

Review



Sustainable pharmacy for training and education of pharmacy professionals

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ABSTRACT

Sustainability and environmental aspects of medicines are generally omitted in pharmacy curricula, despite the recognized burden of the pharmaceutical footprint. Pharmaceutical footprint refers to the societal, economic and environmental impact of pharmaceutical pollution produced during manufacture, distribution, prescription, consumption and waste management of medicines. In order to mitigate the impact of the pharmaceutical sector, a new educational approach based on Sustainable Pharmacy is required. Sustainable Pharmacy integrates education, society, economy, pharmacology, culture and environment into Pharmaceutical Sciences. Current and future drug professionals should receive comprehensive training that includes sustainable aspects across all main disciplines that constitute pharmaceutical science. In the current article, the following six pharmacy disciplines are revisited from a Sustainable Pharmacy perspective: pharmaceutical chemistry, pharmaceutics, pharmacology, pharmaceutical care, public health and pharmacoepidemiology, and drug legislation. Each section provides essential information about the pharmaceutical footprint of medicines, to facilitate understanding of the problem and enable sustainable pharmacy practices. Aside from the essential aspects of the environmental impact, the article compiles additional sources that can serve both as inspiration and as tools for developing training exercises. Furthermore, it introduces new concepts, such as LADME+, lysophore and sustainable and rational use of medicines that can further aid the education of pharmacists. The provided information may be used to inform the integration of environmental considerations into various subjects, or to update current pharmacy curricula to include these aspects.

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1. INTRODUCTION

Medicines are essential in the modern healthcare system, offering treatment, prevention and diagnosis of diseases. The recent COVID-19 pandemic is a representative example of how medicines are essential in disease prevention and treatment. In many cases, they represent the first-line treatment for preventing severe disease outcomes, increasing life expectancy and reducing disability. Advances in the understanding of the mechanistic physiology, pharmacodynamics (PD), pharmacokinetics (PK) and pharmacogenomics have improved drug efficacy and safety in the last century (Gratton et al., 2025). In this way, the transition from drug discovery based on botanical knowledge and trial-and-error to target-based discovery has resulted in the development of numerous new drugs, encompassing both small molecules and biologics (Lu et al., 2025). In the last decades, biopharmaceuticals and nanomedicine have opened new avenues for individualized treatment and precision medicine (Schork and Goetz, 2025). Additionally, the introduction of pharmacovigilance has been fundamental to optimize clinical outcomes, enhancing drug safety, through the identification of adverse outcomes related to drugs that were previously undocumented in the post-commercialisation phase (Wise et al., 2009). Moreover, the integration of patient-centred pharmaceutical care has been associated with enhanced treatment efficacy and improved patient outcomes (FIP, 2025a).

All of these advancements have led to a considerable increase in the consumption rate of medicines for human and veterinary use, as well as in the generation of associated residues. By 2022, it was estimated that the consumption of pharmaceutical compounds reached a significant annual total of 3–4.5 billion doses, generating a considerable pharmaceutical footprint: i.e. the societal, economic and environmental impact of pharmaceutical pollution produced during manufacture, distribution, prescription, consumption and waste management of medicines (Aitken et al., 2023). Pharmaceutical pollution is an intricate issue, embodying a wide variety of pollutants entering the environment through numerous different routes (Orive et al., 2022). On the one side, medicines produce a wide array of noxious and/or persistent organic waste (such as solvents, active pharmaceutical ingredients (APIs) and excipients), which may enter surrounding environments. Additionally, plastic waste derived from packaging may release micro- and nanoplastics that contaminate soil and water systems. To fill out the picture, carbon emissions from manufacturing, distributing, and consuming pharmaceutical products, such as pressurized metered-dose inhalers and anesthetics, also contribute to ozone layer depletion and exacerbate climate change (Egaña et al., 2026).

Recently, the principles of Sustainable Pharmacy have been conceptualised as a framework integrating six domains including education, society, economy, pharmacology, culture and environment into Pharmaceutical Sciences. Sustainable Pharmacy's mission is to “enable disease treatment options for present and future generations through effective prevention and medical and non-medical treatment of diseases” (Witte and Müller, 2025). The Sustainable Pharmacy framework advocates for the reduction of pharmaceutical footprint through the six domains, requiring an environmental education of current and future drug professionals. The basic knowledge pharmacists are required to acquire about medicines and pharmacy practices has been expanded with the amendments of the 2005/36/EC Directive (European Commission, 2025). The course of training has been enhanced with additional modules on biopharmaceutical technology, genetics and pharmacogenomics, immunology, clinical pharmacy, pharmaceutical care, social pharmacy, pharmacoeconomics, public health and pharmacy practice. Modern pharmacy education underscores the ongoing commitment to a patient-centred and outcome-focused pharmacy sector. However, the updated course of training did not succeed in integrating the environmental domain into the minimum curricula of pharmacists (Domingo-Echaburu et al., 2025), although education is crucial for ensuring the availability of professionals prepared to work

closely with environmental and social stakeholders to achieve a zero-pollution future. Recent publications studying the knowledge, attitude and practice regarding pharmaceutical pollution among pharmacy students and graduated pharmacists reveal a lack of knowledge and a positive attitude towards training (Hashad et al., 2026).

Several institutions have begun to address this curricular gap through innovative pilot programs that demonstrate both the feasibility and effectiveness of sustainability integration. At the University of California, San Francisco (UCSF), Gruenberg and colleagues implemented a three-hour sustainable pharmacy session that combined pre-work assignments, interactive lectures, expert panels, and case-based learning activities (Gruenberg et al., 2017). This intervention resulted in significant knowledge gains and high student satisfaction, demonstrating that even brief, well-designed educational interventions can meaningfully enhance pharmacy students' understanding of pharmaceutical environmental impacts. Similarly, the University of Groningen developed an e-learning module titled “Reducing Pharmaceuticals in Water,” which was integrated into a pharmacy simulation game (Fens et al., 2024).

In this review, we propose a novel and integrated approach of the concept of Sustainable Pharmacy within the pharmacy curricula considering six general disciplines: pharmaceutical chemistry, pharmaceuticals, pharmacology, pharmaceutical care, public health and pharmacoepidemiology, and drug legislation. The classification system has been adapted from the concept paper by Atkinson, taking into consideration the updated training course for pharmacy degrees (Atkinson, 2014) (Table 1). A carefully selected and compiled training material on pharmaceuticals has been proposed for each study subject, focusing on the most essential topics for the professional development of future pharmacists. In addition, novel concepts that incorporate the environmental perspective into classical pharmaceutical constructs and which may serve as a valuable resource for pharmacy schools worldwide have been proposed.

2. PHARMACEUTICAL CHEMISTRY

Pharmaceutical chemistry, specifically medicinal chemistry, is a discipline focused on the discovery and invention of new entities, including the study of the relationship between the structure and the mode of action, and the metabolic pathways of APIs. Studying medicinal chemistry, particularly the discovery, design, and synthesis of APIs for human and veterinary uses is essential for trainee pharmacists. Additionally, acquiring expertise in medicinal chemistry may contribute to sustainable pharmacy practices, such as the integration of structure–activity relationship (SAR) into patient-centred decision making and the development of selective and specific APIs with low environmental

Table 1

Six disciplines of pharmaceutical sciences, with associated course of training topics, revisited from a sustainable pharmacy perspective.

Discipline	Related course of training topics
Pharmaceutical chemistry	Organic chemistry Medicinal chemistry
Pharmaceutics	Pharmaceutical technology Biopharmaceutical technology
Pharmacology	Plant and animal biology Physiology and pathophysiology Toxicology
Pharmaceutical care and social pharmacy	Pharmacology and pharmacotherapy Genetics and pharmacogenomics Clinical pharmacy Pharmaceutical care Social pharmacy Pharmacy practice
Public health and pharmacoepidemiology	Analytical chemistry Microbiology Public health and epidemiology
Drug legislation	Legislation

impact (Fernandes, 2018). In this section, some basic concepts of medicinal chemistry are revisited from a Sustainable Pharmacy perspective.

1.1. Traditional drug design

Advances in synthetic chemistry and the industrialisation of pharmacy have made possible the development of stable drugs that can selectively interact with molecular targets and exert specific effects (Campos et al., 2019). However, APIs can selectively bind to certain receptors in non-target organisms due to phylogenetic conservation, with potential consequences highly difficult to estimate during drug design. Although the estimation of possible outcomes in wildlife species is challenging, some computational tools have already been developed to extrapolate data from rich model organisms to non-target species (Schumann et al., 2024). The combination of Sequence Alignment to Predict Across Species Susceptibility (SeqAPASS) and the Genes to Pathways – Species Conservation Analysis (G2P-SCAN) tools can be used to elaborate susceptibility predictions across different species based on the conservation of biologic pathways (LaLone et al., 2023; Rivetti et al., 2023). Normally medicinal chemistry taught in Pharmacy Schools is human centred, but the aforementioned tools may be used to illustrate to pharmacy students the complexity of a drug pharmacological profile.

Apart from presenting high selectivity and specificity, drug candidates are designed to be stable, both during storage and after intake. Correspondingly, drug degradability, closely related to the molecule's stability, depends on the various environmental (e.g. temperature, pH, light) and physiological (e.g. metabolic profile, enterohepatic cycle)

factors. Given that metabolic susceptibility affects a drug's efficacy and safety, molecular structures are often adapted to minimize phase I and phase II metabolism. The structure undergoes chemical tuning in order to achieve the desired metabolic profile. For instance, replacing labile groups with trifluoromethyl groups in celecoxib analogues completely blocks the phase I methyl hydroxylation reaction, while maintaining the target biological activity (Sun and Scott, 2010). However, this particular modification raises certain environmental concerns: trifluoromethyl groups are key elements of per- and polyfluoroalkyl substances (PFAS), referred to as “forever chemicals”, which are ubiquitously detected in the environment where may exert negative impact on wildlife species (Arp et al., 2024).

The identification of moieties that make a molecule more biodegradable can be part of the structural analysis when students are taught about SAR and retrosynthesis, synthesis routes going from simpler molecules to complex compounds (Fig. 1). Apart from identifying the pharmacophore, stereo-electronic features of an API that makes possible the interaction with the biologic ligand, undergraduates should also receive training in recognising chemical groups that favour or hinder biodegradability. Puhlmann et al. have compiled a list of these moieties, which may serve as teaching material (Puhlmann et al., 2021). In contrast to the pharmacophore concept, we hereby present a novel concept – the lysophore, which may be defined as the minimum structural moieties necessary to initiate the process of molecular biodegradation or mineralization once the substance leaves the body. Structure-biodegradability relationship (SBR) analysis may accompany SAR identification exercises, allowing students to acquire a more comprehensive vision.

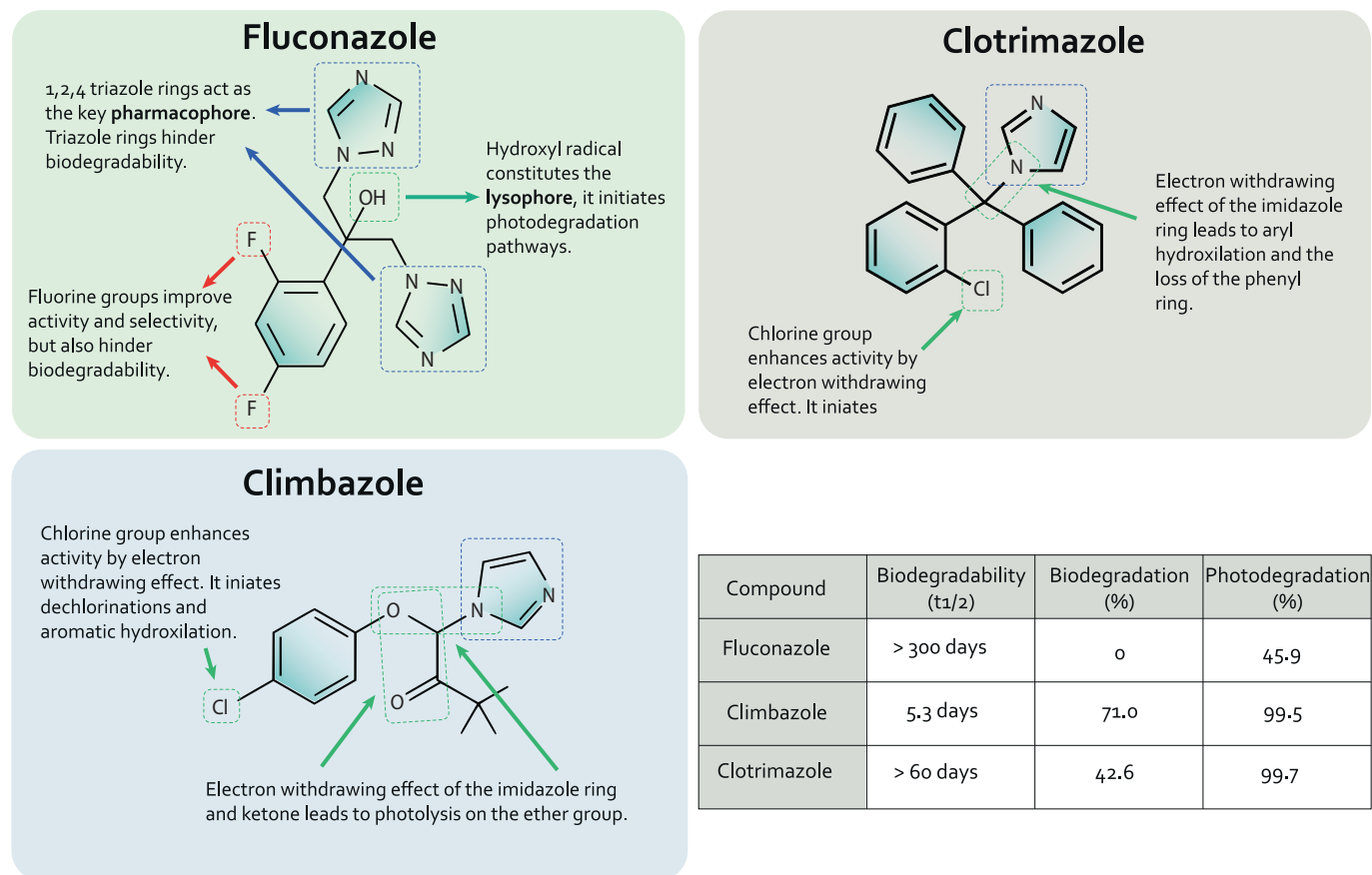


Fig. 1. Structure-biodegradability relationship (SBR) assessment of 3 azole antifungals (fluconazole, climbazole, clotrimazole). Active pharmaceutical ingredients (APIs) contain moieties that may enhance (e.g. hydroxyl groups) or hinder (e.g. fluorine groups) biodegradability; a classification of radicals by their contribution to molecule biodegradability is collected in Puhlmann et al., 2021. Determined by the power of the lysophore to initialize a photodegradation or/and biodegradation pathway, the environmental persistence of the API will vary. Biodegradability related data appearing on the adjacent table was retrieved from Pacholak et al., 2022.

It is imperative to consider stability not only in terms of ensuring drug safety and efficacy, but also in light of its environmental implications. Indeed, currently the designs of newer small molecules favours stability (Straub et al., 2022). Due to environmental concerns, there is an urgent need for reconceptualization of drug stability. Future medicinal chemistry should aim for APIs with dynamic stability – dsAPIs: compounds with high storage and metabolic stability, and low environmental stability.

1.2. Benign-by-design

In terms of environmental risk assessment, ready biodegradability is assessed by following the Organisation for Economic Co-operation and Development (OECD) guideline 301 (OECD, 1992). The molecule is classified as biodegradable if 60% of the theoretically observable CO₂ is formed after 28 days. Studies on ready biodegradability, based on sewer-sediment bacteria revealed that 70 out of 196 APIs possess a combined water–sediment half-life (DT50) higher than 180 days (Schwarz et al., 2021). Drugs with low biodegradability are considered persistent, which is one of the environmental risk assessment criteria. Biodegradability assays may fit into the list of laboratory exercises performed during the pharmacy degree, granting students a novel perspective regarding drug stability and environmental biodegradability.

Compared to other type of pollutants, such as pesticides and heavy metals, estimating the persistence and environmental fate of pharmaceuticals is a challenge due to the API structural particularities. APIs contain moieties that are atypical for other pollutants. This underscores the importance of employing models based on quantitative structure–activity relationship (QSAR) in such contexts. QSAR models can incorporate a variety of descriptors, ranging from the fundamental physicochemical properties (e.g., log K_{ow}, n-octanol–water partition coefficient) utilized in early ecotoxicological studies to more advanced descriptors such as those calculated by quantum-mechanics and which may give information about degradability in several conditions. The US Environmental Protection Agency (EPA) has developed the Estimation Programs Interface (EPI) Suite™, a comprehensive suite of different estimating programs (Card et al., 2017). EPI SUITE and other analogous models, such as CAESAR, can be used in drug development to estimate the biodegradability of newly developed drugs (Cassano et al., 2010). A comparison between experimental data and EPI Suite estimated data for biodegradability of 240 active organic substances revealed a 77% sensitivity and 93% specificity in predicting the biodegradability of compounds (Straub et al., 2022). This indicates that estimations based on physicochemical properties are reliable predictors of biodegradability. Certainly, case studies with EPI Suite are fitting exercises for introducing these concepts to pharmacy students.

Conversely, 3D QSAR models are more complex than standard QSAR models, but they can be advantageous for studying APIs from a specific chemical family, for example for the identification of more biodegradable fluoroquinolone analogues (Zhang et al., 2021). After entering the environment, APIs transform into byproducts due to chemical, physical and biologic reactions. In the case of antibiotics, transformation products (TPs) are formed mainly by microbial degradation and photodegradation. The study revealed the effectiveness of hydroxyl and carboxyl groups as lysophores, and how fluoroquinolones containing these moieties were likely to enter a photodegradation pathway and produce less toxic TPs. Carboxyl and hydroxyl radicals are also associated with the initialisation of microbial degradation, characterized by similar reactions to those observed during photodegradation. It is interesting to note that these biodegradable fluoroquinolone analogues demonstrated remarkable stability when tested against human CYP450 2D6, demonstrating its potential as dsAPIs, environmentally friendly drugs applicable in therapeutics. Furthermore, the methodology for the identification of more biodegradable fluoroquinolones described above is an example of benign-by-design.

Benign-by-design aims for targeted de novo synthesis or the redesign

of already known drugs with higher biodegradability once entered the environment (Puhlmann et al., 2021). Redesigning pharmaceutical compounds is an appealing approach for discovering novel compounds that hold similar efficacy and safety profiles, but due to slight structural changes the biodegradability profile can be improved. This approach does not only add more tools to the pharmacotherapeutic arsenal, giving the possibility of choosing the “greener” options, when possible, but it also unlocks new fields of research and expands drug market competitiveness.

Similar to the classical drug design, benign-by-design consists of several steps, beginning with *in silico* screening (e.g. molecular docking) of molecules formed from a bioactive core structure or pharmacophore. Afterwards, *in vitro* testing of promising compounds is performed to assess the PK/PD, toxicity, stability and biodegradability; which are followed by preclinical studies. Another line of action is the non-targeted synthesis, which is based on the generation of a set of compounds via photolysis, and subsequently tested using the already mentioned assays. Design rules for biodegradability should be applied regardless of the method. As with substituents that enhance stability (e.g. fluorine atoms), there are other structures that ease biodegradability such as hydroxyl groups. The antineoplastic drug cytarabine for instance is more biodegradable than gemcitabine thanks to the lack of fluorine groups in the nucleoside moiety (Kümmerer & Al-Ahmad, 1997). In the case of metoprolol, the addition of a hydroxyl moiety enhances the biodegradability profile, without altering significantly the pharmacological properties (Rastogi et al., 2014).

Based on existing literature, several design rules of thumb can be used for designing biodegradable drugs. Generally, molecules with a smaller molecular weight (<500 Dalton, same as the Lipinski's rule used for evaluating druglikeness), structurally simple and partially oxygenated with medium polarity are affected by biodegradation processes. It might be interesting to design drugs which are specifically metabolized in the environment, and not only to focus on their activity, target specificity and selectivity. The synthesis of dsAPIs can also be approached by identifying environmental degradation routes that are not present in the human body and the gut biota. Drugs sensitive to photocatalysis will rapidly degrade in the environment, while storage stability may be preserved by using brown glass, opaque capsules or brown blister packaging. Benign-by-design approach stemmed from TPs based on photolytic reaction are of high interest, because many pharmaceutical compounds contain aromatic rings and heteroatoms that serve as chromophore groups that can absorb solar radiation or react with photoexcited natural organic matter or reactive oxygen species (Fatta-Kassinos et al., 2011). Metabolism assessment of sewer and wastewater treatment plant (WWTP) microbial communities may reveal metabolic pathways different to those appearing in humans biota, opening the doors for new lead structures. For example, the presence of oxygen atoms and anilines (electron-donating groups) is generally related to the increase of aerobic biodegradability. Moreover, stereochemistry also plays an important role in biodegradability, as different enantiomers may present different metabolic profiles (Achermann et al., 2020).

1.3. Green chemistry

The choice of synthesis reactants and solvents constitutes a relevant matter in drug development as it will deeply affect the environmental impact of the drug's life cycle (Chen et al., 2024). Notwithstanding the challenges associated with optimizing industry processes in accordance with the principles of green chemistry and sustainable pharmacy, a number of alternatives and impact reduction strategies have been proposed (Wynendaele et al., 2021). Advances in drug synthesis involve new transformation strategies, such as electrochemistry (Ghosh et al., 2024), metal–organic frameworks (Binaeian et al., 2023), protein dynamics-based approaches (Lin et al., 2025), magnetic catalysts (Kazemi et al., 2025), enzyme biocatalysis (Kim et al., 2024) and

artificial intelligence-guided *retro*-biosynthesis (Gricourt et al., 2024). An important aspect that is included in pharmacy curricula is *retro*-synthesis, which can be studied from a green and sustainable chemistry point of view using available computational tools such as REAXYS (Teixeira et al., 2024).

The volume of solvents used and the amount that remains as waste is a major concern in the pharmaceutical industry. Organic solvents are volatile and flammable and can have detrimental effects on wildlife by polluting water and soil. Furthermore, organic solvents could affect global warming through three fundamental mechanisms. First, volatile organic compounds (VOCs) derived from these solvents act as chemical precursors that generate tropospheric ozone (Monks et al., 2015). Second, certain solvents possess chemical properties that allow them to act as direct greenhouse gases. Finally, the presence of these compounds in the atmosphere disrupts natural cleansing cycles (IPCC, 2021). Some selection guides based on environmental, health and safety criteria exist for classical and alternative solvents, but the choice on which excipient to use in a certain transformation reaction frequently becomes a game of balancing applicability and sustainability (ACS Green Chemistry Institute Pharmaceutical Roundtable, 2025). During their training, pharmacy students may benefit from learning about the environmental problems posed by solvents and get familiarized with the most common green alternatives for drug synthesis reactions. An additional concept when talking about solvents is bio-based solvents or bio-solvents, a term representing a group of green solvents, including ethyl lactate, limonene and dimethyl carbonate, less volatile, more recyclable and less toxic (Pandit and Saha, 2025). Ionic liquids (e.g. Cyrene™ and methyl soyate) (BMIM)[PF₆], [EtNh₃][NO₃], supercritical fluids (e.g. supercritical CO₂ and supercritical water) and natural deep eutectic solvents (NADES) (based on choline chloride-glycerol and choline chloride-urea) are possible environmentally friendly replacement for classic organic solvents (Ratti, 2020). However, some drawbacks exist for the utilization of these solvents, such as the scale-up limitations, price volatility and inadequate equipment to name a few. An existing gap that limits scaling-up the use of biosolvents is the lack of appropriate life cycle assessments for biosolvents, which includes the inconsistency of inventory data and the inadequacy of the attached occupational exposure. There is still little information regarding what the recovery percentages will be on a large scale; the fugitive emissions, degradation products and energy loss have not been studied. The techniques using biosolvents are at low technological readiness level, and the current regulatory framework possesses not enough information about standardization because expertise is yet to be acquired to provide advice.

3. PHARMACEUTICS AND PHARMACEUTICAL TECHNOLOGY

The pharmaceutical footprint generated by the pharmaceutical industry, and specifically for drug formulation, encompasses a 4.4% of global emissions, 7.2% of global solvent consumption and 300 million tons of annual plastic waste (Ötvös et al., 2025). Reaching the final product intended for consumption also implies the generation of synthesis byproducts and impurities, large volumes of excipients and condition materials, that may access the environment during different stages of the life cycle (Lertxundi et al., 2022). The adoption of safe and sustainable-by-design approach by the pharmaceutical industry has been proposed lately; this approach highlights the importance of a comprehensive lifecycle assessment to (re)design technological processes (Puhlmann et al., 2024). Ultimately, drug development is leaning towards the production and delivery of drugs safe for both human and environmental health, employing in the process sustainable chemical and (bio)technological approaches with minimal waste generation and reduced environmental impact throughout all the life cycle, specially focusing on API synthesis, drug formulation and packaging (Imran & Lück 2023). As advances are made in medicine chemistry, pharmaceutics and pharmaceutical technology, pharmacy curricula should be updated accordingly. Therefore, some concepts about the environmental

impact in drug development are presented in this section.

2.1. Excipients with lower environmental impact

Determined by the administration route, the API's physical/chemical properties, the fabrication method and the desired characteristics of the final product, an amalgamation of different excipients is combined with the API. Normally, excipients are qualified as the "inert" part of a medicine, but it a misleading assumption that is gradually reverting and taken into consideration when choosing excipients (Silvério et al., 2023). A more fitting definition is given by the International Pharmaceutical Excipients Councils (IPEC): any substance with a proven safety included in a pharmaceutical form other than the API (Elder et al., 2016). Several excipients possess biologic activity, as for example diethyl phthalate and methylparaben (Pottel et al., 2020). Usually, excipients are barely absorbed and are rapidly metabolized preventing toxic blood levels, but a significant fraction that is unabsorbed gets excreted, thus posing an additional risk for the environment (Zurita et al., 2007).

For instance, choosing the appropriate excipient should be based on the life cycle impact assessment (LCIA) (Bading et al., 2025). The quantification and discussion of LCIA metrics, including the biodegradability profile, applied to a specific excipient is a fitting introductory exercise for pharmacy students (Bading et al., 2024). The results of a recent study, in which different excipients were scored based on their LCIA, reveal that the use of natural monomeric excipients, such as glucose, sorbitol and glycerol, and agricultural-based excipients, including mannitol and starch, should be prioritized. On the contrary, hydroxypropyl methylcellulose, acetate succinate, sucralose and lactose showed a very high environmental impact due to high bluewater consumption and ozone depletion (Bading et al., 2025). Since some of the excipients with high environmental impact are used in large quantities, there is need for new biodegradable polymeric carriers.

Biodegradable polymeric excipients, frequently used for injectable administrations, are biocompatible materials distinguished by progressive degradation whilst in the body or after excretion (Nkanga et al., 2020). The employment of these polymers facilitates the treatment of chronic diseases as a result of tunable sustained drug release, which positively affects the disease development and the environment by conveying an accurate dose, in addition to enhancing patient adherence and convenience (Fuhrmann, 2023). Polylactic-co-glycolic acid (PLGA) is one of the most frequently used excipients for injectable microspheres, which have been used both for formulating small molecules and peptides. Other non-PLGA delivery systems include sodium hyaluronate, crystal suspensions and oil-based formulations. Moreover, biodegradable polymers, such as PLGA possess an acceptable environmental profile based on reduced greenhouse gas emissions during the manufacturing (Gonella et al., 2025).

Excipients that require special mention are propellants, which are essential for the respiratory route of drug administration of certain drugs, although they raise some important environmental concerns. As an example, 14 million inhalers were sold in Spain during 2023, which has a carbon footprint of CO₂ equivalent of 400.000 tonnes (Spanish Ministry of Health, 2025). Hydrofluorocarbons (HFC) propellants used in pressurized metered-dose inhalers (pMDIs) are volatile organic compounds (VOCs) with global warming potential, source of air pollutants and may condition drug stability and efficacy (Pritchard, 2020). Some green alternatives are currently explored, for example hydrofluoroolefins (HFOs), compressed CO₂ and nitrogen (N₂) or propellant-free alternatives, such as soft mist inhalers and dry powder inhalers, with a 20 to 40 times lower carbon footprint (United Nations Environmental Programme, 2018). While impressed gases, such as CO₂ and N₂, possess certain limitations for formulating aerosols, but there is active research around the world looking for substituting HCF with HFOs. Although the main barrier of broadly employing HFOs is the cost, which is higher than for HCFs, the feasibility of using HFOs for

aerosol formulation should be studied case by case. The first reformulation of an inhaler with lower global warming potential was produced based on European Medicine Agency (EMA) recommendations (EMA, 2025). These novel formulations present a 1000-fold reduction in global warming potential, maintaining the properties of previous inhaler version (Pleasant et al., 2025; Salvadori et al., 2025).

2.2. Novel drug delivery systems

The development of prolonged-release formulations and advanced controlled or targeted drug delivery systems enables localized and sustained drug release, reducing dosing frequency, total drug consumption, and the excretion of active compounds, thereby minimizing their

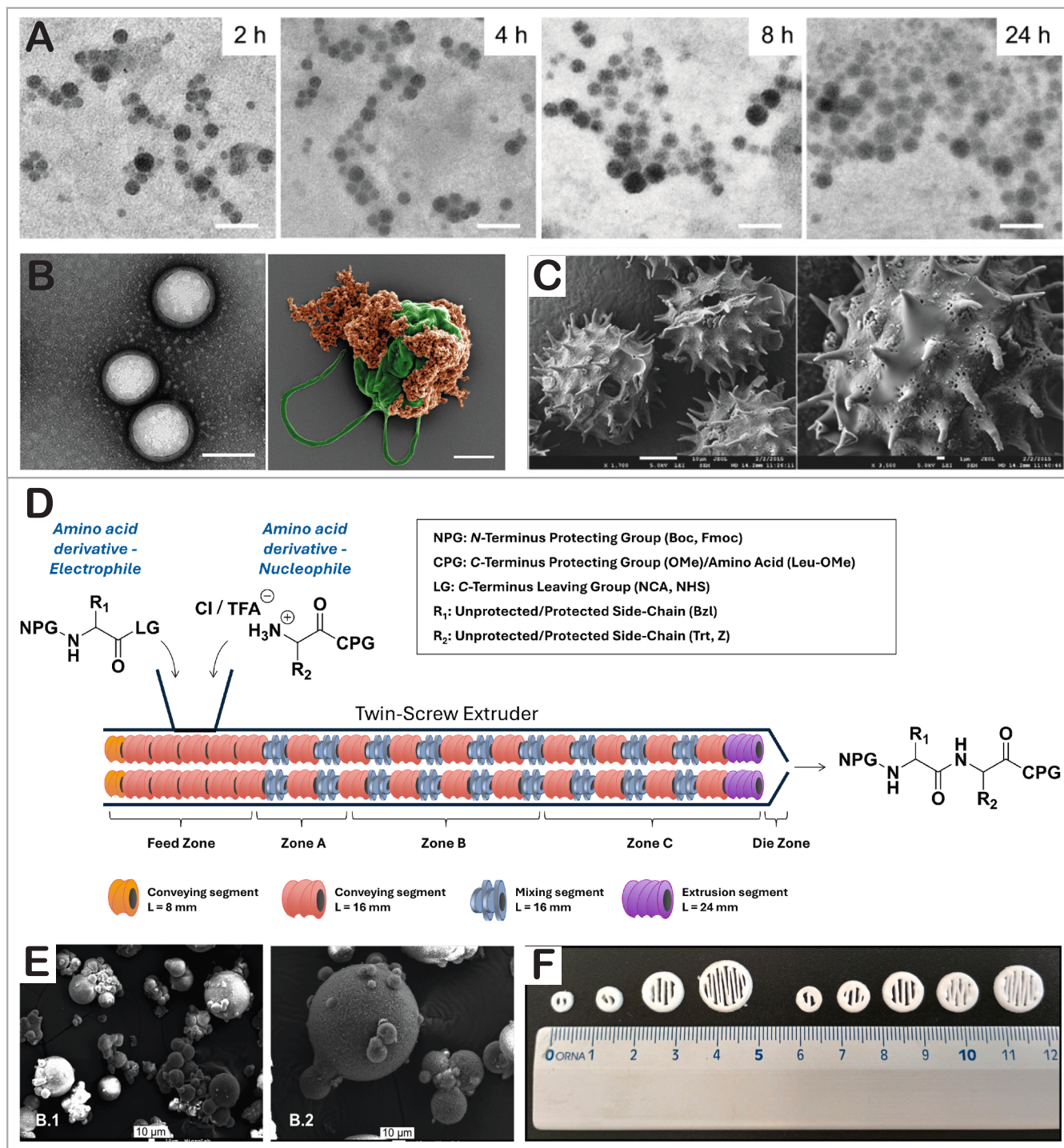


Fig. 2. Novel drug delivery system and sustainable drug manufacturing technologies. A. TEM images of nanoparticles with enhanced retention and release of multiple chemotherapeutics under different pH conditions (adapted from Cao et al. (2022)). B. TEM images of doxorubicin-loaded nanoparticles (left) loaded on a natural green algae (right) to form biohybrid microrobots (adapted from Zhang et al. (2024) with permission). C. SEM images of natural sunflower pollen grains loaded by compression for drug delivery (adapted from Mundargi et al. (2016) with permission). D. Schematics of twin-screw extrusion technology for the synthesis of therapeutic oligopeptides (adapted from Daurio et al. (2025) with permission). E. SEM images of cocrystals of carbamazepine and nicotinamide fabricated by congealing (adapted from Duarte et al. (2016) with permission). F. Dexamethasone printlets with different dosages fabricated by 3D printing (Paccione et al., 2025).

environmental impact. In this sense, advances in pharmaceuticals and nanomedicine from last decades have given entry to a new era of drug delivery systems composed by a new category of excipients – nanoparticles. The big difference between classical and nanoscale-sized formulations is that the latter plays an active role in enhancing efficacy and safety before and after absorption, while the former does not actively participate in drug action following absorption (Hemrich & McNeil, 2023). Targeted drug delivery allows dose reduction, thereby lowering the risk of side effects and minimizing the concentration of residual APIs leaving the organism. Compared with micro-sized particles, nanoparticles can escape mononuclear blood cells. Currently, there are approximately 100 FDA-approved nanomedicines with a continuously growing market size (Thapa & Kim, 2023). Nanoscale drugs exhibit several advantages over other formulations, such as renewable synthesis based on acid hydrolysis or bacterial growth, residue reduction due to targeted action and biodegradability (Cao et al., 2022; Shirzad et al., 2025) (Fig. 2A). Nevertheless, concerns remain regarding the biodegradability and ecotoxicity of certain types of nanoparticles, such as carbon-based systems (Kümmerer et al., 2010). There is still lack of environmental data on what is the ecologic exposure to nanoparticles for instance. While bio-based nanoparticles (e.g. chitosan) do present a higher degree of biodegradability, carbon-based structures are insoluble and hardly biodegradable. Moreover, there is evidence of metabolic alterations caused by fullerenes and carbon nanotubes in fish.

Micro/nanomotors are one of the latest advancements in drug delivery, enabling autonomous movement that adapts to organism's microenvironment, and can be additionally guided by external stimuli (Ju et al., 2025). The self-propulsion of micro/nanomotors is based on chemical reactions produced when entering in contact with body substances, such as glucose, urea or H_2O_2 . In case of requiring precise navigation, external stimuli, such as magnetic fields, can be employed. These systems have been applied for delivering drugs to hardly accessible affected tissues, for example active drug delivery to stop lung metastasis (Zhang et al., 2024) and antibiotic delivery to infected alveoli by using a nebulizer system (Li et al., 2025) (Fig. 2B). The design of micro/nanomotors varies in complexity, but some systems are sufficiently simple for reproducing during standard laboratory practices in Pharmacy Schools around the world, such as the synthesis of CaO_2 - Cu_2O micromotors (Liu et al., 2023).

Other novel and promising drug delivery systems are pollen grains. Pollen grains constitute innovative nature-derived microcarriers made of the pollen outer shell (exine) emptied of allergenic proteins (Ibrahim et al., 2025). Pollen grains are non-toxic, resistant to different conditions and serve as inert encapsulation platforms that vary in shape, size and loading capacity depending on the species. Owing to their characteristics, they have been proposed for different applications, including biotemplates, water pollution remediation and drug delivery (Aylanc et al., 2025). Moreover, they can be functionalized or coated with additional materials, such as alginate to infuse them with advantageous features (Mundargi et al., 2016) (Fig. 2C). Pollen-based drug delivery systems have the potential to become a greener option in pharmaceutical industry or cosmetics.

2.3. Sustainable manufacturing tools

The modern pharmaceutical industry tends towards the environmental optimization and safe and sustainable redesigning of traditional drug manufacturing technologies. For instance, one of the biggest challenges in pharmaceutical technology is achieving higher bioavailability of poorly water-soluble drugs. The main strategies to overcome low water solubility is reducing drug particle size, modifying drug physical and chemical structure, improving drug solubilization and modifying drug solid state. Among the available approaches, spray congealing and mechanochemistry have been proposed as two sustainable pharmaceutical manufacturing methods (Bertoni et al., 2022) (Fig. 2D). Spray congealing involves the formation of solid

microparticles resulting from the atomisation of a fluid in a chamber at a temperature below the melting point of the drug vehicle, followed by droplet solidification (Duarte et al., 2016) (Fig. 2E). Nanosuspensions can be formed by achieving smaller particle size stable, and enabling the limitations of low solubility drugs such as aspirin.

Mechanochemistry is another sustainable strategy for particle size reduction, which involves mechanical forces, grinding, shearing or milling, with no need of big solvent quantities (Daurio et al., 2025). Twin-screw extrusion consists of a barrel containing two rotating screws that serve for mixing solid and viscous reactants until achieving drug synthesis via shearing forces. However, the manufacturing of therapeutic peptides requires the use of solvents, commonly trifluoroacetic acid, a highly persistent PFAS with environmental concerns. Recently, the synthesis of a dipeptide was achieved by twin-screw extrusion method, setting a foundation for future research in synthesizing larger peptide chains for clinical use.

Another technological challenge is treatment individualization, which is crucial from an environmental perspective as it minimizes unnecessary drug use, reduces waste, and limits the release of active pharmaceutical ingredients into the environment. This includes dose adjustment and the combination multiple APIs for polypharmacy. In the field of personalized medicine, 3D printers occupy a prominent position among manufacturing technologies thanks to their versatility of design, fast manufacturing speed and ability to personalize doses (Kapoor et al., 2025). Diverse 3D printing techniques have been used to produce distinct dosage forms and complex delivery systems. Among the existing techniques, extrusion 3D printing relying on the layer-by-layer deposition of hydrogels, semisolid or thermoplastic materials have been widely used for fabricating oral dosage forms. Adequate oral dosage forms can be printed based on the physical-chemical properties of the API and also on the patient particularities, such as impaired swallowing. 3D printing has been used to fabricate solid tablets, orodispersible printlets and chewable formulations, among other formulations for human and veterinary uses (Paccione et al., 2024; Paccione et al., 2025) (Fig. 2F). Actually, FDA-approved drug formulations based on 3D printing processes already exist: e.g. a levetiracetam tablet fabricated using Zip-Dose® 3D printing process (West & Bradbury, 2019). Furthermore, printable tablets with a tunable, modular design created using inkjet printing have been used for antidepressant withdrawal, demonstrating the practicality of incorporating these tools into hospital pharmacy departments (Ahola et al., 2024).

4. PHARMACOLOGY

3.1. Pharmacokinetics

Pharmacokinetics, remains one of the fundamental concepts in pharmaceutical sciences taught in every Pharmacy School. The stages of a drug passing through an organism are summarized by the acronym LADME: Liberation, Absorption, Distribution, Metabolism and Elimination. However, it is important to note that the organism is not generally capable of fully mineralizing APIs, that is, the process of converting a chemical structure down to essential non-toxic molecules such as water and carbon dioxide. Unmineralized APIs, their metabolites and excipients leave the body while maintaining biological activity until their full mineralization. Whilst in the environment, APIs and metabolites may undergo additional chemical transformations due to photodegradation and oxidation by biologic or chemical agents, resulting in the creation of TPs which may exhibit either higher, less or no biological activity. Furthermore, APIs, along with their metabolites and TPs, may interact with any other off-target organisms, and potentially enter another cycle of (L)ADME processes, which may result in the formation of non-primary metabolites (NPMs), another set of potentially active molecules (Aceña et al., 2017).

Considering all these, the classical LADME acronym is incapable of representing the totality of the pharmacokinetic details of an API until

its mineralisation; it merely represents the peak of the iceberg (Fig. 3). Inspired by the One Health concept and the interconnectedness between human, animal and environmental health, herein we propose the novel term “LADME+”: the process that describes the totality of the pharmacokinetic processes occurring in the target and non-target organisms, and the environment through the whole drug's life cycle. Each API may enter multiple pharmacokinetic cycles or LADME cycles, and with every additional cycle the risk of producing toxic effects increases. The LADME mechanisms may vary depending on the exposure pathway, the physiological aspects of the organisms involved and the environmental conditions.

3.1.1. Sewer system kinetics

After elimination by the human body or by direct discharge, APIs enter the sewer system, which consists of a network of pipes connected

to a wastewater treatment plant (WWTP). Inside the sewer system, APIs experience sewer microbiome drug metabolism, distributed between the sewer sediments, free-flow bacteria and the biofilm layers (Riisgaard-Jensen et al., 2025). The concentration of APIs exists in an equilibrium between the fraction dissolved in sewer water and the fraction adsorbed to the sewer sediment. A correlation exists between the drug physicochemical properties, such as solubility and organic carbon–water partition coefficient (K_{oc}), a parameter that increases with the hydrophobicity (also represented by the octanol–water partitioning coefficient (K_{ow})), with the sewer microbial biodegradation (Wen et al., 2024). More hydrophobic (higher K_{oc}) and less soluble drugs will be more unstable in sewer waters, due to their adsorption to the sewer sediment containing metabolically active microbial communities. Although microbial biodegradability increases with K_{oc} values, there are some exceptions to the rule, for example carbamazepine, which is

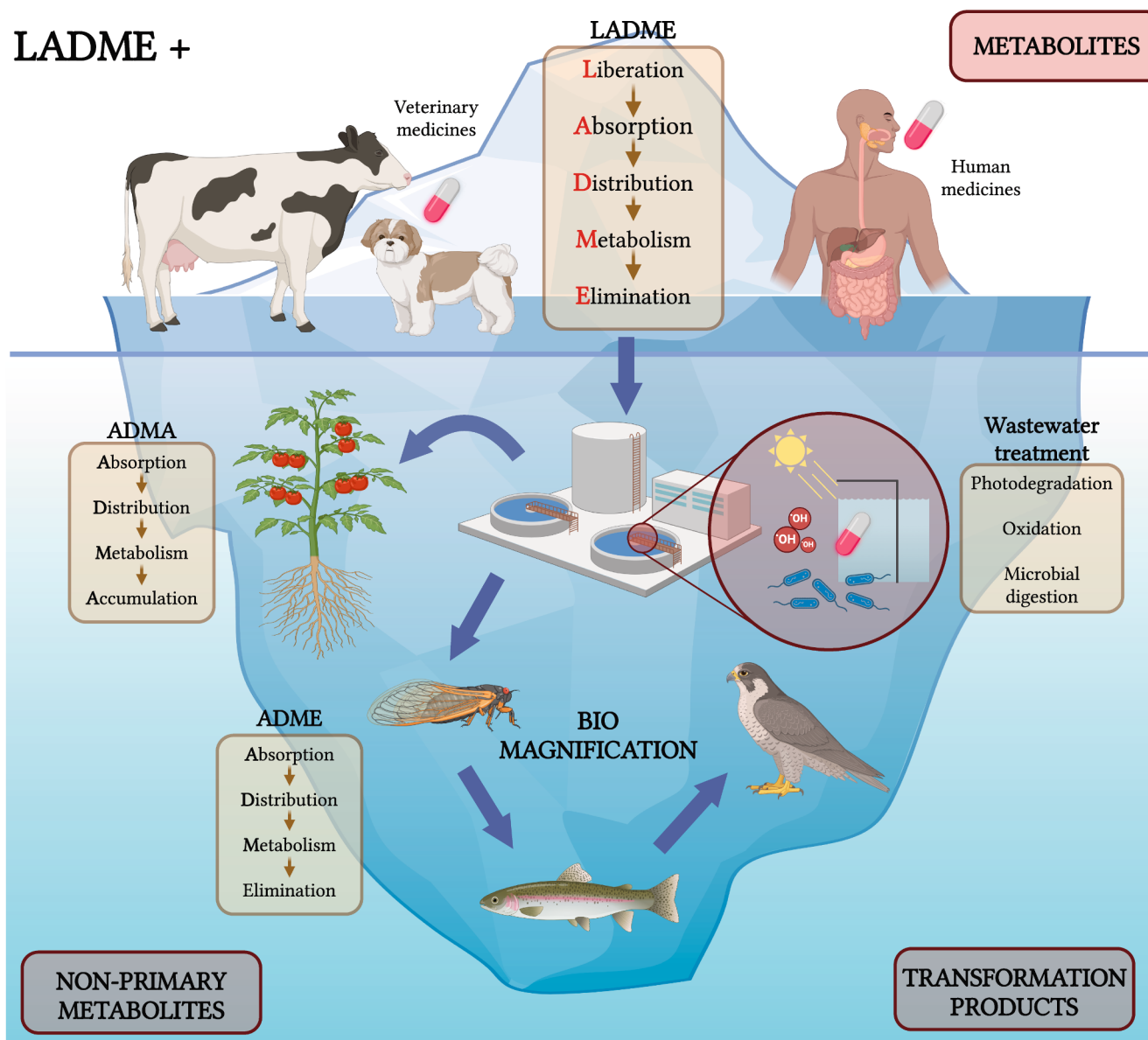


Fig. 3. Illustrative representation of LADME + processes. After finishing the first LADME cycle, active pharmaceutical ingredients (APIs) enter the sewer systems or directly the environment where they can transform into transformation products via photodegradation, biodegradation and/or oxidative reactions. Furthermore, they may interact with non-target organisms, including plants and animals, and start secondary pharmacokinetic cycles, leading to the production of non-primary metabolites and biomagnification throughout the trophic web.

highly stable to microbial metabolism (Schwarz et al., 2021).

A big portion of the excreted molecules will end up at the WWTP. Secondary treatment (also known as biological treatment) is the main mechanism of eliminating organic pollutants in WWTPs, whose removal efficiency depends on the physicochemical properties, operational conditions and seasonal factors, among others. Secondary treatment is normally paired with advanced treatment techniques (also known as tertiary or quaternary treatment), such as Photo-Fenton, active carbon adsorption ozonation or chlorination (Akhrimenko et al., 2025). Combined approaches have been shown to increase the removed fraction and reduce the biodegradation/mineralisation half-life ($t_{1/2}$). However, it should be noted that byproducts of hydrolysis, photolysis and biodegradation (i.e. TPs) may appear. Human phase I primary metabolites are degraded by 35–53%, while phase II metabolites are broken down to produce the active parent compound that can enter the environment (Meyer et al., 2025).

3.1.2. Plant pharmacology

APIs, their metabolites and TPs that were not eliminated at the WWTP may enter surrounding waters through the WWTP's effluent or be adsorbed to the WWTP's sludge. The sludge or biosolids, which consists of the concentrated suspended solids that settle out by sedimentation during wastewater treatment, is frequently used for nourishing crop fields because of its high nutrient content. Moreover, there are well-established technologies capable of treating wastewater to safe quality levels for various reuse purposes, although trace of pharmaceuticals and other pollutant may persist and potentially enter soil-crop systems (Sleight et al., 2023). Medicines for veterinary use can also enter soil-crop systems via landfill leachates or animal waste manure used as organic fertiliser (Kaczala and Blum, 2016).

Pharmaceutical residues enter arable soils in their most bioavailable ionic form and are prone to being absorbed by the root system of local plants. The molecules present in the soil-crop systems are in equilibrium between the fraction adsorbed to the organic carbon embedded in the soil particles and the ionized percentage dissolved in the pore water (Malchi et al., 2022). For instance, the rhizosphere hosts communities of bacteria and fungi with high metabolic capacity. The absorption or uptake occurs mainly via passive diffusion through the plasmodesmata, which is comparable to the gap junctions between animal cells. Following the entry into the xylem, the molecules are distributed between the stem, leaves and fruits. The distribution to different tissues is dependent on the Lipinski's rule of 5; smaller molecules with a lower Kow are more likely to be distributed to different organs of the plant. The metabolism of xenobiotics in plants occurs across the entire organism and consists of 3 phases: phases I, II and III (vacuolization). The mechanism of xenobiotic elimination relies mainly on the abscission of leaves and fruits, although they are more specialized in the accumulation of xenobiotics in vacuoles. Should crops or vegetables be consumed by humans or used to feed livestock, APIs accumulated in the plant may enter back to the first LADME cycle. A recent study conducted in Israel has revealed that individuals who consume vegetables cultivated in fields irrigated with treated wastewater, particularly vegetarians, have been found to contain traces of non-prescribed pharmaceuticals in their plasma (Earl et al., 2024).

3.1.3. Toxicokinetics in fish

Humans and fish share similar pharmacokinetic (ADME) processes, which enables the use of the same compartmental models and pharmacokinetic parameters for studying drug profiles in both humans and fish (Viel et al., 2026). APIs, TPs and excipients may enter surrounding surface waters and bioaccumulate in the tissues of aquatic organisms or even biomagnify across the trophic web (Richmond et al., 2018). Medicines have the potential to also transfer to avian and terrestrial species via biomagnification, but fish exposure to pharmaceuticals has been more and extensively studied (Herrero-Villar et al., 2024). In addition to the classical gut absorption mechanism, fish possess other two

absorption organs, gills and skin absorption (Matthee et al., 2023). The primary mechanism of absorption is passive diffusion, with carrier-mediated transport also contributing to the process. Normally, small fish are more vulnerable to aquatic pollution, but the biomagnification model should also be considered.

The distribution of xenobiotics in the fish is best described by the volume of distribution (Vd) (Saunders & Nichols, 2023). For drugs with Vd values lower than 0.65 L (water content of fish is approximately 65–80%) it can be assumed that they will have a high affinity for plasma proteins (e.g. nitrofurantoin). Conversely, APIs with volumes bigger than 0.8 L indicate bioaccumulation in the tissues (e.g. methyl-testosterone). When using a simplified monocompartmental model and assuming that the drug concentration in water is constant, Vd normalized by body weight will be equivalent to the bioconcentration factor (BCF).

The metabolism of xenobiotics in fish consists of two phases, the purpose of which is to increase the hydrophilicity of the molecule and promote its elimination. The cytochrome P450 superfamily is responsible for the oxidation of xenobiotics in fish (Pihlaja et al., 2024). Some pharmaceuticals, such as atorvastatin, clozapine and esomeprazole are weak inhibitors of CYP1A and CYP3A, which may trigger drug-drug interactions (and potentially with other organic xenobiotics) at the metabolic level increasing the toxicity (Backhaus, 2014).

The main mechanisms involved in excretion are branchial, biliary and renal excretions, which remove xenobiotics from the body. However, faecal and dermal excretions can also contribute. Renal clearance in fish is computed by adding the filtration clearance and secretion clearance and then subtracting the reabsorbed fraction, similar to renal clearance in humans. Renal reabsorption is not common in freshwater species, but it plays a significant role in saltwater species, where it can increase the toxicity of pharmaceutical compounds.

3.2. Pharmacodynamics

A significant proportion of drug targets are shared between different species (Gunnarsson et al., 2008). However, others differ from known human mechanisms of action and could cause non-target toxicity. Shared drug targets are crucial for making *in vivo*/ *in vivo* correlations during preclinical trials in drug development, as well as for environmental toxicity studies and risk assessment. EcoDrug PLUS is a database containing genomic and chemoinformatic data regarding the interaction of drugs with protein targets across different species (Leghehar et al., 2025). EcoDrug PLUS may serve the purpose of facilitating environmental risk assessment, and also as a source for potential training exercises for pharmacy students. Nevertheless, it is worth bearing in mind that several environmental effects may go unnoticed due to the complexity of predicting all possible drug-target interactions (Harrison et al., 2025). At a molecular level, toxicity depends on the fulfilment of two conditions: the biologically active agent must interact with the appropriate target structures, and the interaction must happen at a certain concentration for an appropriate amount of time enough to induce a toxic response. The latter will depend on the API's toxicokinetic profile, whereas meeting the other condition is related to toxicodynamics, which studies the interaction between xenobiotics and biological receptors.

A good example of the complexity of evaluating pharmacokinetics/pharmacodynamics (PK/PD) across different species is diclofenac, a nonsteroidal anti-inflammatory drug (NSAID), and the protagonist of the infamous decimation of Indian vultures during the closing years of the past century (Oaks et al., 2004). Millions of vultures died due to a severe case of visceral gout, which was a result of consuming bovine carcasses that had been treated with diclofenac during their lifetime. Diclofenac has an affinity for glomerular proximal convoluted tubules, where the main secretion of uric acid occurs. The initiation of a cascade of intracellular reactions by diclofenac, and its metabolites (4-OH-diclofenac and the glucuronide conjugate), caused a simultaneous

necrosis of tubular epithelium and the precipitation of uric crystals in the tubular lumen leading to a massive death of these necrophagous scavengers (Meteyer et al., 2005) (Fig. 4). Interestingly, studies have found that the sensitivity to diclofenac varies between avian species. These differences may be explained by distinct PK parameters (C_{max}, CL and V_d) and/or metabolic profiles among different avian species (Hassan et al., 2018).

The study of pharmacotoxicology in wildlife species is not a simple task. However, in addition to human pharmacotoxicology case studies, students may be introduced to some ecotoxicological examples that may include the case about the mechanism of nephrotoxicity in vultures explained earlier. Other notable toxicity mechanism include the loss of olfactory function due to γ -aminobutyric acid (GABA) inhibition in dung beetles exposed to ivermectin (Verdú et al., 2018), anxiety reduction in fish exposed to fluoxetine owing to negative modulation of prolactin and other neurotransmitters (Correia et al., 2023) or the feminisation of male fish because of elevated transcription of vitellogenin when in contact with 17 α -ethinylestradiol (Martyniuk et al., 2020).

5. PHARMACEUTICAL CARE AND SOCIAL PHARMACY

4.1. Sustainable and rational use of medicines

At a global scale, over 77% of pharmacists work in community settings, keeping close contact with patients to ensure high quality pharmacotherapeutic treatment, promoting health by advising non-pharmacological alternatives and healthy lifestyle, and monitoring possible adverse drug events (FIP, 2025b). Modern pharmacy is transforming from a product-centred discipline to a people-centred discipline (Uzman et al., 2019). Person-centred care requires pharmacists to develop clinical practices that go beyond biomedical and pharmacological aspects. A person-centred pharmaceutical care aligns with the Sustainable Pharmacy framework by integrating the educational, economic, social, cultural, environmental and pharmacological/biomedical aspects specific for each patient and situation into decision-making processes.

Furthermore, environmental criteria are being steadily incorporated into pharmacotherapeutic decision-making. Consequently, environmental stewardship is a highly sought-after skill for pharmacy practitioners. Environmentally conscious pharmaceutical care can be defined

as pharmaceutical services provided by a pharmacist which guarantee sustainable and rational use of medicines and effective and safe treatment for both humans and the environment (Fig. 5). The definition of the rational use of medicines given by the World Health Organisation (WHO) in 1985 was: “patients receive medications appropriate to their clinical needs, in doses that meet their own individual requirements, for an adequate period of time, and at the lowest cost to them and their community” (World Health Organization, 2010). However, this definition omits several key points to meet the current demands necessary for the establishment of a more sustainable pharmacy. Specifically, the received medication should be appropriate for the patient’s clinical needs, but also in agreement with their education level, cultural idiosyncrasies and social aspects. Secondly, patients should receive medication that has the lowest cost/impact to them and their communities, but also to the environment, meaning that the most environmentally innocuous option should be chosen when possible (Orive et al., 2021; Giunchi et al., 2025).

Securing the sustainable and rational use of medicines hinges on communicating relevant information in a fitting manner for each patient, taking into account their educational, societal and cultural background. Providers should be able to identify and learn how to manage social determinants of health (SDH) (e.g. stress, social support/well-being, food access and security, transportation) that influences pharmacotherapy (Okoro et al., 2022). From an educational perspective, training of pharmacists by analysing patient case narratives would help providers with identifying those social determinants of health and achieving a more empathic, trustworthy, rational and sustainable clinical practice (Charon, 2001).

Pharmacists should also promote environmental awareness and stewardship about the environmental impact of pharmaceuticals (Lambert et al., 2025; Villén et al., 2025). They should be familiar with all the facets of medicines, including their environmental impact, or at least be able to retrieve and interpret publicly available environmental data of dispensed drugs, and give snippets of information to raise awareness and promote sustainable and rational use of medicines. Moreover, ensuring sustainable and rational use of medicines contributes to a more environmentally friendly pharmacy practices for example, by avoiding excessive generation of carbon emissions derived from the incorrect use of inhalers and reducing the drug amount entering the environment.

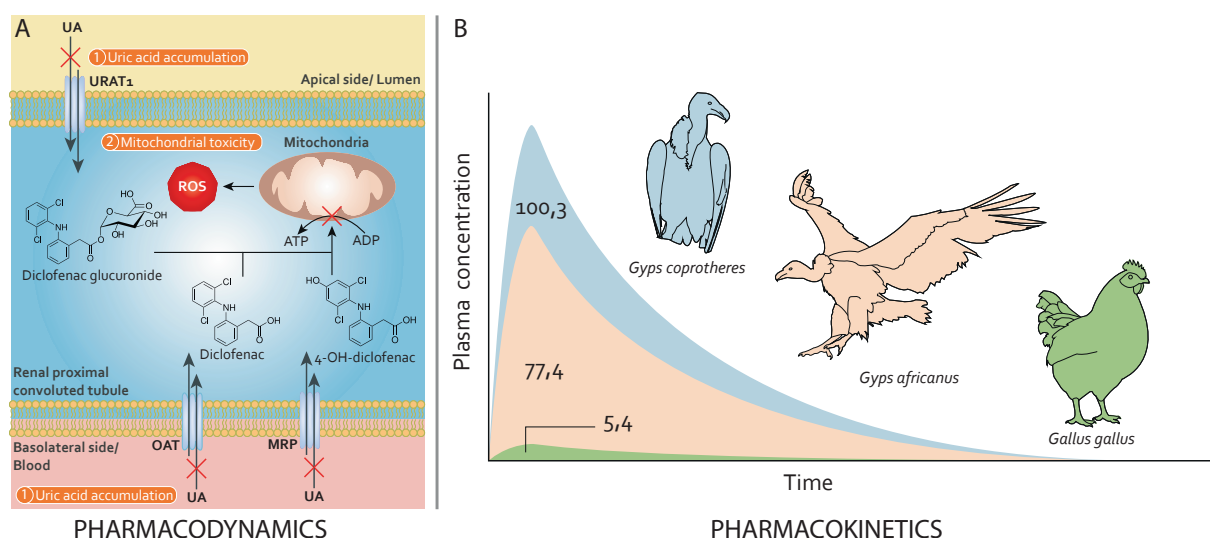


Fig. 4. Representation of the pharmacokinetic and pharmacodynamic profiles of diclofenac in avian species. A. Illustration of the nephrotoxicity mechanisms of diclofenac in vultures: the inhibition of cell membrane transport of uric acid derives in its accumulation in plasma, whereas the inhibition of mitochondrial oxidative phosphorylation by diclofenac and its metabolites (4-OH-diclofenac and diclofenac glucuronide) leads to mitochondrial death and the generation of radical oxygen species in renal proximal convoluted tubule cells followed by cell death. B. Graphic of the plasmatic concentration and AUC (area under the curve) values for diclofenac in different avian species.

Environmentally conscious pharmaceutical care

Pharmaceutical services that guarantee sustainable and rational use of medicines and effective and safe treatment for both humans and the environment

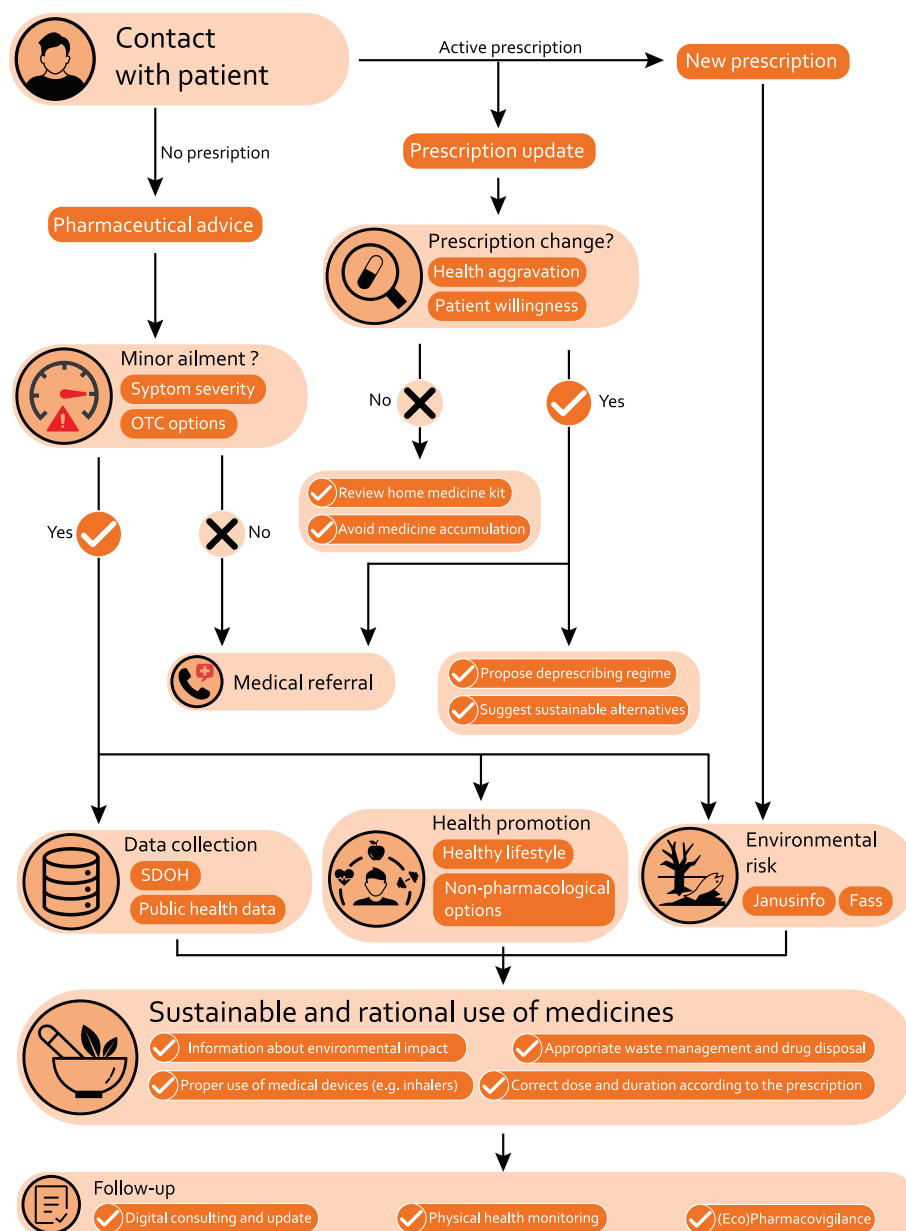


Fig. 5. A decision diagram about how to integrate environmental aspects and sustainable practices into pharmaceutical care and achieve sustainable and rational use of medicines, safe for both humans and environment. SDOH: Social determinants of health. Useful information can be achieved Janusinfo (<https://janusinfo.se/>) and FASS (www.fass.se).

Several sources of information regarding the environmental impact of pharmaceuticals for health professionals to use are available online. For example, two Swedish web-based knowledge databases compile environmental information may be helpful for healthcare professionals: FASS.se (FASS) (LIF, 2025) and Janusinfo.se (Janusinfo) (Ramström et al., 2020). These databases contain information to support decision-making, such as drug-drug interactions, pharmacological data, and environmental information on persistence, bioaccumulation and ecotoxicity. Another useful source of information is provided by the Aarhus University: a report containing short summaries of the ecotoxicological profile of each drug and therapeutic groups with potential environmental risk, in addition to a scored prioritisation drug list based on human toxicology, ecotoxicology, measured and predicted

concentrations and use (Sanderson et al., 2024). Least effective medicines for mild health conditions that are more environmentally friendly are preferred by Swedish adult population based on a web survey, which is a further justification why pharmacists ought to gain environmental expertise (Håkonsen et al., 2023).

Personal care products (e.g. sunscreen, deodorants, moisturizing products) are frequently sold in retail pharmacies and are normally accompanied by use recommendations. Remarkably, personal care products, the same as medicines, have raised concerns about their environmental impact owing to the presence of poorly biodegradable ingredients (e.g. silicones such as dimethicones), microplastics (Kukkola et al., 2024; Haykal et al., 2025) and excipients with PFAS structure (FDA, 2025). In comparison to other establishments selling personal

care products, community pharmacies have the advantage of giving expert advice about the proper use of these products and also transmitting environmental awareness. In the case of sunscreens, inorganic filters (e.g. zinc oxide) should be recommended over organic filters (e.g. avobenzone) when appropriate. Some classification systems based on environmental hazard have been proposed for different sunscreen formulations which can be used by pharmacists to propose clients alternatives with less environmental impact (Kunze et al., 2021).

4.2. Environmentally conscious pharmaceutical care practices

Environmentally conscious pharmaceutical care also integrates other pharmaceutical practices that go beyond the transmission of relevant pharmacological and environmental information. The integration of an environmentally sustainable perspective when teaching pharmaceutical care to pharmacy students may give additional weight to the activities done by pharmacists. Serving to this purpose, Greener Pharmacy Guides and Toolkit developed by the Royal Pharmaceutical Society can be used as educational material (Royal Pharmaceutical Society, 2025). These guides contain a list of actions which contribute to sustainable and rational use of medicines and to the establishment of a more sustainable pharmacy. Among the described actions, health promotion and recommendations in terms of disease prevention and correct medicine management are a starting point for environmentally conscious pharmaceutical care. Retail pharmacy workers ought to be aware of current public health problems and introduce patients to available services and health programs, such as flu vaccination, sexual transmission disease prevention, smoking cessation services and hypertension case-finding services.

Further sustainable practices include regularly checking that periodic retrieval of chronic medication is done appropriately. When retrieving monthly medication, patients should be advised to only take the necessary quantity of prescribed drugs to resupply their house stock. In this way, over supplying and household drug overstocking that leads to significant waste generation are avoided (Yang et al., 2025). The pharmacist should also inquire about possible regimen alterations made due to patient needs or desirability, possible health aggravation of the consumer or willingness to continue with the prescription.

Additionally, proper waste disposal should be encouraged in all instances. This may vary depending on local regulations and the availability of drug take-back systems (Wang et al., 2024). Patients are not always familiar with the correct way to manage leftover medicines, therefore they should be advised on how pharmaceutical waste, including packaging, should be correctly disposed of. Patients should be able to differentiate the appropriate ways of disposing of different types of formulations (e.g. oral antibiotic suspensions), medical devices (e.g. inhalers and insulin pens) and veterinary medicines. In order for this, pharmacy students should be well informed about the local drug disposal system (Abajo et al., 2024).

Healthcare digitalization and digital pharmaceutical care also support sustainable practices by promoting equity and individualized patient care, developing a patient-pharmacist collaboration, easing medication follow-ups and giving an alternative to paper drug leaflets (Aboelzahab et al., 2025). The integration of digital health technologies in community pharmacies such as mobile health applications and telepharmacy services may be used to optimize the use of medicines, provide guidelines about correct drug disposal and raise awareness about the environmental impact, such as the dissemination of antimicrobial resistance genes in the environment (Rawson et al., 2024).

4.3. Eco-oriented prescription

Pharmaceutical prescribing is addressed differently depending on the country (Mesbahi et al., 2025). Many countries such as the United Kingdom, France, Australia and the United States, have a formal framework for non-medical prescribing. Eco-oriented prescription

includes simple prescription adjustments, such as preferably choosing oral doses rather than solutions and intravenous solutions, high dose formulations (e.g. half a tablet of enalapril 20 mg instead of 2 tablets of enalapril 5 mg), drug combining forms (e.g. perindopril/amlodipine tablets) and long-release forms (e.g. extended release tramadol 100 mg tablet rather than 2 tablets of tramadol 50 mg) to reduce the frequency of dosing and improve patient compliance (Eii et al., 2023; Maughan et al., 2016). Adjusting the medication following these simple rules may greatly reduce the amount of drug entering the environment, although the setting, the patient and the pharmacology of the prescribed drug should be taken into consideration when choosing the most sustainable option. Furthermore, eco-prescription may be oriented towards lowering carbon emissions, like the election of dry-powder inhalers rather than metered dose inhalers for respiratory diseases when clinically indicated (Janson et al., 2020).

As illustrated previously, sustainable and rational use of medicines highlights the relevance of the individuality of the person receiving the medicine, including social, educational, economic, cultural, pharmacological and environmental traits of each individual. Pharmacogenomics, which studies gene-drug interactions for the prevention of adverse drug effects and prescription cascade, is one of the pillars of personalized medicine that focuses on individualizing the treatment based on the individual's unique characteristics. The Dutch Pharmacogenetics Working Group has created guidelines with recommendations on how to adjust prescriptions based on a pharmacogenetic test (DPWG: Dutch Pharmacogenetics Working Group, 2025). The implementation of a pharmacogenetic panel to prevent adverse drug effects has proven to be beneficial, making pharmacogenetics a useful tool to master by pharmacists. By lowering drug-related adverse effects and avoiding additional prescription, pharmacogenetics may also contribute to a more sustainable pharmacy practice.

Eco-oriented prescription may go even further: considering ecotoxicological data of the possible drug option when prescribing. Statins can be taken as an example on how to prescribe based on efficacy, safety, cost and environmental data. Atorvastatin, simvastatin and rosuvastatin are among the most prescribed statins for treating hyperlipidemia (Hodkinson et al., 2022). Statins are frequently found in the environment (around 0.01–0.02 mg L⁻¹). Simvastatin exhibits high toxicity (LC50 = 0.02 mg L⁻¹) to zebrafish (*Danio rerio*), whereas atorvastatin (LC50 = 20.83 mg L⁻¹) and rosuvastatin (LC50 = 36.75 mg L⁻¹) have a very low toxicity (Han et al., 2022). In a clinical setting, whenever statin therapy is insufficient to control low-density lipoprotein cholesterol (LDL-C) in diabetic patients with cardiovascular symptoms, the dose may be increased or combination therapy should be considered. However, rather than doubling the dose of simvastatin from 20 mg to 40 mg, and considering the environmental impact for this adjustment, switching to another statin, such as atorvastatin or the combination of ezetimibe/simvastatin (10/20 mg) may be a plausible decision (Le et al., 2015).

Besides adding value to good prescribing by sharing insight about environmental, pharmacological and pharmacogenetic evidence, pharmacists also play an important role in medication review and deprescribing which is as important as proper prescribing (Chan et al., 2023). Polypharmacy is one of the biggest issues in older people, and pharmacists are normally well-equipped to participate in the process of tapering off medication (Hernandez-Palacios et al., 2024). Employing AGS Beers and the STOPP/START criteria in the process of drug conciliation or medication review may help reduce the exposure of older people to inappropriate medication (2023 American Geriatrics Society Beers Criteria® Update Expert Panel, 2023; O'Mahony et al., 2023). Moreover, the labour of psychiatry-specialized clinical pharmacists is even more important in drug discontinuation, because small dose adjustments and switching psychotropic drugs may lead to severe outcomes (Luykx et al., 2025). The last stages of antidepressant discontinuation require employing so small dosage, so it does implicate the reformulation of marketed forms, such as tapering individual pellets

of a venlafaxine capsule or diluting fluoxetine oral solution (Gordon, 2024).

6. PUBLIC HEALTH AND PHARMACOEPIDEMIOLOGY

The thalidomide crisis of the 1950 s turned clinical pharmacology upside down. There was an urgent need to develop methods for studying adverse drug reactions at a population level (Wettermark, 2013). Therefore, it was time for two new pharmaceutical fields to emerge, pharmacoepidemiology and pharmacovigilance, which through the years, have proven to be indispensable for rational use of medicines and the preservation of public health. The former by identifying adverse drug reactions in the post-commercialization phase whereas the latter by researching drug utilization in human populations. Additionally, systematisation, global harmonisation and digitalisation of data have contributed to the swift and noticeable development of both fields in recent decades. This has enabled the study of emerging health threats, such as the triple global crisis of chemical pollution, climate change and loss of biodiversity (Cousins et al., 2021).

The 21st century has brought a wealth of evidence on the impact of climate change and environmental stressors on public health. Environmental factors, such as exposure to air pollution, extreme weather events and increased number of zoonotic hosts in disturbed ecosystems, have an impact on more than 100 different diseases and injuries, starting with infectious and parasitic diseases, and followed by non-communicable diseases (e.g. cancer, neurological disorders, respiratory issues) (Bos et al., 2016). Indeed, as illustrated by the One Health Approach, animal, human and environmental health are co-dependent, which means that preserving global health is necessary to secure human and public health (Winkler et al., 2025). In order to promote Sustainable

Pharmacy, pharmacists would benefit from gaining a basic knowledge of the impact of environmental factors on individual and Public Health, as well as how this impact affects pharmacotherapy and the prevention of negative health outcomes. They must also learn how to interpret environmental surveillance and epidemiological data in order to identify adverse drug effects that may affect human health (Fig. 6).

5.1. Wastewater-based epidemiology

The introduction of electronic health records has facilitated data collection for population-level drug utilization research. However, clinical data and questionnaire-based methodologies may be completed with additional data from wastewater-based epidemiology (WBE). Two decades ago, WBE emerged as a complementary tool to study illicit drug consumption by measuring drug concentrations in wastewater, which has also proven as an excellent tool for studying drug utilization (Zuccato et al., 2005). WBE can complement classical pharmacoepidemiological data collection, adding the advantage of providing objective, potentially stratified data in near-real time. Applications of wastewater surveillance have been extended to measure an extensive variety of biomarkers and health determinants which can be used to study population's lifestyle (e.g. caffeine), disease burden (e.g. viral load) and chemical pollutants (e.g. pharmaceuticals and personal care products) (Eaton et al., 2022).

It would be desirable that trainee pharmacists learn to interpret WBE data so that it can be used to study consumption trends of OTC drugs, seasonal changes in drug use/abuse and illicit consumption of prescription drugs. Monitoring health determinants may help in the preparation of public health campaigns in hospitals and retail pharmacies. Moreover, monitoring programs can be applied to smaller communities

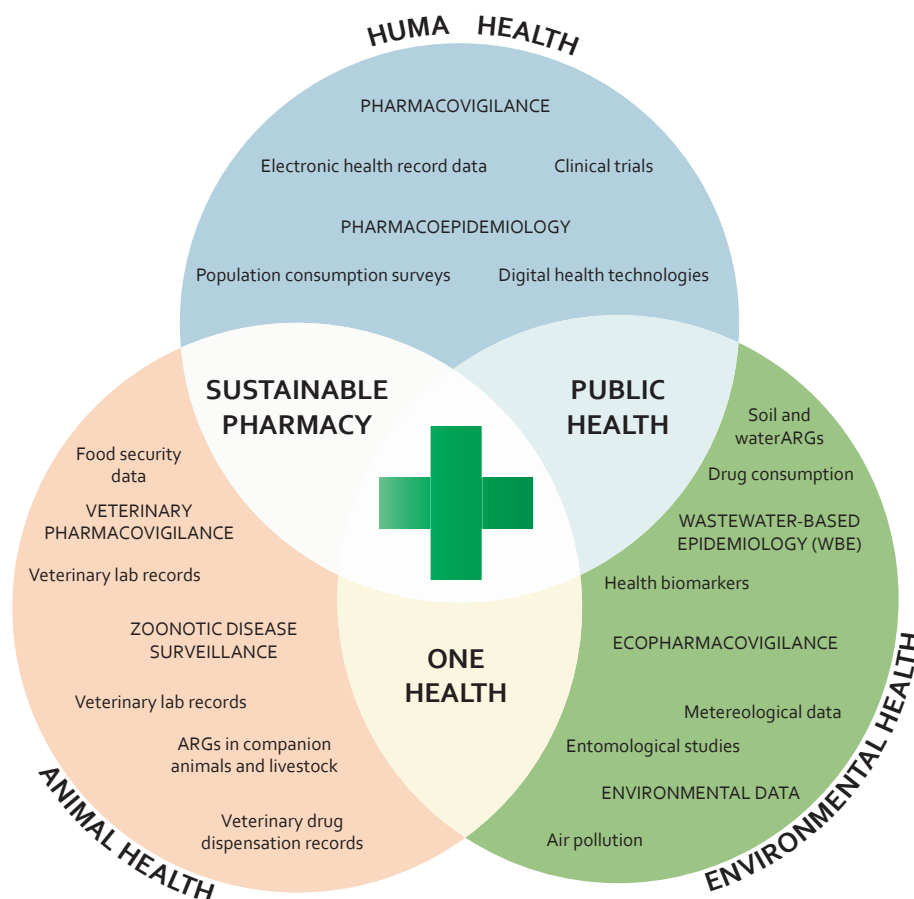


Fig. 6. A diagram of vigilance data and information resources of the use and impact of pharmaceuticals on human, animal and environmental health, the combination of which serves for One Health surveillance, public health studies and Sustainable Pharmacy decision-making.

while preserving anonymity and objectivity avoiding possible stigmatization. For example, pharmacists working at penitentiary centres may find useful information about the misuse of certain licit and illicit drugs based on wastewater surveillance, so that control measures can be imposed (Egaña et al., 2025). Still, ethical and regulatory issues should also be considered (D'Aoust, 2025).

5.2. Public health in a One health context

Antimicrobial resistance is a prevailing public health problem with an estimated 4.71 million deaths occurring each year, and this figure is forecast to rise to 8.22 million by 2050 (GBD 2021 Antimicrobial Resistance Collaborators., 2024). Antimicrobials employed in human medicine, veterinary and crop production reach the environment and pollute rivers, soil and groundwater, which can lead to environmental antimicrobial resistance genes (ARGs) selection and transmission (Larsson and Flach, 2022). This problem particularly affects low- and middle-income countries (LMICs), which lack wastewater treatment infrastructure (Ferro et al., 2025). A One Health approach has been proposed to secure a future that is minimally affected by the consequences of antibiotic misuse (Velazquez-Meza et al., 2022). Recently, the National Health Service (NHS) in England has developed an antimicrobial resistance and antimicrobial stewardship pharmacy undergraduate competency framework to set the minimum knowledge to be acquired by pharmacy undergraduate students (NHS England, 2024). Apart from being familiarized with the mechanisms of ARGs, diagnostic criteria and prescribing, and the rational use of antimicrobial agents, qualified pharmacists should have a demonstrated knowledge regarding infection prevention and control. Therefore, pharmacy professionals need to be capable of raising awareness and educating people about antimicrobials, promoting prevention measures, such as vaccination, and aligning the treatment choice with One Health surveillance data.

At city or national scale, WBE of ARGs can provide specific information on existing resistances to each type of antibiotic (Díaz-García et al., 2025). Knowledge of the most prevalent ARGs can be used to identify antibiotic families that should be used sparingly. Based on this information, adequate and timely campaigns can be developed to promote the use of antibiotics with lower resistance potential. Antimicrobial agents employed in animal farming also contribute to antimicrobial resistance (AMR). Assuming this, several national initiatives have been implemented in recent years, achieving a 50% reduction of overall antibiotic consumption in veterinary medicine (Khamisse et al., 2026).

Climate change, along with the globalization and the reshaping of ecosystems produce an increase of (re)emerging infectious diseases that affect wildlife, plants, animals and humans (Pfenning-Butterworth et al., 2024). The treatment of parasitic diseases affecting human health has been based on a few legacy drugs with resistance potential, since current active research on the discovery of new therapeutic agents is scarce. For example, insecticides such as ivermectin and permethrin, used in humans to treat scabies, show a toxic profile in biologically and economically non-target species (Lima et al., 2024). The current situation regarding zoonotic and vector-borne diseases differs between LMICs and high-income countries (HICs) and requires an adjusted approach. Applying Sustainable Pharmacy concepts could help to resolve this public health problem. Firstly, pharmacists should familiarise themselves with regional disease risks and provide advice on protective measures. For example, due to the resistance of vector agents to insecticides, the use of propellants and protective clothing should be advised instead of insecticide-treated clothing. Topical treatments used for treating or preventing ectoparasite infestations, such as permethrin, should also be used sustainably and responsibly to minimise the potential for resistance development and the environmental risk of parasitocides. Shared decision-making and responsible pet parasiticide prescribing are reliable options to minimize the environmental impact of these treatments (García-Blasco et al., 2023). Pharmacists can help to reduce the amount of drug residue reaching the environment from

topical permethrin used to treat scabies by recommending that excess residue is wiped off with disposable towels after treatment immediately after each application (Bielfeldt et al., 2022; Domingo-Echaburu et al., 2024).

Unlike zoonotic and vector-borne diseases, non-communicable diseases have barely been addressed from a One Health perspective, despite the evidence of the environmental impact on human well-being (Schrijver et al., 2025). The importance of a global mental health approach integrating social health determinants and environmental stressors is gaining traction (Patel et al., 2018). The exposome refers to physical-chemical (e.g. pollen and air pollutants), ecosystemic (e.g. urban land use and green spaces), lifestyle (e.g. sleep behavior and diet) and social (e.g. mental stress and inequality) factors that influence health and disease (Vermeulen et al., 2020). It is estimated that an individual enters in contact with approximately 10.000–100.000 xenobiotics, and although pharmaceuticals are regarded as part of the exposome, normally the exposure is controlled and desired (Pristner & Warth, 2020). Contact with contaminated water, air or soil may cause drug-pollutant interactions on pharmacodynamic or pharmacokinetic levels. Drug-pollutant interactions have been described for different xenobiotics, such as bisphenol A (a commonly used plasticizer), PFAS and particulate matter 2.5 (PM_{2.5}), which may cause cardiac and respiratory diseases (LaPensee et al., 2010; Zhou et al., 2023; Gałęzowska et al., 2026). The consequences of such associations may affect the efficacy and safety of the drug treatment.

With regard to the impact of deteriorating planetary health on public health, extreme weather events and heatwaves are also taken into account (Hunter et al., 2024; Robinson et al., 2024). Medicine use is affected on several levels, starting from drug supply chain disruption, trends in prescribing and drug utilization, and pharmacological alteration on an individual level. Therefore, pharmacists should acquire knowledge, skills and attitudes to minimize the impact of extreme weather situations (FIP, 2025b). These skills include identifying weak points in the healthcare delivery system and pharmaceutical supply chain that are vulnerable to extreme weather events, along with adaptation strategies for medicine distribution and storage in case of environmental emergencies. Moreover, pharmacists should work closely with public health teams to anticipate weather-related stressors and give the necessary advice to patients. As real-time monitoring of environmental health is enhancing and improving, healthcare professionals will want to be able to interpret environmental data (Madsen et al., 2026). For example, Copernicus is the European Union's Space program that provides open and free environmental monitoring data (European Union, 2026a). Recently, a collaborative platform has been created to coordinate the translation of environmental data to healthcare systems and seek potential applications of environmental information to improve public health (European Union, 2026b). The integration of health data and environmental data, despite the existing financial and structural barriers, has already shown positive results in improving health outcomes (Akras et al., 2025). During training in Pharmacy Schools, available case studies of applied environmental data to public health may be employed to familiarize pharmacy students with data interpretation.

5.3. Ecopharmacovigilance

The concept of ecopharmacovigilance (EcoPV) was introduced as an extension of pharmacovigilance, defined as “the science and activities concerning detection, assessment, understanding and prevention of adverse effects or other problems related to the presence of pharmaceuticals in the environment, which affect both human and the other animal species” (Velo & Moretti, 2010). In most undergraduate pharmacy curricula, pharmacovigilance education currently emphasizes the identification and notification of adverse drug reactions (ADRs). EcoPV extends this framework to the environment; however, this science presents its own distinct technical and practical difficulties. For instance,

unlike classical pharmacovigilance, where adverse events are reported by healthcare professionals via spontaneous reporting systems, EcoPV relies on targeted environmental monitoring, sentinel species, and population-level observations (Holm et al., 2013). Moreover, establishing causality between a pharmaceutical and an environmental adverse effect is considerably more challenging due to confounding factors, low concentrations, and delayed effects (Wang and Hu, 2014). These differences must be explicitly addressed when designing EcoPV modules for undergraduate students. The implication for curriculum design is suggested to be based on the World Health Organization and the International Society of Pharmacovigilance WHO-ISoP Core Curriculum (Beckmann et al., 2014), which provides a proven template that can be adapted for ecopharmacovigilance education (Table 2).

Intentional studies or population-level cases (e.g. vultures affected by diclofenac) have been the source of data so far. In order to narrow down the list of suspects to be monitored for adverse environmental events, a list of high-priority pharmaceuticals should be compiled based on current legislation and global monitoring data. Ideally, this list would be centered on local or regional monitoring data (García et al., 2024).

Although there is no established framework for ecopharmacovigilance, some existing cases could be used as examples for future development, as well as for studying by pharmacy students. The recent decommissioning of desflurane is the first case of a human drug withdrawn from the market due to environmental concerns (Moonesinghe, 2024). From January 1st 2026, the use of the anaesthetic desflurane is prohibited in Europe, except in the case when is strictly required and there is no other option (European Commission, 2022a). This is only possible due to the existence of equally effective and safe alternatives, but other medicines (namely the anticonceptive ethynylestradiol) with a meaningful environmental impact (a potent endocrine disruptive effect) are not that easily substituted. However, environmental adverse events should be monitored and when enough evidence exists, environmental safety information should be added to pharmaceutical leaflets and safety reports. In the case of diclofenac for veterinary use, after the vulture crisis this NSAID was banned in some Asian countries, although in India this strategy was not enough due to the toxicity caused by other commercialized NSAIDs and the illicit use of diclofenac for human use in veterinary (Cook et al., 2024).

7. MEDICINES AND THE ENVIRONMENT: REGULATORY FRAMEWORK

Environmental aspects of drug registration for marketing authorisation and the existing regulation on the environmental impact of pharmaceuticals receive barely any attention during pharmacy training, although these aspects are gaining consideration in the current regulatory framework, especially in Europe under the Green Deal umbrella (Harrison et al., 2025). Nowadays, a handful of regulatory initiatives have been proposed for reducing the risks that medicines pose to the environment and public health (Thorner et al., 2026). For example, the updated European Urban Wastewater Treatment Directive, introduces the obligation of eliminating from the wastewater 80% of certain APIs, such as clarithromycin and hydrochlorothiazide, a process that should be partially paid by the pharmaceutical and cosmetic industries (Table 3) (European Commission, 2024). Additionally, the latest version

Table 3
List of pharmaceuticals which removal from wastewater is regulated by the amended Urban Wastewater Treatment Directive.

Category 1 (easily removed substances)	Category 2 (easily disposable substances)
Amisulprid	Benzotriazole
Carbamazepine	Candesartan
Citalopram	Irbesartan
Clarithromycin	Mixture of 4-Methylbenzotriazole and 5-methyl-benzotriazole
Diclofenac	
Hydrochlorothiazide	
Metoprolol	
Venlafaxine	

of the Water Framework Directive includes pharmaceuticals as priority compounds that should be monitored in surface water (Commission, 2022b).

In Europe, the establishment of a mandatory environmental risk assessment (ERA) for medicinal products for human use, when applying for a marketing authorisation (MMA) is an important regulatory reference point (EMA, 2006). Owing to increased knowledge about the impact of pharmaceuticals, the ERA guidance has been recently updated after 20 years (EMA, 2024). For the first time, the amended legislation requires a product lifecycle assessment to be carried out in terms of environmental impact, from manufacturing to disposal. Given its growing relevance, the basic concepts of ERA methodologies should also be considered for inclusion in pharmacy curricula.

The ERA starts with the hazard assessment, which is the identification of the compounds' intrinsic properties that could make it harmful for the environment. The analysis is based on three characteristics: persistence, bioaccumulation and toxicity. After the hazard assessment and depending on the toxicology profile, the substance can be defined as PBT or vPvB (very persistent and very bioaccumulative). Toxicity data is based on apical endpoints such as mortality, reproduction and growth. A predicted no-effect concentration (PNEC) is calculated by dividing the lowest toxicological benchmark value by an appropriate assessment factor (AF), based on the quality and quantity of the available toxicological data. Although currently not included in the ERA, behavioural endpoints can give additional significant data about changes in population. In line with the 3R principles (refine, reduce, replace) and the high costs of fish toxicology bioassays, new approach methodologies (NAMs) in a weight-of-evidence approach are preferred (OECD, 2025). Non-animal approaches include the use of fish cell line cultures, embryos, QSAR analysis and omics, albeit these alternatives are in the early stage of development (Akhrimenko et al., 2025).

After the hazard assessment, risk is analysed by considering the exposure and the probability of toxic effect happening. The risk assessment is divided into two phases: a screening phase or phase I, based on PEC, to determine if a detailed assessment (phase II) is necessary (including a comprehensive evaluation including fate studies, biodegradability, and chronic ecotoxicity testing). The first phase is portrayed as a decision tree with some questions to estimate the exposure: whether it is a naturally occurring substance; if the active substance is a peptide/protein and if so its biodegradability; the fraction of the population receiving the medicine daily, also known as the default market penetration factor (FPEN); if there is some new indications for the drug that

Table 2
Proposed adaptation of the WHO-ISoP PV curriculum (Beckmann et al., 2014) to include ecopharmacovigilance modules.

WHO-ISoP chapter	Classical PV focus	Proposed EcoPV extension
Chapter 4: Individual case safety reports	Human ADR case reports	Environmental case reports (sentinel species, wildlife poisoning events)
Chapter 5: Spontaneous reporting systems	National PV center reporting	Environmental monitoring systems (wastewater surveillance, ecotoxicity databases)
Chapter 6: Signal detection	Statistical signal detection for human ADRs	EcoPV signal detection (emerging pharmaceutical pollutants, temporal trends)
Chapter 7: Pharmacoepidemiology	Drug utilization, cohort and case-control studies	Prescription-environmental concentration linkage, ecological studies
Chapter 11: Risk management	Risk minimization plans for human use	Source control strategies, patient disposal guidelines, green pharmacy
Chapter 13: Communication	Communicating drug risks to HCPs and patients	Communicating environmental risks, leaflet information, public awareness

could increase the exposure and if the predicted effect concentration in surface water (PECSW) is bigger than 0.01. PEC_{SW} can be calculated by the following formula:

$$PEC_{SW} = \frac{DOSE_{AS} * F_{PEN}}{WASTE_{INHAB} * F_D}$$

where $DOSE_{AS}$ [mg/patient*day] is the maximum daily dose of the active substance consumed per patient; F_{PEN} [patients/ inh.] is the fraction of a population receiving the active substance (default value is 0.01); $WASTE_{INHAB}$ [L/inh.*day] is the amount of wastewater per inhabitant per day (default value is 200) and F_D is the dilution factor (default value is 10). The calculated PEC or if available a measured environmental concentration (MEC), is divided by the PNEC to achieve a risk quotient (RQ) value. Acquaintance with basic concepts regarding ERA would be positive for students, so they can manage upcoming regulatory changes.

8. CONCLUSIONS

At present, the environmental crisis demands joint efforts from all the involved stakeholders, including healthcare professionals who are responsible for preventing and treating all kind of diseases, including environmentally-based ones, diseases, as well as consolidating sustainable practices to minimize the environmental impact of the healthcare system. A significant share of the healthcare's environmental footprint comes from drug development, use and disposal. Which is why, pharmacists are a pivotal figure present in all the stages of the drug life cycle, since drug design up to disposal. The foundation of a Sustainable Pharmacy framework that interconnects six domains (education, society, economy, pharmacology, culture and environment) in a whole system requires pharmacists trained to integrate sustainable aspects in their daily work. Currently, sustainability does appear in the pharmaceutical curricula, and green chemistry and rational use of medicines are taught at the Pharmacy Schools. Nevertheless, there is still more significant information and skills that must be transmitted to students across all the main pharmaceutical disciplines. In this article, we have compiled the essential knowledge respecting Sustainable Pharmacy to be acquired by pharmacy undergraduates during their training.

We have reviewed the main blocks of knowledge within pharmaceutical sciences from an environmental point of view. The collected information can be utilized by instructors to reinforce already established topics and give a One Health perspective to the syllabus. Moreover, the articles introduce several new concepts (LADME+, lysophore, dsAPI) and gives examples of different software that can be used to navigate students through the environmental aspects by resolving case studies and resolving real-world situation. The adoption of trans-disciplinary knowledge, including the inclusion of One Health principles in pharmaceutical sciences, can be facilitated by interdisciplinary teaching. Inviting veterinarians, environmentalists and public health experts to instruct students on topics related to One Health and the environmental impact of pharmaceuticals, would benefit Pharmacy Schools. When possible, the interaction and collaborative problem-solving with students from other specialties will provide pharmacy students with a deeper understanding of the interconnection between human, animal and environmental health.

It is clear that the path towards Sustainable Pharmacy is a long road, and the integration of sustainability demands the participation of institutional leaders, curriculum rearrangements and new evaluation metrics. While presenting some limitations, including the focus on the environmental domain and only superficial explanations regarding the other domains (i.e. culture, society, economy) which are equally important, this article sets the fundamentals of Sustainable Pharmacy which may be of aid for establishing the minimal content that should be added to pharmacy programmes. The success of integrating these concepts in the Pharmacy Schools will depend on the perception of the

professoriate, student awareness and the focus of the curriculum. Meanwhile, the information appearing in this article can be used by pharmacists from different sectors and other health professionals, including physicians, nurses, microbiologists and veterinaries, to widen their perspective on the environmental impact of pharmaceuticals.

CRedit authorship contribution statement

Blanca De la Nogal-Fernández: Writing – original draft. **Vladimir Akhrimeko:** Writing – original draft, Conceptualization. **Lidia Maeso:** Writing – review & editing. **Jon Zarate:** Writing – review & editing. **Mirari Ayerbe:** Writing – review & editing. **Saloa Unanue-Arza:** Writing – review & editing. **Mónica Martínez-Cengotitabengoa:** Writing – original draft. **Natalia Burgos-Alonso:** Writing – review & editing. **Giovanna Paolone:** Writing – review & editing. **Linda P. Guamán:** Writing – review & editing. **Karla Lucana:** Writing – review & editing. **Saioa Domingo-Echaburu:** Writing – review & editing. **Unax Lertxundi:** Writing – review & editing. **Gorka Orive:** Writing – review & editing, Conceptualization.

Declaration of competing interest

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

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

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