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Interdisciplinary curriculum reform in toxicology and environmental health education: a case study from the University of Alcalá.

Reforma curricular interdisciplinar en la educación en toxicología y salud ambiental: un estudio de caso de la Universidad de Alcalá.

Antonio Peña-Fernández [1*,2].

[1] Department of Surgery, Medical and Social Sciences, Faculty of Medicine and Health Sciences, University of Alcalá, Ctra. Madrid-Barcelona, Km. 33.600, 28805 Alcalá de Henares, Spain. https://orcid.org/0000-0002-5690-5445

[2] Leicester School of Allied Health Sciences, De Montfort University, Leicester, LE1 9BH, UK.

* Correspondencia: Antonio.penafer@uah.es

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Abstract.

Toxicology plays a critical role in safeguarding public health and the environment, yet its visibility and integration within higher education curricula in Europe have declined over recent decades. At the University of Alcalá (UAH, Spain), a comprehensive strategy has been developed to revitalise toxicology education through curriculum integration, experiential learning, and pedagogical innovation. This review presents a detailed analysis of undergraduate and postgraduate toxicology training at UAH, highlighting its alignment with evolving European Union policies such as the Green Deal and the Chemicals Strategy for Sustainability. Key initiatives include interdisciplinary CBRN (chemical, biological, radiological, and nuclear) preparedness courses, pre-university toxicology rotations, gamified tools like *ToxiGame*©, and high-fidelity forensic simulations. These interventions aim to address educational gaps in risk assessment, regulatory toxicology, and emergency preparedness, while enhancing student engagement and employability. The UAH model demonstrates how toxicology can be effectively embedded into diverse programmes, including Pharmacy, Environmental Sciences, Criminalistics, and Medicine, in a manner that is scalable, policy-relevant, and responsive to emerging health threats. This work contributes to international efforts to modernise toxicology education and may serve as a blueprint for institutions aiming to strengthen workforce readiness in CBRN safety and environmental health.

Keywords: Toxicology education, environmental health, CBRN preparedness, curriculum innovation, University of Alcalá, gamification.

Resumen.

La toxicología desempeña un papel fundamental en la protección de la salud pública y del medio ambiente, pero su visibilidad e integración en los planes de estudio de la educación superior en Europa han disminuido en las últimas décadas. En la Universidad de Alcalá (UAH, España) se ha desarrollado una estrategia integral para revitalizar la enseñanza de la toxicología mediante la integración curricular, el aprendizaje experiencial y la innovación pedagógica. Esta revisión presenta un análisis detallado de la formación en toxicología de grado y posgrado en la UAH, destacando su alineación con las políticas de la Unión Europea en evolución, como el Pacto Verde y la Estrategia de Sostenibilidad para las Sustancias Químicas. Las principales iniciativas incluyen cursos interdisciplinares de preparación NRBQ (amenazas químicas, biológicas, radiológicas y nucleares),

rotaciones preuniversitarias en toxicología, herramientas gamificadas como *ToxiGame*© y simulaciones forenses de alta fidelidad. Estas intervenciones tienen como objetivo abordar lagunas formativas en evaluación de riesgos, toxicología reguladora y preparación ante emergencias, al tiempo que potencian la implicación del estudiantado y su empleabilidad. El modelo de la UAH demuestra cómo la toxicología puede integrarse de forma eficaz en titulaciones diversas, como Farmacia, Ciencias Ambientales, Criminalística y Medicina, de un modo escalable, relevante para las políticas y sensible a las amenazas emergentes para la salud. Este trabajo contribuye a los esfuerzos internacionales por modernizar la educación en toxicología y puede servir de modelo para las instituciones que deseen reforzar la preparación de su personal futuro en seguridad NRBQ y salud ambiental.

Palabras clave: educación en toxicología, salud ambiental, preparación NRBQ, innovación curricular, Universidad de Alcalá, gamificación.

1. Introduction

Toxicology plays a fundamental role in protecting public health, ensuring environmental safety, and informing regulatory decision-making. In recent years, there has been growing recognition at both European and international levels of the urgent need to modernise toxicology education to address evolving challenges. These include novel types of exposures, increasingly interdisciplinary threats, and rising demands for improved risk communication and emergency preparedness. Recent global crises—such as the COVID-19 pandemic and the war in Ukraine—have further highlighted the strategic importance of toxicology in emergency response and public health planning (1-2). At the same time, emerging scientific developments in artificial intelligence, predictive toxicology, the exposome, and big data analytics are reshaping the skill sets required in the toxicology workforce (3-4).

To respond to these demands, toxicology education must evolve to address complex public health and environmental challenges, including those associated with chemical incidents, emerging pollutants, and industrial exposures. European policy frameworks such as the Chemicals Strategy for Sustainability and the European Green Deal underscore the need to integrate sustainability, One Health thinking, and risk-based decision-making into toxicology curricula (5-6). In parallel, international initiatives call for embedding interdisciplinary and practice-oriented toxicology training within university programmes (7).

Despite these policy drivers, toxicology has experienced a progressive erosion in curricular visibility and credit allocation across many European universities—particularly at the undergraduate level. The implementation of the European Higher Education Area (EHEA) has led to structural curricular reforms that often embedded toxicology within broader modules, such as pharmacology or general biosciences, diluting its disciplinary identity and limiting student exposure to applied toxicology and regulatory principles (8-10). This fragmentation has restricted understanding of toxicology's core contributions to environmental health and chemical safety, even as demand for trained professionals continues to rise.

Standalone courses in environmental and regulatory toxicology remain scarce at the undergraduate level, and critical domains such as exposure science are underrepresented in formal education. Connolly (11) notes that no undergraduate programmes dedicated to exposure science currently exist in Europe. A recent survey also identified significant gaps in toxicological competencies across professional contexts—particularly in exposure interpretation, probabilistic analysis, and the application of New Approach Methodologies (NAMs)—highlighting widespread deficits in professional preparedness (12). Digital learning platforms have emerged as promising

tools to address these gaps by delivering structured, hands-on training in toxicokinetics, chemical mixture assessment, and read-across approaches (13).

At the regulatory level, the European Commission and the European Chemicals Agency (ECHA) continue to support the implementation of NAMs—including in vitro assays, in silico tools, high-throughput screening, organ-on-a-chip systems, and omics-based platforms—as part of a broader effort to reduce reliance on animal testing (14). Nevertheless, practical adoption of these methods under the REACH regulation (Registration, Evaluation, Authorisation and Restriction of Chemicals; 15) remains limited. Chemical safety dossiers submitted under REACH still rely heavily on animal-based studies, especially for complex endpoints such as repeated-dose or developmental toxicity (16). Although the legislation places the burden of proof on industry and includes provisions to encourage alternative testing strategies, the uptake of NAMs has been hampered by regulatory conservatism, entrenched testing paradigms, and practical implementation barriers (17-18).

In light of these challenges, universities are increasingly encouraged to design curricula that promote interdisciplinary, practice-oriented toxicology training with real-world applications. Key policy documents and academic reviews emphasise the importance of student-centred pedagogies, digital platforms, and the integration of real exposure scenarios into teaching (19-20). The University of Alcalá (UAH, Spain), a historic public university founded in 1499 and located near Madrid, is widely recognised for its strong commitment to interdisciplinary education and public health research. In response to recent educational and regulatory calls, UAH has embedded toxicology into a wide range of degree programmes and developed innovative teaching tools that emphasise practical skill-building, interprofessional collaboration, and societal relevance. With over 28,000 students enrolled across diverse disciplines—including health sciences, environmental sciences, law, and education—UAH ranks among Spain's leading academic institutions in the biomedical and environmental fields. Its strategic focus on interdisciplinary collaboration and applied research has created a fertile ground for curriculum innovation, particularly in toxicology, exposure science, and chemical risk preparedness (21-22).

This manuscript contributes to the expanding literature on toxicology education reform by presenting a detailed case study from UAH. It outlines how the institution is advancing toxicology training through interdisciplinary integration, pedagogical innovation, and alignment with key public health, environmental, and regulatory frameworks. These efforts may serve as a model for other institutions seeking to revitalise toxicology education and strengthen professional preparedness for 21st-century challenges.

2. Toxicology education at the University of Alcalá

Toxicology education at the UAH has traditionally spanned multiple faculties and programmes, including Pharmacy, Environmental Sciences and Medicine. However, the introduction of the Bologna Process and the EHEA brought about considerable changes in curriculum structure and credit distribution, often resulting in a reduction of contact hours and a loss of independent visibility for toxicology as a discipline (23). Given these shifts, a detailed review of how toxicology is currently embedded across UAH's undergraduate and postgraduate offerings is both timely and necessary.

Currently, toxicology is formally included in several undergraduate programmes at the UAH, particularly within the health sciences and environmental fields (24). Within the health-related degrees, toxicology is taught as a standalone compulsory module in the fourth year of the MPharm Pharmacy programme (Grado en Farmacia), and it is integrated within a broader medico-legal module in the fourth year of the Medicine MBChB programme (Grado en Medicina). Although clinical and forensic toxicology are addressed in Medicine, there is limited emphasis on environmental or regulatory toxicology.

In the environmental sciences domain, toxicology is delivered as a compulsory second-year subject in the BSc in Environmental Sciences (Grado en Ciencias Ambientales), with a strong focus on ecotoxicology, chemical risk assessment, and public health. Additionally, in the BSc in Criminalistics: Sciences and Forensic Technologies (Grado en Criminalística: Ciencias y Tecnologías Forenses), toxicology is offered as a dedicated module titled Forensic Toxicology, which provides students with structured training in the toxicological analysis of substances, forensic detection methods, and their application in legal and criminological investigations. By contrast, toxicology is not currently offered as a formal subject in other science programmes such as the BSc in Biology or the BSc in Chemistry, where relevant content may appear only marginally through electives or individual research projects.

This fragmented and discipline-specific integration reflects a broader trend across European higher education, which increasingly prioritises multidisciplinary and competency-based learning. However, such integration has also contributed to a decline in toxicology's visibility as a distinct academic discipline—potentially limiting students' awareness of its scientific breadth and applied relevance in areas such as chemical risk governance, One Health, and environmental sustainability.

To reduce fragmentation across programmes, UAH could adopt a core set of toxicology competencies and a spiral curriculum approach, mapped to common learning outcomes in hazard identification, exposure assessment, risk characterisation and risk communication. This would enable aligned teaching and assessment across Medicine, Pharmacy, Environmental Sciences and Criminalistics, while allowing discipline-specific depth (*e.g.*, clinical management in Medicine, regulatory risk governance in Pharmacy, ecotoxicology in Environmental Sciences and medico-legal interpretation in Criminalistics). A pragmatic first step would be a cross-programme curriculum map and shared assessment blueprint for these core competencies, supported by common digital resources and standardised rubrics.

2.1. MPharm Pharmacy

In Pharmacy, toxicology is delivered as a stand-alone compulsory fourth year 6-credit module (4.5 theoretical and 1.5 practical), named *Toxicology* (25). Coordinated by the Department of Biomedical Sciences, this course offers one of the most comprehensive undergraduate toxicology programmes at UAH. The curriculum places particular emphasis on the toxicology of pharmaceutical compounds, alongside occupational and environmental exposures, and the fundamentals of human health risk assessment. These include the interpretation of dose–response relationships, threshold-based toxicological endpoints, and exposure metrics, as well as legal and ethical considerations relevant to clinical, regulatory, and industrial contexts. The integration of legal and ethical considerations in this course aligns with evolving EU expectations for pharmacists to manage pharmaceutical and environmental risks in line with REACH and European Medicines Agency (EMA) standards.

A significant portion of the course is dedicated to practical training (1.5 ECTS), during which students gain hands-on experience with laboratory techniques used in toxicological analysis. These practicals involve the use of diagnostic and analytical tools for the identification and quantification of toxic substances, simulation of intoxication scenarios, and interpretation of toxicological data and case studies. This applied component is designed to prepare students for professional roles in pharmacovigilance, drug development, environmental monitoring, and public health.

Toxicological principles are also explored within the optional 5th year module *Environmental Health* (6 ECTS; 25), which addresses chemical risk factors such as hazardous compounds, pesticides, endocrine disruptors, and their effects on human health. The course includes applied training in biomonitoring, environmental exposure assessment, and public health surveillance, thus reinforcing key toxicology competencies in the context of environmental and pharmaceutical safety.

2.2. Medicine MBChB

In Medicine, toxicology is included as part of a broader fourth-year compulsory module titled Legal Medicine, Deontology and Medical Legislation (9 ECTS), which is coordinated by the Department of Legal and Forensic Medicine (UAH, 26). Within this module, toxicology is primarily addressed from a clinical and forensic perspective, offering future physicians essential training in the recognition, management, and medico-legal implications of poisoning and substance-related harm.

The toxicology content includes topics such as the classification of toxic agents, mechanisms of acute and chronic toxicity, and medical response to intoxications, with a particular focus on drugs of abuse, alcohol, pharmaceuticals, and household and industrial chemicals. Students are also introduced to forensic toxicological procedures, including the interpretation of toxicology reports and their role in legal investigations.

While the module effectively underscores the relevance of toxicology in medical and forensic practice, it offers limited coverage of environmental, occupational, or regulatory toxicology, areas that are increasingly critical for modern medical curricula. Despite these limitations, the inclusion of toxicology within this core module reinforces the importance of the discipline in medico-legal education and provides students with essential competencies for interpreting toxicological findings in forensic and clinical settings. It also lays the foundation for interdisciplinary collaboration between medical professionals, forensic scientists, and public health practitioners.

However, there is clear scope for curricular enhancement to better reflect the toxicological challenges faced by modern medical practice. Current European and national frameworks, including Orden ECI/332/2008 (27), highlight the need for physicians to be trained in the identification, prevention and clinical management of environmental and chemical health hazards. Moreover, recent European policy developments such as the European Green Deal and the EU Chemicals Strategy for Sustainability increasingly emphasise the importance of healthcare professionals in recognising and responding to the health impacts of pollution, endocrine-disrupting chemicals, persistent contaminants and other environmental exposures (5, 28). This could be strengthened further by introducing core concepts in regulatory toxicology and human health risk assessment, including practical training in risk characterisation and risk communication.

As the burden of chronic diseases associated with environmental and chemical exposures continues to rise, including conditions such as developmental neurotoxicity, endocrine disruption, and metabolic or reproductive disorders (29-30), it becomes increasingly important for medical practitioners to expand their focus beyond the management of acute intoxications. Physicians should be equipped to recognise, evaluate, and manage the long-term health consequences of low-dose, cumulative, and chronic exposures. Strengthening toxicology education within medical curricula—particularly in areas such as environmental health, differential diagnosis, and public health—would enhance clinical reasoning, support accurate patient management, and foster competencies relevant to preventive medicine, occupational health, and risk communication. Improved training in these domains would better prepare future clinicians to address emerging chemical risks and to incorporate toxicological evidence into patient care and public health practice.

Although the word "toxicology" does not explicitly appear in the module titles, relevant content is included within Preventive Medicine and Public Health, taught in the fifth year of the MBChB programme (6 ECTS; 26). Within its block on environmental and occupational health, students are introduced to key principles of exposure prevention, food safety, and environmental risk management. Although toxicology is not explicitly named, the course aligns with essential toxicological competencies such as environmental health, occupational health, and prevention and protection against diseases and injuries. These topics reinforce toxicological literacy in the context of

public health, preparing students to recognise and respond to health risks associated with environmental and chemical exposures, even though content related to regulatory or mechanistic toxicology remains underdeveloped.

2.3. BSc in Environmental Sciences

Toxicology is explicitly integrated into the Environmental Sciences programme through a combination of core and elective subjects. The most prominent is the compulsory second-year module Environmental Toxicology and Public Health (6 ECTS), delivered during the second semester (UAH, 31). This course provides foundational training in toxicokinetics, toxicodynamics, and the classification of toxic substances relevant to ecosystems and human health. It introduces students to toxicological mechanisms of action for contaminants such as metals, pesticides, persistent organic pollutants, and endocrine-disrupting chemicals, as well as concepts in human and ecological risk assessment. Practical sessions involve basic ecotoxicological assays, case studies on chemical exposures, and the application of risk evaluation tools used in environmental decision-making and public health surveillance.

Additional toxicology-related instruction is provided through two third-year core modules. The first, Atmospheric Pollution (6 ECTS), introduces students to airborne chemical contaminants, their environmental transformation processes, transport mechanisms, and health effects. Students gain familiarity with pollutant sampling and analytical techniques, air quality indices, and emission control technologies, supported by a strong regulatory and public health framework. The second module, Environmental Impact Assessment (6 ECTS), covers methodologies for identifying, characterising, and mitigating the environmental and health impacts of anthropogenic activities. While more interdisciplinary in scope, the course reinforces toxicological principles by training students to evaluate the human health implications of environmental disturbances and pollutant emissions, using predictive tools and case-based learning.

Finally, in the fourth year, students can choose an elective module titled Analysis of Environmental Chemical Contaminants (6 ECTS), within the "Environmental Technology for Sustainability" pathway. This course offers advanced training in instrumental analytical techniques (*e.g.*, AAS, ICP, UV-Vis, HPLC, GC) for the detection and quantification of organic and inorganic environmental toxicants. The curriculum bridges analytical chemistry with applied toxicology, focusing on the preparation, validation, and interpretation of environmental samples from air, water, and soil.

Taken together, these modules provide students of Environmental Sciences at UAH with one of the most comprehensive undergraduate toxicology learning experiences currently available at the institution. They equip graduates with the theoretical and practical competencies necessary to work in chemical risk management, pollution control, regulatory toxicology, and environmental consultancy, while supporting interdisciplinary engagement with public health and sustainability agendas.

2.4. BSc in Criminalistics: Sciences and Forensic Technologies

In Criminalistics, toxicology is strategically embedded through a structured sequence of core and elective modules. The most prominent is the dedicated third-year compulsory subject *Forensic Toxicology* (6 ECTS), which is complemented by toxicology-relevant content in Forensic Chemistry, Forensic Instrumental Analysis, Legal and Forensic Medicine, and the elective module Environmental Criminalistics (UAH, 32). Together, these modules provide a comprehensive and applied overview of toxicology in both human forensic investigation and environmental crime analysis.

Across the first and second years, toxicology is progressively introduced through *Forensic Chemistry* and *Forensic Instrumental Analysis*, providing foundational knowledge of biological matrices, analytical techniques, and interpretation of toxicological evidence.

In the third year, students undertake the compulsory *Forensic Toxicology* module (6 ECTS), which builds upon the foundational knowledge acquired earlier. The curriculum addresses the classification of toxic agents, toxicokinetics and toxicodynamics, exposure pathways, and the instrumental detection of xenobiotics in biological matrices. Focus is placed on common forensic toxicants, including pesticides, pharmaceuticals, illicit substances, and household or occupational poisons. Students are trained in interpreting analytical results and preparing legal-toxicological reports, with a strong emphasis on the ethical responsibilities of toxicology experts.

In parallel, the *Legal and Forensic Medicine* module (6 ECTS) consolidates the medico-legal foundations that support toxicological practice. Although broader in scope, this subject reinforces core forensic competencies such as the interpretation of forensic autopsies, diagnosis of toxic lesions, and the determination of cause of death in suspected poisoning cases.

In the fourth year, students can also choose *Environmental Criminalistics*, an elective 6 ECTS module, extending the application of toxicology to environmental offences. This module covers pollution forensics, monitoring of chemical contaminants, biomonitoring protocols, and the legal prosecution of environmental crimes. Students develop competencies in ecotoxicological interpretation and forensic environmental sampling.

Collectively, these modules ensure that graduates of the Criminalistics programme develop both theoretical foundations and practical skills in forensic and environmental toxicology. The curriculum reflects a strong commitment to interdisciplinary training, preparing students for careers in forensic laboratories, public health services, and criminal justice systems, where toxicological knowledge is increasingly indispensable.

Although both programmes offer approximately 18 ECTS in toxicology-relevant content, only the BSc in Criminalistics includes a dedicated compulsory subject in *Legal and Forensic Medicine*, whereas toxicology in Environmental Sciences is distributed across broader modules, reducing its curricular visibility. A comparative overview of toxicology teaching across UAH undergraduate degrees is provided in Table 1.

2.5. BSc in Human Nutrition and Dietetics

The Human Nutrition and Dietetics programme was initially delivered through an affiliated centre and has progressively transitioned to full integration within the University of Alcalá. From the 2025–2026 academic year, the programme is offered directly by the Faculty of Health Sciences at UAH (33–36).

Within its curriculum, toxicology is addressed through two compulsory modules that highlight the intersection of nutrition, food safety, and chemical risk. In the second year, students undertake the 6 ECTS course *Food Toxicology*, which introduces toxicokinetics, toxicodynamics, and the presence of toxic agents, such as contaminants, residues, biotoxins, and additives, in the food chain. The course includes practical components and case-based learning on acute and chronic foodborne toxic effects, endocrine disruptors, and regulatory thresholds. In the third year, the 6 ECTS module Food Hygiene and Safety expands on hazard analysis and critical control points (HACCP), legislation, microbiological and chemical food risks, and the toxicological impact of contaminants, with references to parasitology and exposure pathways. Together, these modules contribute significantly

to the toxicological literacy of future dietitians and nutritionists, preparing them to navigate complex regulatory environments and participate in multidisciplinary food safety efforts.

2.6. Postgraduate Education in Toxicology at UAH

Toxicology is also addressed at postgraduate level at the UAH through a combination of official and university-specific programmes, reflecting the evolving demand for toxicological expertise across pharmaceutical, environmental, and forensic sectors.

2.6.1. Doctoral-level toxicology research at UAH

Toxicology is recognised as a strategic and interdisciplinary research area across several programmes, most notably the Doctoral Programme in Health Sciences (UAH, 37), the Doctoral Programme in Forensic Sciences (UAH, 38), and the Doctoral Programme in Medicinal Chemistry (UAH, 39). These programmes support doctoral research across a wide range of toxicologically relevant fields.

The Doctoral Programme in Health Sciences fosters research in pharmaceutical safety, environmental toxicology, biomonitoring of trace elements, toxicological modelling, and exposure assessment in vulnerable populations, with many projects developed in coordination with public health and regulatory agencies. The programme places emphasis on interdisciplinary training, with students engaging in advanced techniques in toxicokinetics, biomarker interpretation, and data integration for risk assessment.

The Doctoral Programme in Forensic Sciences incorporates toxicology through lines of research such as post-mortem toxicological analysis, drug-facilitated crimes, CBRN (chemical, biological, radiological and nuclear) incident preparedness, and analytical validation of forensic toxicology methods. This programme often collaborates with legal medicine departments and forensic institutes, reinforcing the integration of toxicology into judicial and medico-legal contexts.

Meanwhile, the Doctoral Programme in Medicinal Chemistry allows for research in toxicological evaluation of new chemical entities, design and screening of bioactive molecules with reduced toxicity, mechanistic toxicology, and in silico and in vitro predictive safety profiling. These studies align with EU regulatory priorities for safer-by-design pharmaceuticals and the development of alternatives to animal testing.

Compared to leading international doctoral programmes in toxicology, UAH's offerings align well in their research breadth but currently lack formalised coursework and structured exposure to regulatory or industrial settings. For example, doctoral training at Utrecht University (Netherlands) emphasises a triad of exposure science, mechanistic toxicology, and environmental epidemiology, offering a structured curriculum and close links with risk governance institutions (40). Similarly, the University of Porto (Portugal) offers a PhD in Environmental Toxicology and Contamination with a strong focus on pollutant toxicodynamics, exposure modelling, and remediation (41). In Spain, the University of Valencia coordinates a doctoral programme in Pollution, Toxicology and Environmental Health that integrates exposure characterisation, public health protection, and environmental contamination (42). While UAH's doctoral programmes incorporate research in pharmaceutical safety, forensic toxicology, and human biomonitoring, there is a clear opportunity to embed formal training in regulatory toxicology, strengthen connections to risk agencies, and enhance international visibility through structured interdisciplinary tracks, in line with evolving global standards in doctoral toxicology education.

2.6.2 Toxicology in official and university-specific Master's programmes

Toxicology content at the postgraduate level at the UAH is delivered across a variety of official and university-specific Master's programmes, reflecting the interdisciplinary application of toxicological knowledge in pharmaceutical, forensic, industrial, environmental, and public safety contexts.

Among the official Master's programmes, the Master's in Police Sciences integrates toxicology-relevant modules in forensic investigation, analytical chemistry, and exposure science (43). The programme is coordinated by the University Institute of Police Science Research (IUICP) and is delivered in collaboration with national institutions such as the INTCF and the Guardia Civil's Criminalistics Service, providing practical training in the identification and analysis of toxic substances in forensic contexts.

The Master's in Operational Military Health, which is jointly coordinated with the Centro Universitario de la Defensa, also incorporates toxicology-related competencies. These include preparedness for chemical threats, pharmaceutical risk management, and environmental health in military and crisis scenarios, particularly within the pharmacy and veterinary medicine specialisations (44).

Among the university-specific (non-official) programmes, the Master's in Industrial and Galenic Pharmacy includes toxicology teaching within modules focused on environmental and occupational exposures, pharmaceutical safety, and the evaluation of active pharmaceutical ingredients (APIs), excipients, and manufacturing by-products. The curriculum aligns with key regulatory frameworks, such as the REACH Regulation, ICH guidelines, and standards from the EMA, providing future industrial pharmacists with skills relevant to product safety and compliance (45).

The Master's Degree in Brewing Science and Technology, developed in partnership with the Spanish Association of Beer and Malt Technicians, includes applied toxicology content in food safety, occupational risk, and environmental impact monitoring. The programme prepares students for roles in quality assurance, regulatory oversight, and sustainable production within the brewing sector (46).

Despite the presence of toxicology content across these postgraduate pathways, instruction remains fragmented and largely integrated into broader disciplinary modules. There is currently no standalone toxicology Master's degree at UAH, highlighting a strategic opportunity to develop dedicated postgraduate training in areas such as regulatory toxicology, human biomonitoring, chemical risk assessment, and new approach methodologies (NAMs). These gaps contrast with emerging educational standards in Spain and across Europe, where toxicology education is increasingly shaped by regulatory demands, interdisciplinary competencies, and digital innovation. Developing a dedicated postgraduate programme at UAH would respond directly to the growing need for trained professionals in regulatory toxicology, environmental risk assessment, and chemical safety governance—sectors that are undergoing rapid transformation under the EU's Green Deal, Chemicals Strategy for Sustainability, and the implementation of safe-and-sustainable-by-design (SSbD) principles (5-7).

Table 1. Analysis of toxicology content in undergraduate degrees at the University of Alcalá (UAH).

Programme	Module	ECTS	Year	Type	Toxicology Content
MPharm Pharmacy	Toxicology	6	4th	Compulsory	General and specific toxicology, pharmaceuticals, environmental exposure, risk assessment, practical lab
Medicine (MBChB)	Legal Medicine, Deontology and Medical Legislation	9	4th	Compulsory	Clinical and forensic toxicology, intoxications, medico-legal aspects
	Preventive Medicine and Public Health	6	5th	Compulsory	Environmental health, occupational risks, food safety
BSc Environmental Sciences	Environmental Toxicology and Public Health	6	2nd	Compulsory	Toxicokinetics, contaminants, ecotoxicology, public health impact
	Atmospheric Pollution	6	3rd	Compulsory	Airborne contaminants, exposure, health effects
	Environmental Impact Assessment	6	3rd	Compulsory	Health impacts of anthropogenic activities, chemical hazards
	Analysis of Environmental Chemical Contaminants	6	4th	Elective	Instrumental analysis of pollutants, applied toxicology
BSc Criminalistics: Sciences and Forensic Technologies	Forensic Chemistry	6	1st	Compulsory	Detection of toxic substances, biological matrices, forensic interpretation
	Forensic Instrumental Analysis	6	2nd	Compulsory	GC-MS, LC-MS, real case studies, toxicological reporting
	Forensic Toxicology	6	3rd	Compulsory	Xenobiotics, postmortem toxicology, expert witness training
	Legal and Forensic Medicine	6	3rd	Compulsory	Autopsies, poisoning diagnosis, medico-legal implications
	Environmental Criminalistics	6	4th	Elective	Environmental contamination, ecotoxicological indicators, forensic sampling

3. Towards the future: curriculum innovation and strategic recommendations.

In response to the need to revitalise toxicology education is increasingly recognised across Europe, UAH has undertaken a suite of pedagogical innovations aimed at enhancing engagement, interdisciplinarity, and real-world preparedness in toxicology education, in line with the European Chemicals Strategy for Sustainability and broader frameworks such as One Health, CBRN preparedness, and digital education (5, 7, 19).

Against this backdrop, our international innovation group, jointly established between the UAH and De Montfort University (DMU, United Kingdom, UK), has been developing a series of pioneering strategies since the 2012/2013 academic year to strengthen toxicology education from an interdisciplinary and applied perspective. Key initiatives include: a) the design of a course focused on responding to CBRN incidents, in collaboration with the UK Health Security Agency (UKHSA) (47-48); and b) the creation of a comprehensive virtual platform named e-Pathogens© (49), conceived as an open-access resource to support training in biological incident response, toxicological emergencies, and medical preparedness and capacity building for such events.

Since 2023, these initiatives have been coordinated by the interdisciplinary teaching innovation group Responding to Chemical, Biological, Radiological and Nuclear Incidents (CBRNtraining), now based at the UAH. Originally established as a collaborative effort between UAH and DMU, the group has progressively consolidated its leadership and core activities within UAH, reflecting both the institutional relocation of its principal investigator and the increasing allocation of funding from UAH internal innovation programmes. Supported by strategic collaboration with DMU and other international partners, the group has implemented a range of pedagogical innovations and curriculum developments aimed at modernising toxicology education. The key actions undertaken are summarised in the sections that follow.

3.1. Experiential learning: pre-university toxicology rotations.

In line with current EU initiatives to foster early interest in STEM disciplines and strengthen foundational competencies in public and environmental health (5,50), we developed and implemented an innovative pre-university rotation in toxicology in 2024/25. Developed within the framework of the *4ºESO+Empresa* initiative—a regional educational programme in the Madrid Region aimed at fostering early career exploration among secondary school students (51)—this three-day immersive experience provides participants aged 15–16 with hands-on exposure to toxicology and environmental health practices within the Faculties of Medicine and Health Sciences and Pharmacy. The programme was coordinated by academic staff from the Department of Biomedical Sciences (area of Pharmacy and Pharmaceutical Technology) and the Department of Surgery, Medical and Social Sciences (areas of Human Anatomy and Embryology, and Legal and Forensic Medicine), offering a multidisciplinary learning experience that integrates toxicology, public health, pharmacology, and human anatomy.

4ºESO+Empresa broadly aligns with Key Stage 4 work experience and work-shadowing schemes in the UK (52) and with comparable work-based learning and career-orientation programmes implemented across many European education systems (53-54). These initiatives typically involve short, structured observational placements undertaken by lower secondary pupils (generally aged 15–16 years) within host organisations, with the primary aim of supporting informed educational and career decision-making rather than providing vocational training or formal employment. In line with international practice, such placements emphasise exposure to real-world professional environments, observation of day-to-day activities, and supervised engagement with workplace routines, while remaining embedded within the school curriculum and safeguarding frameworks. Similar models are widely recognised as effective mechanisms for early career awareness,

contextualisation of academic learning, and the development of transversal skills, and they constitute a well-established component of secondary education pathways in the UK and across Europe.

Students participated in hands-on workshops designed to introduce key biomedical and toxicological concepts through interdisciplinary, scenario-based activities. These sessions were structured to simulate real-world challenges and emphasised the application of toxicological reasoning in public health and clinical contexts. Among the various components of the rotation, the most relevant for toxicology were the case-based learning modules focused on chemical exposure scenarios and emergency response frameworks, which enabled students to explore the impact of contaminants on human health. Additionally, interactive seminars on risk prevention strategies and the broader societal role of toxicology helped reinforce the discipline's relevance to both individual and community-level health protection. These activities were designed to foster early engagement with scientific thinking and to promote toxicology as a dynamic and socially impactful field.

Activities were delivered under the official regional programme and followed institutional safeguarding procedures; no identifiable research data were collected as part of routine delivery. Preliminary informal evaluation, based on verbal feedback and the outcomes of the various learning activities, suggests that students notably enhanced their understanding of emerging chemical and biological risks, hygiene protocols, and the formulation of pharmaceutical countermeasures. In addition, several participants reported a greater interest in pursuing university-level studies in health, pharmacy, and biomedical sciences. These early findings are consistent with results from comparable educational interventions documented in the literature. Thus, Gairal-Casadó et al. (55) demonstrated that extracurricular science workshops led by academic researchers significantly enhance adolescents' academic motivation and their perception of science as socially relevant. Likewise, Walan and Gericke (56) reported that informal learning activities embedded in structured school–university partnerships foster long-term engagement with STEM subjects.

This rotation also appears to align with European initiatives promoting innovative pedagogies and sustainability competencies, such as those outlined in the European Education Area and the GreenComp framework (57). These frameworks advocate for experiential and challenge-based learning approaches designed to foster environmental awareness, systems thinking, and informed decision-making in younger learners. Although modest in scale, the initiative implemented at UAH may represent a promising model for introducing toxicological concepts earlier in the educational pathway, with the potential to enhance public health literacy, science communication, and interest in STEM-related careers among secondary school students.

3.2. Capacity building in CBRN risk preparedness

In response to increasing societal and regulatory demands for enhanced preparedness against CBRN threats, the foundational short course on chemical and biological (CB) incident response originally developed at UAH (47,48,58) was comprehensively revised and embedded into the curricula of various undergraduate and postgraduate programmes during the 2023/24 and 2024/25 academic years (59). The updated course was designed to reinforce toxicology-related competencies in risk assessment, medical countermeasures, and emergency response planning. It incorporates case-based learning centred on real toxicological incidents—including sulphur mustard exposure, mercury poisoning, and anthrax release—which serve as focal points for class discussions on emergency risk communication, rapid decision-making, and hands-on sessions focused on the development and application of countermeasures. These practical components also address the roles and responsibilities of health professionals during CBRN events (59-60).

Students participating in this course work with official guidance from the UK Health Security Agency (UKHSA), including the UK Recovery Handbooks for Chemical and Biological Incidents and

the Chemical Recovery Record Form (CRRF), which provide practical frameworks for developing science-based response strategies (61-63). The revised teaching model has now been formally integrated into several official UAH degrees, including the MPharm Pharmacy, BSc Environmental Sciences, BSc in Criminalistics: Sciences and Forensic Technologies, and the MSc in Industrial and Galenic Pharmacy. This curricular innovation reflects a growing European trend to incorporate formal disaster education and resilience planning within health science programmes (64).

Building on this foundation, a new summer course titled *Responder y prevenir ataques con agentes químicos, biológicos, radiológicos y nucleares* (QBRN) was launched in July 2025 (65). Co-developed with international experts from the UKHSA and the Spanish Ministry of Defence (CEMILFARDEF), the course was structured around the five core pillars of CBRN response as defined by the European Commission and further operationalised into a competency-based training framework by Djalali et al. (66). It began with situational assessment, where students were trained to recognise CBRN threats and appraise the severity and scope of incidents. The second component, exposure evaluation, focused on triage protocols, principles of toxicokinetics, and the rapid interpretation of clinical and environmental data. Acute medical management formed the third pillar, covering toxicodynamics, the use of antidotes, supportive therapies, and ethical decision-making during emergencies. The fourth element, long-term surveillance and biomonitoring, introduced methodologies for tracking affected populations, detecting delayed health effects, and informing public health responses. Finally, environmental and infrastructural recovery involved evidence-based decontamination strategies, principles of crisis communication, and procedures for restoring essential public services.

Together, these pillars formed an integrated curriculum aimed at building core toxicological and public health competencies essential for effective CBRN preparedness and response. As part of the practical training, students also participated in formulation workshops, where they designed and prepared pharmaceutical countermeasures, including topical antidotes, decontaminant gels, and radiological antidote tablets containing Prussian blue. These sessions were delivered by academic pharmacists from the Department of Pharmacy and Pharmaceutical Technology at the University of Alcalá (60).

The course offered multidisciplinary content spanning toxicology, forensic science, pharmacology, and environmental health. It adopted active learning methodologies, particularly case-based learning (CBL), to foster critical thinking and collaborative problem-solving—skills considered essential for future professionals involved in emergency planning and response. Evidence from health sciences education increasingly supports the use of experiential and problem-centred pedagogies such as CBL, demonstrating their effectiveness in enhancing student engagement, integration of knowledge, and preparedness for real-world challenges (20, 67).

This integrated strategy is fully consistent with current European and international recommendations for embedding disaster preparedness and emergency health competencies into higher education curricula. A recent review of European health emergency training programmes has highlighted the importance of multidisciplinary, simulation-based education in building effective response capacity (64). Similar models, such as Germany's national disaster medicine curriculum for medical students, demonstrate how scalable educational frameworks can enhance preparedness across diverse national contexts (68). By aligning toxicology teaching at UAH with these frameworks, particularly through its expanded CBRN content and summer training course, the institution is contributing to a modernised and more resilient approach to health and environmental education.

Recent international developments reinforce the value of case-based learning for strengthening CBRN preparedness in health and science education. Beyond the use of historical incidents and official response frameworks integrated into our teaching, comparable initiatives have demonstrated

the pedagogical advantages of structured, scenario-driven instruction. For example, the military medical curriculum described by Sardarian and colleagues (69) employs a progressive sequence of chemical, biological, radiological and nuclear exposure cases to train learners in clinical evaluation, triage and operational decision-making within high-uncertainty environments. Their findings highlight how carefully scaffolded case analysis not only consolidates technical competencies but also enhances essential non-technical skills such as communication, prioritisation and coordinated team reasoning. These observations align closely with our experience in the present intervention, supporting the view that guided exposure to complex, realistic CBRN scenarios enables students to integrate toxicological principles more effectively into professional practice and to develop confidence in applying them during simulated emergency response situations.

Although the European policy context is emphasised, preparedness and response to CBRN incidents is a global public health and security priority. The competencies discussed—hazard identification, exposure assessment, risk characterisation and risk communication—are transferable across jurisdictions and align with international One Health and emergency preparedness frameworks. Thus, the design and delivery of the UAH CBRN course are well aligned with the core elements identified in recent WHO competency mapping studies and literature reviews on Health Emergency and Disaster Risk Management education (70). The curriculum addresses key domains such as situational assessment, exposure evaluation, and medical countermeasures, while also incorporating simulation-based and case-based learning strategies strongly endorsed by these frameworks. Compared to CBRN response existing programmes—which tend to emphasise general disaster response—UAH's course introduces a unique toxicological and pharmaceutical dimension, reflecting the interdisciplinary strengths of the institution. However, opportunities remain to further strengthen alignment with the World Health Organization's Health Emergencies (WHE) framework, by making competencies related to systems thinking, behavioural attributes, and long-term psychosocial recovery more explicit in the learning design and evaluation strategy.

3.3. Gamification, simulation, and forensic training innovation.

To strengthen student engagement and applied learning in toxicology and forensic education, our team is developing a suite of pedagogical innovations rooted in gamification and simulation. This approach reflects growing evidence that game-based learning (GBL) strategies—including card games, serious games, and digital platforms—can improve knowledge retention, critical thinking, and learner motivation in health science education (71). A recent mini-review highlighted the capacity of GBL to support experiential learning through mechanisms such as active feedback, scenario-based testing, and spaced repetition, while also fostering skills in clinical decision-making and interprofessional collaboration. These benefits are echoed in toxicology-specific interventions such as Toxicolitaire™, a digital card game shown to promote self-regulated learning, critical reasoning, and exam preparedness among postgraduate toxicology students (72). Our developments —ToxiGame©, e-Pathogens©, and forensic simulation training—align with these trends, aiming to bridge theoretical instruction with realistic toxicological and medico-legal contexts. Preliminary evaluations mirror international findings supporting the pedagogical value of simulation and gamification in health education (73).

A cornerstone of this approach is the development of ToxiGame©, an educational board game aimed at reinforcing core toxicology and risk assessment competencies through gameplay (Figure 1). The game, which will be launched at the end of this course, adopts a challenge-based format where players—assuming professional roles such as toxicologist or environmental health officer—collaborate to identify, evaluate, and manage chemical threats across different ecosystems. The board is divided into thematic biomes that simulate various exposure scenarios, requiring players to solve science-driven tasks and accumulate "evidence tokens." This interactive approach supports decision-

making, teamwork, and applied learning, reflecting literature that underscores the effectiveness of game-based learning in the environmental and toxicological sciences (72).

Figure 1. Overview of the *ToxiGame*© prototype (images courtesy of De Montfort University and Peña-Fernández A.; 2025): a) preliminary design of the game board, structured by thematic biomes focused on natural, chemical and biological toxic agents; b) prototype of the player token in the shape of a CBRN suit, designed for 3D printing and colour customisation; c) initial models of challenge and hazard cards, intended to assess knowledge, introduce unforeseen dynamics and reinforce active, simulation-based learning.

In parallel, the digital platform e-Pathogens©, co-developed with DMU and academics from Spanish institutions including Universidad CEU San Pablo, Universidad de Sevilla, Universidad Pablo de Olavide, Universidad Miguel Hernández de Elche, and Universitat de València, is currently being completed as part of an international educational innovation programme (49). Designed as an open-access resource, the platform includes four interactive modules aimed at supporting training in biological incident preparedness and toxicological emergencies: a) **Pathogen Units**, will offer structured theoretical content focused on priority pathogens distributed across targeted learning units; b) **Biosafety, Risk and Health Units**, will provide applied public health training covering environmental risk assessment and recovery, hospital preparedness, epidemiological surveillance, and biosafety procedures for laboratories operating under containment levels 2 to 4; c) **Virtual microscope** with high-resolution clinical and environmental specimens, accessible through adjustable magnification for practical diagnostic training; d) **Case studies**, with scenario-based simulations that replicate real-world decision-making in outbreak control and deliberate or accidental contamination events. The project aligns with EU educational frameworks by advancing One Health literacy and crisis preparedness through digital learning environments (5, 7).

In addition, the UAH is expanding its use of high-fidelity simulation in forensic toxicology and medico-legal education. Drawing on validated models from clinical simulation training, recent initiatives include the integration of hyper-realistic silicone prosthetics and moulage kits (acquired from MedicFX™, New Zealand; 74) into the design of educational simulations involving trauma, poisoning, and forensic pathology. These tools have been introduced within the practical component of the *Legal and Forensic Medicine* module (6 ECTS), delivered in the third year of the BSc in Criminalistics: Sciences and Forensic Technologies (75). This approach allows students to safely engage with realistic scenarios such as crime scene reconstruction and chemical exposure investigations, thereby strengthening the development of essential practical competencies in medico-legal assessment and forensic toxicology. In addition, the use of simulation-based training (SBT) supports the development of critical transversal skills including ethical reasoning, decision-making, situational awareness, and teamwork, which are increasingly recognised as essential for multidisciplinary healthcare and forensic environments. This aligns with current evidence in the literature, which highlights how moulage-based simulations improve learner engagement, immersion, and critical thinking, particularly in complex or emergency situations (76), and how high-fidelity simulation enhances non-technical competencies such as interprofessional communication and crisis management (77-79).

Pilot implementation of these simulations has begun with BSc Criminalistics students; participation (n) is reported in Table 2. Competence is assessed through an OSPE-style station integrated into summative assessment (10% of the final mark), using a standardised rubric focused on lesion recognition, structured description, and defensible medico-legal reasoning. We will analyse whether implementation is associated with improvements in aligned assessment components (including relevant module marks) across cohorts, while maintaining consistent marking criteria. Detailed quantitative outcomes from the OSPE station, including relevant marks, will be analysed at the end of the module. This innovation is expected to be progressively incorporated into the curricula of the Medicine and Law programmes, as part of a broader strategy to modernise applied forensic education. These initiatives follow international best practices in simulation-enhanced education (79,80) and mark a key step in consolidating UAH's commitment to interdisciplinary, competency-based toxicology and forensic training.

A summary of the key pedagogical innovations described above, including their curricular context and alignment with EU policy frameworks, is presented in Table 2.

3.4. Monitoring and evaluation of educational impact.

To strengthen the evidence base beyond informal feedback, we will implement a structured evaluation framework across the educational innovations described, building on the mixed-methods evaluation approach previously applied by our team to institutionally deployed, open-access digital learning resources in the biomedical sciences (*e.g.* our e-Biology© platform, 81, 82). The framework will include (82): i) participation and reach indicators (*e.g.*, number of students engaged, contact hours, completion and uptake rates, and, where feasible, basic engagement analytics such as access frequency and time-on-task); ii) learning outcomes, assessed using two short knowledge tests administered pre- and post-intervention (*i.e.*, brief MCQ tests aligned with the intended learning outcomes), alongside structured performance evidence (rubric-based assessment of practical competencies and, where applicable, OSCE-style stations); and iii) short- and medium-term outcomes (*e.g.*, student satisfaction captured through structured questionnaires and self-efficacy items, plus follow-up indicators such as elective uptake, internship applications, or dissertation topic selection).

In operational terms, the evaluation will be implemented across the specific tools developed by our team that are embedded in the teaching offer (as described in this manuscript), including—where applicable—interactive learning pathways, short formative quiz banks with automated feedback,

case-based/problem-based scenarios, structured practical worksheets and rubrics, simulation or skills stations, and curated digital learning objects (*e.g.*, guided activities and workbooks). Consistent with our prior cohort-level evaluations, we will also analyse whether implementation is associated with improvements in summative attainment by comparing module marks/grades across cohorts pre- and post-implementation (and, where possible, conducting within-cohort comparisons of assessment components most directly linked to the innovations). For pre/post knowledge testing, paired analyses will be undertaken where anonymous identifiers allow matching, mirroring the approach used in our earlier work. Where dissemination beyond internal quality assurance is intended, the evaluation will be submitted for ethics review in line with institutional requirements.

In parallel, ToxiGame© and e-Pathogens© will incorporate embedded analytics (*e.g.*, completion rates, item-level performance and common error patterns) to enable continuous improvement. Any studies intended for publication as educational research, particularly those involving minors or identifiable data, will be submitted for ethical review in accordance with institutional requirements.

4. Conclusions

- In conclusion, toxicology education at the University of Alcalá has evolved into a multidisciplinary and practice-oriented model aligned with emerging public health, environmental, and regulatory needs. While the subject remains unevenly distributed across academic programmes in Spain, UAH demonstrates a strong commitment to interdisciplinary toxicology through its integration in multiple undergraduate and postgraduate curricula.
- Innovations such as CBRN preparedness training, the e-Pathogens© digital platform, and simulation-based forensic education are positioning UAH as a reference point for modern, competency-based toxicology instruction. These developments not only strengthen student engagement and employability but also address critical educational gaps in biomonitoring, risk communication, and exposure science.
- Implementation is constrained by institutional and resource factors, including credit allocation within EHEA/Bologna structures, competing curricular demands, the need for staff time and specialist materials for simulation-based delivery, and the limited availability of sustained funding for scaling digital tools and evaluation. Regulatory complexity also poses a barrier: integrating current practices in regulatory toxicology and NAMs requires continuous updating, access to expertise and alignment with external agencies' evolving guidance. These constraints reinforce the need for coordinated cross-programme planning and dedicated postgraduate provision to improve visibility and sustainability.
- To consolidate these advances, future efforts should focus on: 1) expanding toxicology content within medical and public health curricula; 2) developing a dedicated postgraduate programme in toxicology; and 3) embedding formal evaluation strategies to assess the impact of pedagogical innovations. These actions are necessary to fully prepare the next generation of professionals for the complex toxicological challenges of the 21st century.

Table 2. Pedagogical innovations in toxicology education at the University of Alcalá (UAH): scope, curricular context, policy alignment, and intended learning outcomes.

Intervention / Innovation	Description	Programme	EU / Policy Alignment and References	Students	Intended learning outcomes
CBRN Teaching Integration (2023/24–2024/25)	Curriculum revision embedding real-world CBRN toxicology scenarios, risk communication, and formulation of countermeasures.	MPharm Pharmacy, BSc Environmental Sciences, BSc Criminalistics, MSc Industrial and Galenic Pharmacy	Aligned with the EU Civil Protection Mechanism and WHO Health Emergency and Disaster Risk Management (Health EDRM) framework (66).	MPharm (2023/24 n=40; 2024/25 n=40) BSc Environ. (2023/24 n=61; 2024/25 n=69) BSc Criminalistics (2023/24 n=41; 2024/25 n=52) MSc (2023/24 n=10*)	Students will be able to: (1) identify likely CBRN-relevant hazards from scenario cues; (2) outline key exposure pathways and susceptible populations; (3) propose proportionate countermeasures and risk communication messages; (4) justify decisions with reference to evidence and governance constraints.
CBRN Summer Course (2025)	Multidisciplinary training covering situational assessment, toxicokinetics, medical management, biomonitoring, and environmental recovery. Includes hands-on formulation workshops.	Open to postgraduate and advanced undergraduate students	Reflects European Commission recommendations for CBRN preparedness and One Health integration in education (5,7).	July 2025: n=8	Learners will be able to: (1) undertake structured situational assessment; (2) explain relevant toxicokinetics and medical management principles; (3) outline biomonitoring and environmental recovery considerations; (4) apply formulation concepts in a supervised practical

					workshop.
4ºESO+Empresa Toxicology Rotations	Experiential three-day pre-university rotation including lab exposure, histology, simulations, and toxicological case studies.	Pre-university outreach	Supports educational goals in the European Education Area and the GreenComp sustainability framework (57).	2024/25: n=14	Participants will be able to: (1) describe what toxicology is and where it is applied; (2) recognise basic exposure routes and everyday risk situations; (3) interpret simple, age-appropriate toxicology case scenarios; (4) identify safe behaviours and the role of evidence in decision-making.
ToxiGame©	Board game using challenge-based learning to build teamwork, critical thinking, and toxicological decision-making.	Supplementary to undergraduate modules	Consistent with research supporting gamification in environmental health and toxicology (71,72).	*The tool is currently in development; cohort size will be reported upon first pilot implementation*	Students will be able to: (1) apply toxicological reasoning under uncertainty; (2) collaborate effectively within a team; (3) prioritise evidence and articulate decisions; (4) integrate hazard, exposure and risk-management concepts.
e-Pathogens© Platform	Open-access digital simulation platform with interactive modules on biosafety, virtual microscopy, and outbreak response.	Cross-cutting tool for health, environmental and forensic sciences	Aligned with EU Green Deal, One Health training and digital innovation in toxicology education (5,20).	*The platform is in development; pilot cohort size and usage analytics will be reported upon deployment*	Participants will be able to: (1) apply biosafety principles; (2) interpret virtual microscopy and case-based evidence; (3) respond to outbreak scenarios using structured decision-making; (4) link exposure scenarios to health protection

					measures.
Mannequin-based practical sessions (2025/26)	High-fidelity forensic simulation using ultra-realistic silicone wound simulants/moulage and mannequins to support applied medico-legal reasoning, documentation, and evidence handling in trauma/poisoning scenarios, delivered through supervised skills stations.	BSc Criminalistics (Legal and Forensic Medicine)	Consistent with international best practice in simulation-based education and the evidence base supporting moulage and high-fidelity simulation for competency development and non-technical skills (74, 76–80).	2025/26 (Semester 1): n=58	Students will be able to: (1) recognise and describe key lesions/toxicological indicators using standardised medico-legal terminology; (2) apply structured scene-to-injury/toxic exposure reasoning to support case reconstruction; (3) demonstrate correct sampling, documentation, and chain-of-custody procedures within simulated forensic workflows; (4) justify conclusions and communicate uncertainty appropriately in a defensible medico-legal format.

Participant numbers (n) refer to enrolled learners per implementation cycle/academic year where available. For interventions under development, cohort size will be reported upon first pilot delivery. Intended learning outcomes summarise the primary competencies targeted by each innovation; evaluation is described in Section 3.4. *For the MSc in Industrial and Galenic Pharmacy, the CBRN content was delivered in the first year of the two-year programme (2023/24); more details have been published in Peña-Fernández et al. [59].

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