitata

The acute toxicity of the treated and untreated cocktail solutions was measured on the freshwater algae *R. subcapitata* after 96 h of exposure. A growth rate greater than 16 was observed for all the negative controls carried out with water at 0.01 % ACN with a mean cell concentration of 49.10^5 cells/mL. The population was multiplied by 248 in 96 h. This indicates a favourable development of microalgae and negligible effect of ACN at 0.01 % on cell growth. The assays were validated using a positive control ($K_2Cr_2O_7$) with a EC50 (effective median concentration) at 0.52 mg/L after 96 h which complies with the supplier's provided value ranging 0.42–0.63 mg/L.

The growth inhibition of the PL-treated samples was significantly lower than that of the untreated ones, and the development of *R. subcapitata* was particularly slowed down in the untreated samples, with a very low algal concentration compared to the PL-treated samples (Figure S4). In fact, the EC20 (Fig. 4) of the treated samples was 24 times higher than that of the untreated samples, indicating an acute toxicity reduction by a factor of 24 for the algae between the untreated and treated samples. The acute toxicity profile follows the same trend as the one on the bacteria model.

3.2.3. Acute toxicity test on fish larvae O. latipes

The acute toxicity of PL-treated (T) and untreated (UT) pesticide cocktail solutions was measured on larvae of the freshwater fish *O. latipes* after 48 h of exposure. Larval mortality at 48 h in the negative

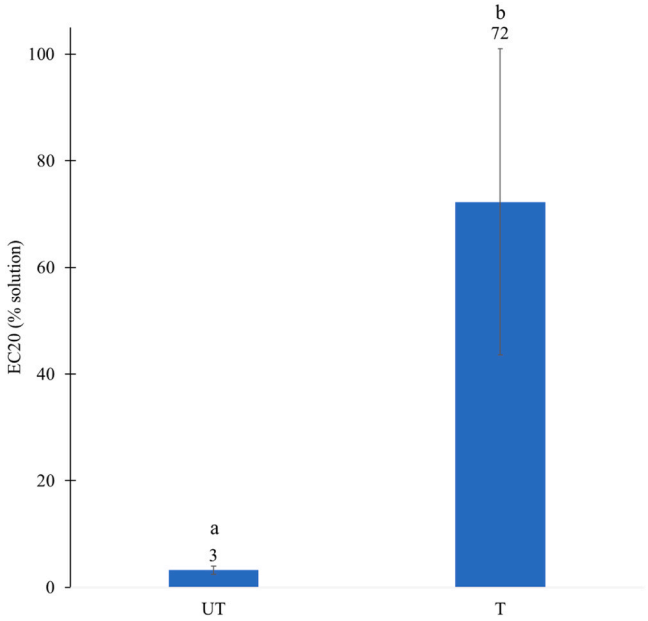


Fig. 4. EC 20 of PL-treated (T) and untreated (UT) pesticide cocktail samples on the microalgae *R. subcapitata* (Mean ± Standard Deviation, *t*-test, n = 3, p-value < 0.05).

control with 0.01 % ACN aqueous solution was 7 ± 7 %. Dead larvae were recorded in both pesticide cocktail exposure conditions but the larval mortality in the PL-treated samples was significantly reduced in comparison to the untreated one (Fig. 5). For the untreated cocktail solution, the mortality was at 100 % for all the replicates after 48 h of exposure, while for the PL treated samples the mortality was only of 6.6 % on average for all the replicates. This result highlights a drastic reduction in acute toxicity after PL treatment. However, it is important to note that sublethal effects were noticed in 22.2 % of the larvae exposed to the PL-treated pesticide cocktail but not in the untreated pesticide cocktail due to 100 % of dead larvae. In particular, induction of axial skeletal deformations (Figure S5) was observed, with some variability between replicates. These results therefore indicate that PL treatment appears to be very effective in reducing the acute toxicity of samples with high pesticide loads. However, a residual sublethal toxicity remained in the experimental conditions, putatively induced by photoproducts of pesticides or residual parent pesticides.

4. Discussion

PL treatment significantly reduces pesticide concentrations by photodegradation, but also generates TPs that may be more or less toxic than the parent compounds (Sinclair and Boxall, 2009). The study by Esposito et al. (2021). showed 100 % degradation of imidacloprid, 80 % of terbuthylazine, and 70 % of azoxystrobin after 8 h of UV-treatment of pesticide-spiked aqueous solutions. However, the impact on toxicity toward bioluminescent bacteria varied. Thus, for imidacloprid, no observable toxicity remained after treatment, whereas for terbuthylazine, toxicity did not decrease during the treatment, and the bioluminescence inhibition rate remained at 100 % despite substantial degradation of the compound.

In the current study, we conducted acute toxicity assessments across the aquatic trophic chain to investigate the impact of PL on pesticide-contaminated waters for different taxa of aquatic ecosystem. Our results demonstrated that, for all three tested species, PL treatment led to a significant reduction in the acute toxicity of all samples. These results are in agreement with the study of Stamatis et al. (2015), which showed an absence of toxic effects on *A. fischeri* of the tebuconazole samples treated by photocatalysis. The degradation mechanisms in this study were tert-butyl chain cleavage, hydroxylation, oxidation and dehalogenation. Their study revealed the formation of two tebuconazole TPs also observed in the present work, TP-tebuco-278 and TP-tebuco-250.

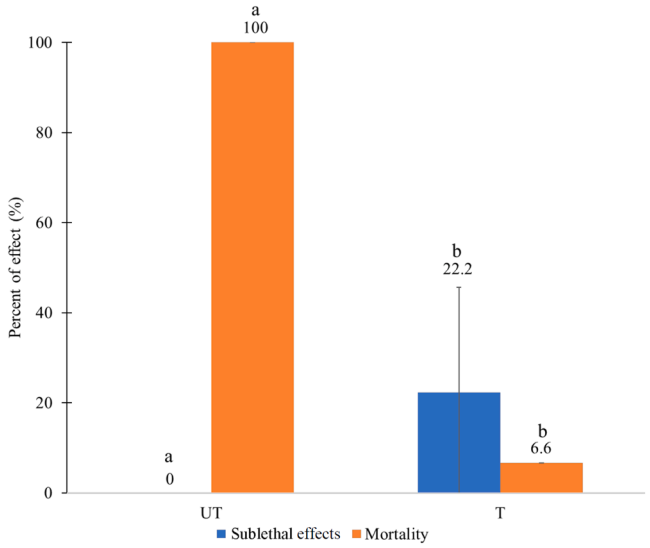


Fig. 5. Lethal and sublethal effects induced in larvae of the fish *O. latipes* after 48 h of exposure to PL-treated (T) and PL-untreated (UT) pesticide cocktail samples. (Mean ± Standard Deviation, *t*-test, n = 3, p-value <0.05).

Del Puerto et al. (2022) reported similar results for tebuconazole using a combined vacuum UV and UVC treatment. A test battery including the bioluminescent bacterium *A. fischeri*, the Gram-positive bacterium *Bacillus subtilis*, the fungus *Fusarium graminearum*, the green microalga *R. subcapitata*, and the microcrustacean *Daphnia magna* was performed to represent different trophic levels. The combined vacuum UV / UVC treatment of drinking water containing tebuconazole effectively degraded the parent compound at concentrations ranging from μg/L to mg/L. These reductions in pesticide concentration were accompanied by significant decreases in toxicity at a fluence of 12.5 J/cm^2. For *F. graminearum*, *B. subtilis*, and *D. magna*, toxicity was reduced to such an extent that no EC50 could be determined following vacuum UV / UVC irradiations. In the case of *R. subcapitata*, toxicity was reduced by a factor of 4.8. Results for *A. fischeri*, however, were more mitigated due to a weak response of this microorganism, highlighting the importance of assessing multiple trophic levels in ecotoxicological studies.

On the other hand, Man et al. (2021) studied the degradation, particularly through photolysis, of difenoconazole in water and soil. The main degradation mechanisms observed were again oxidation, dechlorination, and hydroxylation. TP-difeno-278, TP-difeno-370, and TP-difeno-388 were detected in their study as in the present work. Toxicity analyses were conducted using ECOSAR predictions and laboratory tests. They showed that the acute toxicities of the four novel TPs selected on *Brachydanio rerio*, *D. magna*, and *Selenastrum capricornutum* were substantially lower than that of difenoconazole. However, all the TPs, except TP-difeno-278, were predicted to be very toxic to fish after chronic exposure, which may pose a potential threat to aquatic ecosystems. This potential toxicity further highlights the need to conduct chronic toxicity assessments when developing remediation techniques based on compound breakdown. However, the implementation of such tests is often challenging due to their high cost and time-consuming nature.

Zhu et al. (2022) in turn, studied the photodegradation of enestroburin, also known as enoxastrobin, in water using simulated sunlight irradiation. They employed an untargeted approach with LC-HRMS, which allowed the detection of 12 TPs. The main transformation reactions included hydration, hydrolysis, oxidation, reduction, and decarboxylation. They estimated the toxicity of these TPs using the QSAR model ECOSAR, and 2 TPs (M-313 and M-327) were classified as "very toxic", highlighting that insufficient photodegradation can lead to hazardous TPs whose toxicity could pose a problem for ecosystems.

These studies thus showed that while the acute toxicity of photoproducts generally decreases compared to their parent compound, significant sublethal residual toxicity may remain. Hence, it is possible that the sublethal toxicity observed for fish in the current experiment may be due to TPs with low acute toxicity but with high chronic toxicity. It would therefore be crucial to optimize photolysis to not only degrade pesticides but also their TPs. Such optimization requires the use of non-targeted analytical tools like LC-HRMS (Guo et al., 2020). Indeed, LC-MS/MS in MRM mode only tracks known TPs, whereas non-targeted methods would provide a comprehensive view of TPs evolution as a function of fluence. LC-HRMS would also provide more accurate structural information on TPs, which could enable their toxicity to be studied using QSAR models. This optimization should also be based on a joint approach that measures both acute and sublethal toxicity across various taxa in aquatic and terrestrial trophic chains, in order to demonstrate the safety of pesticide-contaminated water that has been treated by PL photolysis.

5. Conclusion

PL technology was investigated as a pesticide removal process for 18 phytosanitary products widely used in viticulture. PL was able to degrade all compounds, with 14 compounds decreasing from

concentrations between 304 and 506 μg/L to concentrations below their LOQs. Among these compounds, 10 were even reduced at concentrations below their LOD. The remaining pesticides were degraded by more than 93.5 %. These results demonstrated that PL is a very efficient process for degrading pesticides, due to the wide range of wavelengths emitted. The LC-MS analysis enabled the detection of 42 out of 81 expected photoproducts. This could be explained by the formation and then the degradation of photoproducts by PL. This work shows the interest of using mass spectrometry to monitor the impact of a process on the degradation of pesticides and their photoproducts. The mass spectrometry enabled also to study the photodegradation products from a structural point of view and the mechanisms involved during photodegradation. The major probable pathways observed for degradation products were dehalogenations and hydroxylations for the halogenated compounds. For the non-halogenated pesticides, breaking bonds, photoisomerizations, and hydroxylations were observed. The acute toxicity of the cocktail solution of 18 pesticides was significantly reduced for all taxa studied (bacteria, algae and fish) after PL treatment at 91 J/cm^2. These results therefore show that PL appears to be an interesting technology for reducing the acute toxicity of pesticide-contaminated water. However, it is important to note that sublethal toxicity was observed for the treated samples. This sublethal toxicity is likely due to residual parent pesticide and TPs not degraded which, although less toxic than their parent compounds, may still remain significantly harmful to aquatic life. It will therefore be essential, in order to avoid any environmental risks, to optimize photolysis in such a way that it degrades not only the pesticides but also the TPs. This research demonstrates the value of optimizing a process using combined analytical chemistry and ecotoxicological approaches. PL therefore appears to be a promising process for treating fresh water or wastewater contaminated with high concentrations of pesticides. Further optimizations are required to ensure complete degradation of pesticides and their degradation products to mitigate any remaining toxicity. These optimizations could lead to the development of a continuous PL treatment process for wine-growing wastewater. The implementation of continuous processing will enable the process to be scaled up, allowing for semi-industrial-scale processing.

An in-depth study of the impact of the continuous PL process on pesticide degradation and chronic toxicity for various aquatic and terrestrial taxa would be necessary to demonstrate the safety of such technology for ecosystems.

CRediT authorship contribution statement

François Clavero: Writing – original draft, Visualization, Validation, Software, Investigation, Formal analysis. **Jérôme Cachot:** Writing – review & editing, Validation, Supervision, Resources, Methodology. **Christelle Clérandeau:** Writing – review & editing, Methodology. **Laure Sandoval:** Conceptualization, Writing – review & editing. **Fanny Meytraud:** Writing – review & editing. **Warren Albertin:** Writing – review & editing, Formal analysis. **Gilles de Revel:** Writing – review & editing, Resources. **Rémy Ghidossi:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **Céline Franc:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Clavero Francois reports financial support was provided by Sanodev. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

None.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ecoenv.2025.119232.

Data availability

No data was used for the research described in the article.

References

Abedi-Firoozjah, R., Ghasempour, Z., Khorram, S., Khezerlou, A., Ehsani, A., 2021. Non-Thermal techniques: a new approach to removing pesticide residues from fresh products and water. Toxin Rev. 40 (4), 562–575. https://doi.org/10.1080/15569543.2020.1786704.

Antonkiewicz, J., Łabętowicz, J., 2016. Chemical innovation in plant nutrition in a historical continuum from ancient Greece and Rome until modern times. Chem. Didact. Ecol. Metrol. 21 (1–2), 29–43. https://doi.org/10.1515/cdem-2016-0002.

Baranda, A.B., Barranco, A., de Marañón, I.M., 2012. Fast atrazine photodegradation in water by pulsed light technology. Water Res. 46 (3), 669–678. https://doi.org/10.1016/j.watres.2011.11.034.

Baranda, A.B., Fundazuri, O., Martínez de Marañón, I., 2014. Photodegradation of several triazidic and organophosphorus pesticides in water by pulsed light technology. J. Photochem. Photobiol. A Chem. 286, 29–39. https://doi.org/10.1016/j.jphotochem.2014.03.015.

Baranda, A.B., Lasagabaster, A., de Marañón, I.M., 2017. Static and continuous Flow-through pulsed light technology for pesticide abatement in water. J. Hazard. Mater. 340, 140–151. https://doi.org/10.1016/j.jhazmat.2017.07.012.

Blaise, C., Férard, J.-F., Vasseur, P., 2018. Microplate toxicity tests with microalgae: a review. Microscale Testing in Aquatic Toxicology. CRC Press, Boca Raton, pp. 269–288. https://doi.org/10.1201/9780203747193-18.

Chowdhury, A.Z., Jahan, S.A., Islam, M.N., Moniruzzaman, M., Alam, M.K., Zaman, M. A., Karim, N., Gan, S.H., 2012. Occurrence of organophosphorus and carbamate pesticide residues in surface water samples from the rangpur district of Bangladesh. Bull. Environ. Contam. Toxicol. 89 (1), 202–207. https://doi.org/10.1007/s00128-012-0641-8.

Clavero, F., Cachot, J., Clérandeau, C., Sandoval, L., Meytraud, F., Picard, N., Albertin, W., De Revel, G., Ghidossi, R., Franc, C., 2025. Study of intense pulsed light as a new remediation process for pesticides in water using mass spectrometry and ecotoxicological approaches. J. Hazard. Mater. Adv. 17, 100577. https://doi.org/10.1016/j.hazadv.2024.100577.

Clavero, F., Cachot, J., Clérandeau, C., Sandoval, L., Meytraud, F., Picard, N., Albertin, W., de Revel, G., Ghidossi, R., Franc, C., 2025. Study of the impact of a pulsed light process on phytosanitary products and ecotoxicity of viticultural wastewaters. Oeno one 59 (2). https://doi.org/10.20870/oeno-one.2025.59.2.8346.

Del Puerto, O., Gonçalves, N.P.F., Medana, C., Prevot, A.B., Roslev, P., 2022. Attenuation of toxicity and occurrence of degradation products of the fungicide tebuconazole after combined vacuum UV and UVC treatment of drinking water. Environ. Sci. Pollut. Res 29 (38), 58312–58325. https://doi.org/10.1007/s11356-022-19691-0.

Domínguez, C.M., Ventura, P., Checa-Fernández, A., Santos, A., 2023. Comprehensive study of acute toxicity using Microtox® bioassay in soils contaminated by lindane wastes. Sci. Total Environ. 856, 159146. https://doi.org/10.1016/j.scitotenv.2022.159146.

EN ISO 8692 (2012) Water Quality – Fresh Water Algal Growth Inhibition Test with Unicellular Green Algae (ISO 8692:2012).

Esposito, B., Riminucci, F., Di Marco, S., Metruccio, E.G., Osti, F., Sangiorgi, S., Ferri, E. N., 2021. A simple device for the On-Site photodegradation of pesticide mixes remnants to avoid environmental point pollution. Appl. Sci. 11 (8), 3593. https://doi.org/10.3390/app11083593.

Fadaei, S., Taheri, E., Fatehizadeh, A., Aminabhavi, T.M., 2022. New combination of pulsed light and iron (II) for carbonate radical production to enhanced degradation of bisphenol A: parameter optimization and degradation pathway. J. Environ. Manag. 322, 116059. https://doi.org/10.1016/j.jenvman.2022.116059.

Gómez, V.A., Pozo, K., Clérandeau, C., Cachot, J., Montes, C., Přibylová, P., Glabán-Malagón, C., Clarke, B., Klanova, J., Morin, B., 2023. Plastic debris, persistent organic pollutants and their toxicity impacts in coastal areas in central Chile. Mar. Pollut. Bull. 194, 115361. https://doi.org/10.1016/j.marpolbul.2023.115361.

Guo, Z., Zhu, Z., Huang, S., Wang, J., 2020. Non-Targeted screening of pesticides for food analysis using liquid chromatography High-Resolution mass Spectrometry-a review. Food Addit. Contam. Part A 37 (7), 1180–1201. https://doi.org/10.1080/19440049.2020.1753890.

Hadi, S., Taheri, E., Amin, M.M., Fatehizadeh, A., Aminabhavi, T.M., 2021. Advanced oxidation of 4-Chlorophenol via combined pulsed light and sulfate radicals methods: effect of co-existing anions. J. Environ. Manag. 291, 112595. https://doi.org/10.1016/j.jenvman.2021.112595.

Hildebrandt, A., Guillamón, M., Lacorte, S., Tauler, R., Barceló, D., 2008. Impact of pesticides used in agriculture and vineyards to surface and groundwater quality

(North Spain). Water Res. 42 (13), 3315–3326. https://doi.org/10.1016/j.watres.2008.04.009.
Hong, M., Yang, X., Zhang, X., Ji, Y., Zhou, L., Xiu, G., Ni, Z., Richard, C., 2021. Aqueous photodegradation of the benzophenone fungicide metrafenone: Carbon-Bromine bond cleavage mechanism. Water Res. 206, 117775. https://doi.org/10.1016/j.watres.2021.117775.
Ikehata, K., Gamal El-Din, M., 2005. Aqueous pesticide degradation by ozonation and Ozone-Based advanced oxidation processes: a review (Part II). Ozone Sci. Eng. 27 (3), 173–202. https://doi.org/10.1080/01919510590945732.
ISO, D. 11348-3 (2007) Water Quality—Determination of the Inhibitory Effect of Water Samples on the Light Emission of Vibrio Fischeri (Luminescent Bacteria Test)—Part 3: Method Using Freeze-Dried Bacteria. International Organization for Standardization 2007.
Laranjeiro, F., Rotander, A., López-Ibáñez, S., Vilas, A., Södergren Seilitz, F., Clérandeau, C., Sampalo, M., Rial, D., Bellas, J., Cachot, J., Almeda, R., Beiras, R., 2024. Comparative assessment of the acute toxicity of commercial Bio-Based polymer leachates on marine plankton. Sci. Total Environ. 946, 174403. https://doi.org/10.1016/j.scitotenv.2024.174403.
Lashuk, B., Yargeau, V., 2021. A review of ecotoxicity reduction in contaminated waters by heterogeneous photocatalytic ozonation. Sci. Total Environ. 787, 147645. https://doi.org/10.1016/j.scitotenv.2021.147645.
Lassalle, Y., Kinani, A., Rifai, A., Souissi, Y., Clavaguera, C., Bourcier, S., Jaber, F., Bouchonnet, S., 2014. UV-Visible degradation of boscalid - structural characterization of photoproducts and potential toxicity using *in silico* tests: UV-Visible degradation of boscalid. Rapid Commun. Mass Spectrom. 28 (10), 1153–1163. https://doi.org/10.1002/rcm.6880.
Man, Y., Stenrød, M., Wu, C., Almvik, M., Holten, R., Clarke, J.L., Yuan, S., Wu, X., Xu, J., Dong, F., Zheng, Y., Liu, X., 2021. Degradation of difenoconazole in water and soil: kinetics, degradation pathways, transformation products identification and ecotoxicity assessment. J. Hazard. Mater. 418, 126303. https://doi.org/10.1016/j.jhazmat.2021.126303.
Manjarres-López, D.P., Andrades, M.S., Sánchez-González, S., Rodríguez-Cruz, M.S., Sánchez-Martín, M.J., Herrero-Hernández, E., 2021. Assessment of pesticide residues in waters and soils of a vineyard region and its temporal evolution. Environ. Pollut. 284, 117463. https://doi.org/10.1016/j.envpol.2021.117463.
Martínez-López, S., Lucas-Abellán, C., Serrano-Martínez, A., Mercader-Ros, M.T., Cuartero, N., Navarro, P., Pérez, S., Gabaldón, J.A., Gómez-López, V.M., 2019. Pulsed light for a cleaner dyeing industry: azo dye degradation by an advanced oxidation process driven by pulsed light. J. Clean. Prod. 217, 757–766. https://doi.org/10.1016/j.jclepro.2019.01.230.
Massot, A., Estève, K., Noilet, P., Méoule, C., Poupot, C., Mietton-Peuchot, M., 2012. Biodegradation of phytosanitary products in biological wastewater treatment. Water Res. 46 (6), 1785–1792. https://doi.org/10.1016/j.watres.2011.12.055.
OECD Guidelines for the Testing of Chemicals. 2011.
Pose-Juan, E., Sánchez-Martín, M.J., Andrades, M.S., Rodríguez-Cruz, M.S., Herrero-Hernández, E., 2015. Pesticide residues in vineyard soils from Spain: spatial and temporal distributions. Sci. Total Environ. 514, 351–358. https://doi.org/10.1016/j.scitotenv.2015.01.076.
Schaefer, R., Grapperhaus, M., Schaefer, I., Linden, K., 2007. Pulsed UV lamp performance and comparison with UV Mercury lamps. J. Environ. Eng. Sci. 6 (3), 303–310. https://doi.org/10.1139/s06-068.
Sinclair, C.J., Boxall, A.B.A., 2009. Ecotoxicity of transformation products. In *transformation products of synthetic chemicals in the environment*. In: Boxall, A.B.A. (Ed.), The Handbook of Environmental Chemistry, 2P. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 177–204. https://doi.org/10.1007/698_2_019.
Skanes, B., Ho, J., Warriner, K., Prosser, R.S., 2021. Degradation of boscalid, pyraclostrobin, fenbuconazole, and glyphosate residues by an advanced oxidative process utilizing ultraviolet light and hydrogen peroxide. J. Photochem. Photobiol. A Chem. 418, 113382. https://doi.org/10.1016/j.jphotochem.2021.113382.
Stamatis, N., Antonopoulou, M., Konstantinou, I., 2015. Photocatalytic degradation kinetics and mechanisms of fungicide tebuconazole in aqueous TiO2 suspensions. Catal. Today 252, 93–99. https://doi.org/10.1016/j.cattod.2014.09.023.
United Nations, 2022. World Population Prospects 2022: Summary of Results; Statistical Papers - United Nations (Ser. A), population and vital statistics report. United Nations. https://doi.org/10.18356/9789210014380.
Varma, K.S., Tayade, R.J., Shah, K.J., Joshi, P.A., Shukla, A.D., Gandhi, V.G., 2020. Photocatalytic degradation of pharmaceutical and pesticide compounds (PPCs) using doped TiO2 nanomaterials: a review. WaterEnergy Nexus 3, 46–61. https://doi.org/10.1016/j.wen.2020.03.008.
Wekhof, A., 2000. Disinfection with flash lamps. PDA J. Pharm. Sci. Technol. 54 (3), 264–276.
World Health Organization, 2019. Food and Agriculture Organization of the United Nations. Pesticide Residues in Food: 2018: Toxicological Evaluations / Joint Meeting of the Fao Panel of Experts on Pesticide Residues in Food and the Environment and the Who Core Assessment Group on Pesticide Residues, Berlin, Germany, 18–27 September 2018. World Health Organization: Geneva.
Zhu, Y., Zheng, Y., Jiao, B., Zuo, H., Dong, F., Wu, X., Pan, X., Xu, J., 2022. Photodegradation of enestroburin in water by simulated sunlight irradiation: kinetics, isomerization, transformation products identification and toxicity assessment. Sci. Total Environ. 849, 157725. https://doi.org/10.1016/j.scitotenv.2022.157725.