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Sustainable Recovery of Bioactive Compounds from unused and expired antibiotics

Sanjana Sarma, Ridhima, Harsh Singh, and Rajashree Das

Centre for Medical Biotechnology, Amity Institute of Biotechnology, Amity University Noida UP, India
*Corresponding author: rdas@amity.edu

Abstract

This review summarizes that methodology of bioactive compounds for sustainable recovery by the principles of circular economy, green chemistry and advanced waste management. Ecological damages are mitigated by the use of incineration, chemical treatment of waste and filtration of wastewater. The 3Rs (reduce, reuse, recycle), Waste to Energy (WTE) and thirdly, reducing cost through resource use are more sustainable lab practices. Emerging technologies like AI driven waste monitoring should be used to treat and improve their efficacy. To contribute in economic growth and to prevent environment, sustainable recovery strategies are designed to regulate compliance for better future.

Keywords: Active pharmaceutical ingredients (API), AI in waste management, Antibiotic resistance, Circular economy, Green Chemistry, Opioid and Non-opioid analgesics.

1. Introduction

In recent days, people have started believing that expired drugs are becoming toxic, but originally, they lose their therapeutic efficacy. This believes leads to irregular disposal of drugs. In this regard, there are multiple possibilities to extract and reuse API (Active pharmaceutical ingredients) from unused and expired drugs like painkillers [1].

Nowadays, many organizations are over concern of environmental pollution, which is caused by irregular disposal of drugs, which are being dumped in landfills and many water sources which causes contamination of these sources that promotes the growth of bacteria which are resistant to antibiotic. The organization introduced a concept of circular economy to spread awareness for bringing back the recycle waste into the production house [2].

The transformation of antibiotic waste into beneficial products decreases the harmful impacts on environment and also leads to economic growth [3].The appropriate guidelines and protocols are required to rightfully discard antimicrobial drugs and to promote sustainability.

2. Active Ingredients in Painkillers

Painkillers – called as analgesics are medicines that are particularly designed for pain relieve. The effectiveness of an analgesics will depend upon its active metabolite that determines its action in the body and its potency [4] [5] [6].

Aspirin: It is a Nonsteroidal Anti-Inflammatory Drugs (NSAIDs), it works on mild pain relievers [7] [8] [9].

Ibuprofen: It is a drug which is used for fever and pain relief [10] [11].

Diclofenac: This drug is used for migraine and osteoarthritis [12].

Morphine: It is an opioid drug that works against severe pain and post-surgery [13].

2.1 Types of analgesics

2.1.1 Non-Opioids**-** Non opioids are NSAIDS (non-steroidal anti-inflammatory drugs) / non narcotics, aspirin like analgesics [14]. Non opioid analgesics which relieves pain by reducing local inflammatory responses. These compounds are used for short-term pain relief and for mild pain, such as that of migraine muscle strain, bruising, or osteoarthritis [15] [16] [17].

2.1.2 Opioids- Narcotics or morphine like analgesics is included in this category. The

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opioid analgesics were called narcotic drugs because they act on the brain (CNS) and can induce sleep[18] [19]. The opioid analgesics are addictive and can be taken for shorter or longer period of time[20] [21].

2.2 Aspirin (acetylsalicylic acid)

Aspirin is an NSAIDS that reduces inflammation, mild pain, thins blood to prevent clots and during fever it lowers the body temperature [22] [23].

2.2.1 Harmful effects of aspirin on environment:

The waste water treatment plants are not able to eliminate all pharmaceutical residues that lead to contamination of water which has harmful effect on aquatic life, and it also affects the growth pattern in marine species [24].

The irregular dumping of antimicrobial waste containing aspirin in landfills affect the nutrient cycle.

Continuous exposure of aspirin has a harmful effect causing long term ecological balance [25].

2.3 Ibuprofen (2-(4-isobutylphenyl) propanoic acid)

Ibuprofen is an NSAIDS which reduces pain and inflammation; it is also an antipyretic drug [26].

2.3.1Harmful effects of ibuprofen on environment:

The risk of consumption of drugs for a long term is high.

It impacts the behavior and reproduction of aquatic organisms [27].

2.4 Diclofenac (2-(2,6-dichloroanilino) phenylacetic acid)

Diclofenac is used for osteoarthritis, migraine and menstrual pain; it relieves severe pain and inflammation. This can also be used to reduce post-surgery pain during the time of recovery [28] [29].

2.4.1 Harmful effects of diclofenac on environment:

Due to diclofenac there is decrease in the number of vulture species in South Asia

It causes damage of organs in aquatic organisms (fish)[30].

2.5 Morphine

Morphine is a strong opioid drug that works directly on the CNS. It relieves severe pain, mainly after surgery and on cancer patients [31] [32].

2.5.1 Harmful effects of morphine on environment:

Pharmaceutical waste production from morphine manufacturing becomes hazardous to the environment unless proper waste management protocols exist. Professional cultivation of morphine-producing opium poppies leads to deforestation and damage to land quality in addition to requiring intensive pesticide use during production [33].

Manufacturing 100 mg of morphine results in carbon dioxide emissions that equal driving an average car one kilometer. End-stage manufacturing activities including both sterilization and packaging processes create most of these emissions because they demand considerable energy consumption [34].

3. Sources of medical painkiller waste

3.1 Pharmaceutical manufacturing

*3.1.1 Raw material waste:*In pharmaceutical manufacturing, raw material waste consists of excessive usage of chemical reagents from drug synthesis, expired or decayed API, and also from unused excipients like filters, preservatives and benders [35].

*3.1.2 Production waste:*It consists of left over materials from tablets and formulation residues, out of specification, painkiller batches, liquid production and capsule [36].

*3.1.3 Expired or recalled products:*It consists of those painkillers that have exceeded their life span before use and also from those painkillers that are withdrawn from the production due to safety concerns or regulatory violations [37].

3.2 Hospitals and healthcare facilities

*3.2.1 Patient leftovers:*It consists of unutilized medications from discharged or expired

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patients, syringes, pill bottles or partial doses of medication in IV bags [38].

*3.2.2 Spilled or contaminated medication:*It consists of tablets and capsules become unusable due to irregular handling and also from spills of liquid painkiller during administration [39].

*3.2.3 The disposal of controlled substances:*It includes those painkillers that are needed to go through strict procedure to inhibit medications discarded and misuse due to legal or regulatory compliances [40] [41].

3.3 Household and community waste

*3.3.1 Irregular disposal:*When medications which are not in use are discarded into the trash in the house can increase the risk of environmental harms and also from the medications that are flushed down the toilet or sink that leads to water contamination [42] [43].

3.3.2 Illegal or recreational use waste: This consist of rejected packaging from misuse and leftover substances from unauthorized consumption [44].

3.3.3 Medication waste from caregivers: This consist of drugs that are not in use after a patient recovers or passed away and also it includes unused painkillers from disabled or temporary ill patients [45] [46].

3.4 Research and laboratory waste

*3.4.1 Expired or unused chemicals:*It consists of compounds that are degraded or expired before use and also from surplus reagents and solvents from drug development [47].

*3.4.2 Contaminated laboratory materials:*It includes the usage of glassware gloves, vials with painkiller residues lab coats and also from protective equipment exposed to chemicals in laboratory[48] [49].

*3.4.3 Waste from quality control and testing:*It includes discarded batches of painkillers that do not meet regulatory standards and also from leftover samples from potency and stability test[50] [51].

4.Reuse of extracted active ingredients from expired drugs

Extracting pharmaceutical substances from wasted drugs presents an environmentally friendly solution for pharma waste disposal [52]. These pharmaceutical compounds become valuable when repurposed for scientific research and industrial production as well as medical treatments which simultaneously supports drug development initiatives and lowers expenses and environmental harm[53] [54].

4.1 Aspirin

Aspirin that has been recovered from expired drugs has many applications. It is used in pharmaceutical research as an aid to stabilize and formulation trials. It is brought to the ph of skin in industry for skincare to convert it into salicylic acid [55]. It is used as lab experiments in educational institutions, and purified aspirin is repurposed in veterinary medicine for the pain management [56].These practices in the pharmaceutical sector encourage waste reduction, cost effectiveness and optimization of the resources [57].

4.2 Ibuprofen

Ibuprofen can be used in many fields of applications. It can be used in pharmaceutical research and development as a tool for drug formulation studies, a tool for stability testing and a tool for bioavailability research [58]. Ibuprofen itself is used as a precursor to chemical synthesis in industrial applications to produce related anti-inflammatory drugs. Extracted ibuprofen can be used in analytical chemistry and pharmaceutical training for benefit to educational institutions. In veterinary medicine, purified ibuprofen can be repurposed as a pain medication in animals under veterinary supervision [59]. They are related to waste reduction, resource optimization and circular economy principles in the pharmaceutical industry [60].

4.3 Diclofenac

The recovered diclofenac from the expired drugs has several applications in

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diverse fields. In chemical synthesis, diclofenac serves as a precursor for novel derivative and related anti-inflammatory compounds, and thus potentially improved therapeutic profiles[61]. In addition, purified diclofenac can be used by educational institutions in laboratory experiments, as a purification, analysis or formulation training. By contributing to sustainability, waste reduction and the circular economy principles through these reuse practices, these reuse practices are relevant to the pharmaceutical industry [62] [63].

4.4 Morphine

The extracted morphine can be used to study the pharmacological properties of morphine in laboratories and optimize drug formulation. This helps in improving the existing therapies or the creation of new drugs for the treatment of pain [64]. It is an important precursor for the synthesis of a number of opioids. It can be used to make compound like codeine or semi synthetic opioids which would have differed therapeutic profiles or lack of side effects [65] [66].

5. Disposal of painkiller waste in research and laboratory

5.1 Classification of painkiller waste

Painkiller waste can be classified on its disposal challenges and different composition of chemicals [67] (Figure 1).

5.1.1 Composition based: Strict regulations are needed for painkillers like morphine which are opioid analgesics whereas ibuprofen causes risk on environment which is a non-opioid analgesic. Expired painkillers convert into dangerous substances during their decomposition process. Specific classes of painkillers decompose naturally whereas synthetic NSAIDs are present in the environment [68].

5.1.2 Disposal Challenges: The degradation of expired painkillers produces dangerous compounds and unused painkillers

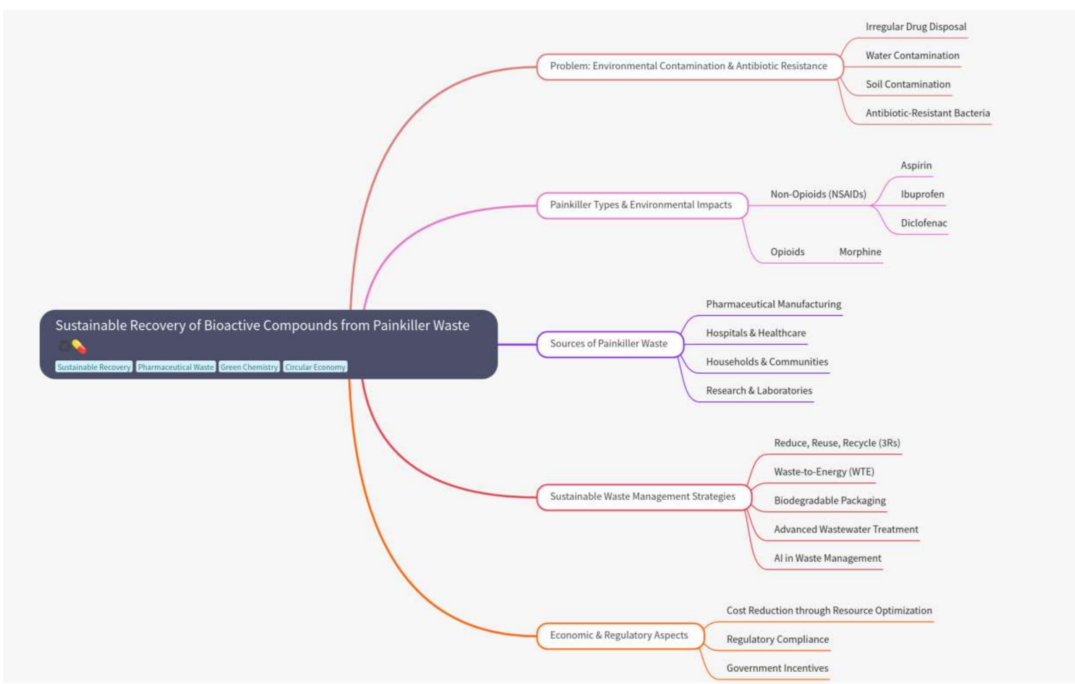

Fig. 1: Sustainable Recovery of Bioactive Compounds from Painkiller Waste

Sustainable Recovery of Bioactive Compounds

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causes contamination, while manufacturing waste requires appropriate management schemes. Proper disposal methods are essential [69].

5.2 Sources of painkiller waste in laboratories

5.2.1 Expired painkillers: Proper disposal of expired or unused painkiller which is stored for research purposes [70].

5.2.2 Residues from experiments research methodologies and testing procedures create experimental residues consisting of active ingredient which represents a hazard to environmental health [71].

5.2.3 The process of drug formulation produces waste materials which contains hazardous substances [72].

5.3 Regulations and guidelines for painkiller waste disposal

Practices for disposing waste painkillers are regulated through environmental safety protocols to prevent improper usage. The authorities of biomedical waste management rules require appropriate disposal methods for both discarded and unnecessary painkillers for reducing environmental pollution [73]. The environmental protection agency through its resource conservation and recovery act governs hazardous pharmaceutical waste disposal. The world health organization offer international standards such as incineration and take-back programs. The regulations of local and national waste disposal authorities specify detailed procedures for pharmaceutical waste transport and safe disposal. All pharmaceutical waste disposals must follow these regulations[74] [75].

5.4 Methods of painkillers waste disposal

The various methods of painkiller waste are:

(i) Incineration process involves destroying of waste from painkiller at high temperatures so that active ingredients are fully destroyed. This process is typically applied for toxic wastes from pharmaceuticals[76].

(ii) Treatment with chemical agents is needed before disposal; to breakdown the compound of hazardous painkillers into substances that are not harmful [77].

(iii) For accurate disposal, different programs are been run by government to return expired painkillers.

(iv) Advancement processes in filtration and treatment from chemicals serves the intended purpose of removing pharmaceutical residues in wastewater, effective for reducing pollutants in water bodies [78].

6. Sustainable and economic growth of laboratory waste

Laboratory waste management is very important as irregular disposal of the waste can lead to various environmental problems taking up sustainable and cost-effective waste management techniques can help laboratories minimize their ecological footprint while optimizing operational costs [79][80].

6.1 Principles of Sustainable Laboratory Waste Management

The principles mainly focus on reducing the waste products, recycling it and adopting green chemistry approaches. Laboratories can reduce waste generation by optimizing resource use, substituting hazardous chemicals with safer alternatives, and implementing circular economy principles that promote reuse [81]. Properly segregating the waste at the source ensures that recyclable and biodegradable materials are effectively processed which reduces the overall burden on landfills and incineration facilities [82].

6.2 Economic Impact of Laboratory Waste

Laboratories produce waste like hazardous chemical, biological, and radioactive, which requires costly specialized disposal.Compliance with regulations demands investments in segregation, storage, equipment, and external services, raising operational costs. Research and healthcare labs assign substantial budgets to

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waste management, often limiting funds for core research, innovation, and scientific advancements [83].

Inefficient inventory management in most laboratories causes undue consumption of reagents, chemicals, and single-use plastics, creating unnecessary waste and loss of money. Disposable items such as plastic pipettes, gloves, and petri dishes add a lot to the volume of waste and need to be replaced continuously, adding more to the cost. Poor planning and inappropriate storage of perishable reagents or temperature-sensitive chemicals also lead to spoilage, compelling labs to replace materials and adding to the total expenditure [84][85].

The improper disposal of any hazardous waste generated in a laboratory can lead to soil, water, and air contamination with associated high costs of remediation and long-term government and institutional funding for cleanup operations [86]. Other than the health complications posed to laboratory personnel, hazardous waste also complicates the health risks borne by the waste handlers, as well as by the surrounding communities. These factors altogether increase healthcare treatment costs and issues of prolonged health risks [87].

6.3 Sustainable Waste Disposal Methods

6.3.1 Reduce, reuse and recycle (3Rs): It plays crucial role in reducing the environmental impact. The concept of reduce, consist of both reducing the consumption of resources through limited usage and also by choosing environment friendly material [88].The concept of Reuse, can easily extend the lifespan of the product by repairing the product, repurposing or through donation to lower the need for new production. The concept of recycling is to turn waste into materials such as paper, plastic, metals and glass into new product which saves resources and also minimizes the need to dump waste in landfills [89][90].

6.3.2 Waste to Energy (WTE): The process of conversion of waste to energy (WTE) uses, unusable waste to produce useful forms of energy by using techniques which consist of incineration and anaerobic digestion. The production of energy from this method reduced the amount of waste ending upon landfills [91][92].

6.3.3 Biodegradable and Eco-friendly packaging: The adaptation of environmentally friendly packaging consists of materials from plant sources that naturally degrade into the environment easily instead of conventional plastics. These packaging are manufactured to decompose in nature which helps in reduction of environmental harm [93].

*6.3.4 Landfill Management and gas recovery:*A specialized site known as sanitary landfills incorporates liners and leachate treatment methods to stop untreated liquid from contaminating to earth and aquatic environments. The emissions of methane from waste decomposition are a huge source of renewable energy, the facilities capture and transform this gas into usable electricity [94].

6.3.5 Ocean and plastic waste reduction: To fight against the ocean plastic pollution it requires to prohibits the single use plastics and addressing people for carrying out organized cleanups or recycling to reduce marine contamination. Marine plastic waste reduction gets additional helps from the development of biodegradable plastics and improvements in waste collection methods [95][96].

6.4 Regulatory Compliance & Incentives

The practice of regulatory compliances requires organisation to follow strict environment laws in order to protect both sustainable operations or to prevent penalties[97]. To boost, industrial green adaptation government provides eco-friendly technology incentive by reducing the taxes. This helps organisation to achieve better environmental performance by the time regulations remain strict while beneficial incentives exist alongside them [98].

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7. Current technologies for laboratory waste management

7.1 Waste to Energy (WTE) Technique:

To decrease contamination in the environment, waste to energy technology is used, as it changes pharmaceutical waste into energy that can be utilized. Incineration systems using energy recovery, burn painkillers at high temperature to create energy that produces electricity or steam. The gasification method changes waste into syngas (synthetic gas). Microorganisms produce biogas when they decompose organic pharmaceutical waste in anaerobic digestion process. Safe painkiller waste management through these technologies offer both on environmentally responsible method and sustainable energy generation while reducing contamination risks [99][100].

7.2 Advanced wastewater treatment:

The removal of pharmaceutical residues such as painkiller waste is needed to prevent environmental contamination and requires advanced wastewater treatment. Drug residues can be absorbed by activated carbon filtration, effectively contaminating them. Ozone, UV light and hydrogen peroxide are advanced oxidation processes that break down pharmaceutical compounds. Microorganisms (such as Pseudomonas spp, Bacillus spp, and White rot fungi) are used in biological treatment for the degradation of the pharmaceutical waste naturally. These methods help assure cleaner water and minimize the risks related to health [101].

7.3 Green chemistry and Biodegradable materials:

The main goal of green laboratory is to protect environmental damage by using resources effectively with the possible alternate energy sources and selecting non-hazardous material. When available bioplastic and compostable packaging decompose naturally to provide an opportunity for reducing the environmental waste and minimizing the amount of material which ends up in landfills [102].

7.4 Smart waste segregation and monitoring

Fielding uses sensors based on artificial intelligence, internet and technologies to established automated waste sorting system that helps in the recognition of different materials as well as organic or harmful waste. Efficient waste management system can develop through the implementation of waste tracking system together with routing optimization. System technologies improvement will help in greenhouse gas reduction by providing better eco-friendly waste management solutions for waste diversion [103].

7.5 Bioprocesses and Enzymes based treatment:

Fungal and bacterial microbes convert toxic substances into less toxic end products that are an environmental remediation for environmental pollutions. Enzyme based treatments enhancewaste destruction rate by the application of certain enzymes that decomposes industrial pollutants with destruction rate by the application of certain enzymes that decomposes industrial pollutants [104] [105].

Enzymes such as Oxidoreductases which breaks complex organic pollutants into simpler ones and Hydrolases, this breaks complex molecules into simpler ones[106].

8. Sustainability Approaches in laboratory Waste Management

8.1 Waste Reduction and circular economy:

Waste reduction focus on methods that are used to reduce material usage during the process of developing environmentally friendly methods that reduces waste production in the model of circular economy, product, materials and resources continue through regenerative cycles by the help of 3R's model that increases their lifespan. These waste reduction technique helps in reducing landfill waste and also conserve natural resources to establish an economic model which is based on sustainability [107] [108].

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8.2 Digital Transformation to reduce waste:

To enhance waste management with smarter monitoring system and automated waste sorting abilities with analytical predication and analysis by merging AI based model with Internet of Things (IOT) and block chain method [109]. A paperless system together with cloud computing in business operations will decrease waste materials while real-time waste tracking systems implemented through electronic waste containers enhance collection methods. Innovative solutions generate swift sustainability benefits to both environment and costs and assist circular economic innovation [109].

Conclusion

The bioactive compounds recovery from pharmaceutical wastes, and consequently from the painkillers specifically, is an important sustainable recovery that can minimize environmental contamination and promote economic growth. Disposal of expired or unused drugs in water or soil contaminates the environment and human health. Mitigation of these risks can be realized through implementing circular economy principles, green chemistry, and advanced waste management technology.

Methods for effective disposal including incineration, chemical treatment, and filtration of wastewater, diminish the environmental hazards. Sustainable laboratory wastes management assumes the 3Rs (Reduce, Reuse, Recycle) and waste to energy (WTE) techniques to reduce waste and optimize resource use while reducing costs. Eco-friendly practices would also benefit from regulatory compliance and government incentives.

Pharmaceutical waste management can be improved via future innovations in AI driven waste monitoring, bioprocessing as well as digital solutions. Since environmental protection, resource conservation, and a healthier future shall be achieved through prioritizing sustainable recovery and proper disposal, these elements need to top the priority list during this period.

Conflicts of Interest

The authors declare no conflicts of interest in this work.

References

1. Sharma, M.; Kumar, A.; Chaudhary, A. Reuse API (Active Pharmaceutical Ingredients) from expired dosage form. Int. J. Eng. Res. Technol. 2021, 10, 350655597.
2. Pratama, D. E.; Hsieh, W.-C.; Elmaamoun, A.; Lee, H. L.; Lee, T. Recovery of active pharmaceutical ingredients from unused solid dosage-form drugs. ACS Omega 2020, 5, 29147-29157.
3. Ciannella, S.; Wu, X.; Gonzalez-Fernandez, C.; Rezaei, B.; Strayer, J.; Choe, H.; Wu, K.; Chalmers, J.; Gomez-Pastora, J. Kinetic and parametric analysis of the separation of ultra-small, aqueous superparametric iron oxide nanoparticle suspensions under quadrupole magnetic fields. Micromachines 2023, 14, 2107.
4. National Cancer Institute. Analgesic. NCI Dictionary of Cancer Terms. Available online: https://www.cancer.gov/publications/dictionaries/cancer-terms/def/analgesic
5. Analgesic. Wikipedia. Available online: https://en.wikipedia.org/wiki/Analgesic
6. Analgesics. Drugs.com. Available online: https://www.drugs.com/drug-class/analgesics.html.
7. Analgesics.ClevelandClinic, 22 March 2021. Available online: https://my.clevelandclinic.org/health/drugs/21483-analgesics.
8. Gotter, A. Aspirin: Is it an NSAID? Healthline, 29 September 2022. Available online: https://www.healthline.com/health/pain-relief/is-aspirin-nsaid.
9. Nonsteroidal anti-inflammatory drug. Wikipedia. Available online: https://en.wikipedia.org/wiki/Nonsteroidal_anti-inflammatory_drug.
10. Ibuprofen (DB01050). DrugBank. Available online: https://go.drugbank.com/drugs/DB01050.
11. Ibuprofen Oral: Uses, Side Effects, Interactions, Pictures, Warnings & Dosing. WebMD. Available online: https://www.webmd.com/drugs/2/drug-5166-9368/ibuprofen-oral/ibuprofen-oral/details.

Vol. 19 (Supplementary Issue 3A), September 2025, ISSN 0973-8916 (Print)., 2230-7303 (Online)
10.5530/ctbp.2025.3s.8

12. Diclofenac (DB00586). DrugBank. Available online: https://go.drugbank.com/drugs/DB00586.
13. Morphine sustained-release tablets. Cleveland Clinic. Available online: https://my.clevelandclinic.org/health/drugs/18845-morphine-sustained-release-tablets.
14. Narouze, S. Multiple actions of non-opioid analgesics. Pain Res. Treat. 2009, 2009, Article ID 326859.
15. Samad, T. A.; Moore, K. A.; Sapirstein, A.; Bubb, M. R.; Woolf, C. J. Multiple actions of non-opioid analgesics. Br. J. Pharmacol. 2009, 158, 3-26.
16. McGetrick, M.; O'Connor, M. Non-steroidal anti-inflammatory drugs: A review of their efficacy and safety in the treatment of osteoarthritis. Ther. Adv. Musculoskelet. Dis. 2010, 2, 215-223.
17. Vane, J. R.; Botting, R. M. Anti-inflammatory drugs and their mechanism of action. Inflamm. Res. 1998, 47, 78-87.
18. Centers for Disease Control and Prevention. CDC guideline for prescribing opioids for chronic pain. Available online: https://www.cdc.gov/mmwr/volumes/65/rr/rr6501e1.htm.
19. Davis, M. A.; Uezato, A. Alcohol and opioid misuse: Neurobiological and behavioral mechanisms. Int. J. Environ. Res. Public Health 2018, 15, 431.
20. Information for consumers - Opioid Analgesic Stewardship in Acute Pain Clinical Care Standard. Available online: https://www.safetyandquality.gov.au/standards/clinical-care-standards/opioid-analgesic-stewardship-acute-pain-clinical-care-standard/information-consumers-opioid-analgesic-stewardship-acute-pain-clinical-care-standard.
21. Darker, C. D.; Sweeney, B. P.; Barry, J. Opioid analgesics for chronic non-cancer pain: a narrative review of the effectiveness and safety. Clin. Drug Investig. 2014, 34, 829-842.
22. Aspirin. Wikipedia. Available online: https://en.wikipedia.org/wiki/Aspirin.
23. Recchiuti, A.; Serhan, C. N. Aspirin-triggered lipoxins: Resolution pharmacology in pregnancy complications. Front. Immunol. 2017, 8, 261.
24. Environmental Protection Agency. The impact of pharmaceuticals released to the environment. Available online: https://www.epa.gov/household-medication-disposal/impact-pharmaceuticals-released-environment.
25. Pedrini, S.; Stevens, J. C.; Dixon, K. W. Seed encrusting with salicylic acid: A novel approach to improve establishment of grass species in ecological restoration. PLoS ONE 2021, 16, e0242035.
26. Ibuprofen - Mechanism of action. DrugBank. Available online: https://go.drugbank.com/drugs/DB01050#mechanism-of-action (accessed on 29 March 2025).
27. Schnörr, S. J.; Steenbergen, P. J.; Richardson, M. K.; Champagne, D. L. The influence of behavioral, social, and environmental factors on reproducibility and replicability in aquatic animal models. Front. Behav. Neurosci. 2020, 14, 586680.
28. Diclofenac oral: Uses, side effects, interactions, pictures, warnings & precautions - WebMD. WebMD. Available online: https://www.webmd.com/drugs/2/drug-4284-4049/diclofenac-oral/diclofenac-sodium-enteric-coated-tablet-oral/details.
29. Diclofenac. DrugBank. Available online: https://go.drugbank.com/drugs/DB00586).
30. Iqbal, M.; Nogueira, J. M. F. Diclofenac: Environmental fate and effects. Environ. Toxicol. Pharmacol. 2017, 49, 121-130.
31. Compound Summary for CID 5288826, Morphine. PubChem. Available online: https://pubchem.ncbi.nlm.nih.gov/compound/Morphine (accessed on 29 March 2025).
32. Morphine. DrugBank. Available online: https://go.drugbank.com/drugs/DB00295.
33. Sherman, M. A.; Overton, Y.; Nielsen, E.; Harley, K.; McAlister, P.; McGain, F. The carbon footprint of intravenous morphine: A 'cradle-to-grave' life cycle assessment. BMJ Open 2016, 6, e013302.
34. McAlister, S.; Ou, Y.; Neff, E.; Hapgood, K.; Story, D.; Mealey, P.; McGain, F. The environmental footprint of morphine: A

Vol. 19 (Supplementary Issue 3A), September 2025, ISSN 0973-8916 (Print)., 2230-7303 (Online)
10.5530/ctbp.2025.3s.8

life cycle assessment from opium poppy farming to the packaged drug. BMJ Open 2016, 6, e013302.

35. VLS Environmental Solutions. Types of pharmaceutical waste and how to dispose of them. Available online: https://lms.thsti.in/wp-content/uploads/2024/04/Types-of-Pharmaceutical-Waste-and-How-to-Dispose-of-Them-_-VLS.pdf.

36. World Health Organization. Safe management of pharmaceutical waste from health care facilities: Global best practices. Available online: https://iris.who.int/bitstream/handle/10665/380586/9789240106710-eng.pdf?sequence=1.

37. Netsol Water. What are the environmental impacts of unused or expired medicine? Available online: https://www.netsolwater.com/what-are-the-environmental-impacts-of-unused-or-expired-medicine.php?blog=3992.

38. Disposing of unused or expired medicines. MedlinePlus, 9 October 2024. Available online: https://medlineplus.gov/ency/patientinstructions/000943.htm.

39. U.S. Food and Drug Administration. Disposal of unused medicines: What you should know. Available online: https://www.fda.gov/drugs/safe-disposal-medicines/disposal-unused-medicines-what-you-should-know.

40. Controlled substances disposal procedure. University of Iowa Environmental Health & Safety. Available online: https://ehs.research.uiowa.edu/controlled-substances-disposal-procedure.

41. Hayes, B. D.; Garwood, C. L. Role of the pharmacist in proper medication disposal. US Pharmacist 2011, 36, 52-55. Available online: https://www.uspharmacist.com/article/role-of-the-pharmacist-in-proper-medication-disposal.

42. Yimer, A.; Moges, G.; Kahissay, M. H. Household storage and disposal of unused and expired medicines in Dessie, Ethiopia: a cross-sectional study. Front. Public Health 2024, 12, 1422304.

43. Waste Today Staff. The dangers of improper drug disposal. Waste Today, 29 October 2018. Available online: https://www.wastetodaymagazine.com/article/the-dangerous-of-improper-drug-disposal/.

44. McAlister, S. L.; van Leeuwen, W.; van Zelst, B. D.; Steuten, L. M. G.; van Harten, W. H.; Huijgens, P. C. Environmental and economic outcomes of redispensing unused oral anticancer drugs. Front. Public Health 2024, 12, 1367340.

45. Samuel, A.; King, A. M.; Szydlowski, V.; Ramirez, A. G.; Delgado, A.; Schroeder, A.; Cumpston, K. L. Leftover medications in homes with children: Prevalence, disposal practices, and knowledge. Am. J. Emerg. Med. 2023, 63, 122-126.

46. O'Keeffe, G. S.; Clarke-Pearson, K. Clinical report—The impact of social media on children, adolescents, and families. Pediatrics 2011, 127, 800-804.

47. Grajek, M.; Jóźwiak, B.; Szpyrka, E. Improper handling of unused/expired pharmaceuticals by society as an important problem in waste management systems—A review. Sustainability 2022, 14, 15844.

48. Centers for Disease Control and Prevention. Regulated medical waste. Guidelines for Environmental Infection Control in Health-Care Facilities. Available online: https://www.cdc.gov/infection-control/hcp/environmental-control/regulated-medical-waste.html.

49. Requirements for chemical disposal to sinks and drains. Environmental Health and Safety Office, Ball State University, November 2011. Available online: https://www.bsu.edu/-/media/WWW/DepartmentalContent/Facilities/PDF/BSU%20Sewer%20Disposal%20Nov%2016%202011.pdf

50. Waste management in quality control laboratory. PharmaGuideline.co.uk. Available online: https://www.pharmaguideline.co.uk/waste-management-in-quality-control-laboratory/.

51. World Health Organization. WHO good practices for pharmaceutical quality control laboratories (WHO Technical Report Series, No. 957, Annex 1). Available online: https://www.who.int/docs/default-source/medicines/norms-and-standards/guidelines/quality-control/trs957-

Vol. 19 (Supplementary Issue 3A), September 2025, ISSN 0973-8916 (Print)., 2230-7303 (Online)
10.5530/ctbp.2025.3s.8

annex1-goodpractices-harmaceuticalquality control-laboratories.pdf.

52. Tjandra, J.; Putra, I. N.; Soetaredjo, F. E. Drug Recycle: Recovery of Active Pharmaceutical Ingredients (APIs) from Unused Tablets and Capsules. Ind. Eng. Chem. Res. 2020, 59, 21462-21470.

53. Tjandra, J.; Putra, I. N.; Soetaredjo, F. E. Chemical Upcycling of Expired Pharmaceuticals: Synthesis of Azaspirocycles from Gabapentin and Pregabalin. Int. J. Mol. Sci. 2024, 25, 6391.

54. Sharma, M.; Kumar, A.; Chaudhary, A. Reuse API (Active Pharmaceutical Ingredients) from Expired Dosage form. Int. J. Eng. Res. Technol. 2019, 8, IJERTV8IS060251.

55. Expired medications: Dangerous or just less effective? UH Hospitals, 23 August 2023. Available online: https://www.uhhospitals.org/blog/articles/2023/08/expired-medications-dangerous-or-just-less-effective

56. Shmerling, R. H. Is it ok to use medications past their expiration dates? Harvard Health Publishing. Available online: https://www.health.harvard.edu/staying-healthy/is-it-ok-to-use-medications-past-their-expiration-dates.

57. Cantrell, L.; Suchard, J. R.; Wu, A.; Gerona, R. R. Stability of active ingredients in long-expired prescription medications. Arch. Intern. Med. 2012, 172, 1685-1687.

58. Borak, J.; Diller, W. F. Phosgene exposure: Mechanisms of injury and treatment strategies. J. Occup. Environ. Med. 2001, 43, 110-119.

59. Rainsford, K. D. Ibuprofen: pharmacology, efficacy and safety. J. Pharm. Pharmacol. 2009, 61, 309-330.

60. Ibuprofen. DrugBank. Available online: https://go.drugbank.com/drugs/DB01050.

61. Goel, R. Do diclofenac expire on there expiry date? Drugs.com, 18 July 2010. Available online: https://www.drugs.com/answers/do-diclofenac-expire-on-there-expireing-date-292208.html.

62. Kumar, A.; et al. Investigation of the change in the physical, chemical, and efficacy parameters of commonly used analgesic agents over a period of two years after their expiry date. J. Pharm. Investig. 2022, 53, 153-165.

63. Goodwin, $$First Initial if Available]. From waste to worth: Circular economy approaches in the pharma sector. LinkedIn Pulse. Available online: https://www.linkedin.com/pulse/from-waste-worth-circular-economy-approaches-pharma-sector-goodwin-sd2xc.

64. The dangers of improper drug disposal. Waste Today Magazine, 1 October 2018. Available online: https://www.wastetodaymagazine.com/article/the-dangerous-of-improper-drug-disposal/.

65. Yimer, A.; Moges, G.; Kahissay, M. H. Household storage and disposal of unused and expired medicines in Dessie, Ethiopia: a cross-sectional study. Front. Public Health 2024, 12, 1422304.

66. Medication disposal: How — and why — to do it safely. Harvard Health Publishing, 1 March 2024. Available online: https://www.health.harvard.edu/staying-healthy/medication-disposal-how-and-why-to-do-it-safely.

67. VLS Environmental Solutions. Types of Pharmaceutical Waste and How to Dispose of Them. VLS Environmental Solutions, 31 October 2022. Available online: https://www.vlses.com/2022/10/31/types-of-pharmaceutical-waste/.

68. Tello-Ruiz, M. K.; Cajamarca-Guzmán, M.; Dávila-Sánchez, P. Ibuprofen as an Emerging Contaminant: Biodegradation Potential of Bacteria. Int. J. Mol. Sci. 2023, 24, 5745.

69. Drug expiration dates - Are expired drugs still safe to take? Drugs.com. Available online: https://www.drugs.com/article/drug-expiration-dates.html.

70. VLS Environmental Solutions. Types of pharmaceutical waste and how to dispose of them $$PDF Document]. Available online: https://lms.thsti.in/wp-content/uploads/2024/04/Types-of-Pharmaceutical-Waste-and-How-to-Dispose-of-Them-_-VLS.pdf.

71. Kumirska, J. (Ed.). Pharmaceutical residues in the environment (Special Issue). Molecules (MDPI).

Vol. 19 (Supplementary Issue 3A), September 2025, ISSN 0973-8916 (Print)., 2230-7303 (Online)
10.5530/ctbp.2025.3s.8

72. Mohtar, W. H. M.; et al. Environmental Fate and Ecological Risk Assessment of Non-Steroidal Anti-Inflammatory Drugs (NSAIDs) in the Urban Water Cycle. Int. J. Environ. Res. Public Health 2023, 20, 3277.

73. Wawrzyniak, P. A.; Nowicki, M.; Kujawski, J. Consumption of Pharmaceuticals and Disposal of Unused/Expired Pharmaceuticals by Polish Residents. Int. J. Environ. Res. Public Health 2019, 16, 5137.

74. U.S. Food and Drug Administration. Disposal of unused medicines: What you should know. Available online: https://www.fda.gov/drugs/safe-disposal-medicines/disposal-unused-medicines-what-you-should-know

75. Wiśniewska, M.; Kulczyński, B.; Gramza-Michałowska, A. Improper Handling of Unused/Expired Pharmaceuticals by Society as an Environmental Problem. Sustainability 2022, 14, 16803.

76. How does a medical waste incinerator work? Addfield Environmental Solutions. Available online: https://addfield.com/how-does-a-medical-waste-incinerator-work/.

77. United Nations Office on Drugs and Crime. Guidelines for the safe handling and disposal of chemicals used in the illicit manufacture of drugs (ST/NAR/36/Rev.1; Sales No. E.11.XI.14); United Nations, 2011.

78. Mellam, I. P. (Ed.). Guidelines for safe disposal of hazardous wastes generated from laboratories: Environmental safeguard measures; ICAR-National Agricultural Higher Education Project (NAHEP), 2021. Available online: https://nahep.icar.gov.in/pdf/Final HWMguidelines23.09.2021.pdf

79. Safeguarding the environment: A guide to laboratory waste management. CrelioHealth Blog. Available online: https://blog.creliohealth.com/safeguarding-the-environment-a-guide-to-laboratory-waste-management/.

80. Waste and recycling in laboratories. University of Oxford - Sustainability. Available online: https://sustainability.admin.ox.ac.uk/lab-waste.

81. Opperman, C. J.; Singh, S.; Barton, F. Appropriate disposal of waste in the laboratory: Neglected but not forgotten. Afr. J. Lab. Med. 2022, 11, 1786.

82. 5 ways to make your laboratory more sustainable. Biosistemika Blog. Available online: https://biosistemika.com/blog/5-ways-to-make-your-laboratory-more-sustainable/.

83. Rajadurai, M.; Chawla, S.; Satheesh, M. A. Waste management: An overview of the economic impact and health hazards. J. Pharm. Sci. Res. 2021, 13, 179-187.

84. The importance of proper waste management in laboratories. Advisory Excellence. Available online: https://www.advisoryexcellence.com/the-importance-of-proper-waste-management-in-laboratories/.

85. Institute of Environmental Sciences, Bogazici University, Laboratory Commission Safety and Waste Management Team. Laboratory waste management plan, June 2021. Available online: https://esc.bogazici.edu.tr/sites/iesc.boun.edu.tr/files/Research/Lab_safety/laboratory_waste_management_plan.pdf

86. A laboratory waste disposal guide. Business Waste. Available online: https://www.businesswaste.co.uk/news/a-laboratory-waste-disposal-guide/

87. The importance of hazardous waste management for laboratories. Broadview Waste Services, 4 December 2019.

88. 5 consequences of mismanaging hazardous waste. Triumvirate Environmental. Available online: https://www.triumvirate.com/blog/consequences-of-mismanaging-hazardous-waste.

89. Ten ways to reduce laboratory waste. NEBInspired Blog, New England Biolabs, 1 April 2021. Available online: https://www.neb.com/en/nebinspired-blog/ten-ways-to-reduce-laboratory-waste.

90. The significance of proper waste disposal in laboratory settings. Advisory Excellence. Available online: https://www.advisoryexcellence.com/the-significance-of-proper-waste-disposal-in-laboratory-settings/.

91. What is waste-to-energy? RTS. Available online: https://www.rts.com/blog/what-is-waste-to-energy/

Vol. 19 (Supplementary Issue 3A), September 2025, ISSN 0973-8916 (Print)., 2230-7303 (Online)
10.5530/ctbp.2025.3s.8

92. Waste-to-energy. IBM. Available online: https://www.ibm.com/think/topics/waste-to-energy.
93. Eco-friendly packaging alternatives for your business. British Business Bank. Available online: https://www.british-business-bank.co.uk/business-guidance/guidance-articles/sustainability/eco-friendly-packaging-alternatives
94 .Mojiri, A.; Ohashi, A.; Ozaki, N.; Vakil, S. Treatment of landfill leachate with different techniques. J. Water Resour. Dev. 2021, 11, 66-85.
95. Sustainable packaging: Types, benefits, and challenges. ThomasNet. Available online: https://www.thomasnet.com/insights/sustainable-packaging/.
96. From popular to lesser-known types of biodegradable packaging. Weavabel. Available online: https://www.weavabel.com/blog/from-popular-to-lesser-known-types-of-biodegradable-packaging.
97. Environmental compliance: A comprehensive guide. Advisera. Available online: https://advisera.com/articles/environmental-compliance/.
98. Industrial Compliance Section. Government of Newfoundland and Labrador, Department of Environment and Climate Change. Available online: https://www.gov.nl.ca/ecc/env-protection/ics/.
99. Top 5 trends in science laboratory equipment in 2025. Microlit, 20 January 2025. Available online: https://www.microlit.com/top-5-trends-in-science-laboratory-equipment-in-2025/.
100. 10 technological innovations shaping waste management in 2025. Circular Online, 27 March 2025. Available online: https://www.circularonline.co.uk/features/10-technological-innovations-shaping-waste-management-in-2025/.
101. Advanced wastewater treatment for separation and removal of pharmaceutical residues and other hazardous substances - Needs, technologies and impacts: A government-commissioned report (Report 6766). Naturvårdsverket (Swedish Environmental Protection Agency), 2018.
102. Wastewater treatment in pharmaceutical industry. Condorchem Envitech. Available online: https://condorchem.com/en/blog/wastewater-treatment-in-pharmaceutical-industry/.
103. Bui, J.; Wong, J. W.; Ma, S.; Ganzen, A. M.; Abadeer, R.; Musuuza, J. Greening up laboratories by reducing waste production and water and energy use. Infect. Control Hosp. Epidemiol. 2024, 46, 408-417.
104. Namratha, A. M.; Nandini, S.; Nanditha, K.; Meghashree, C.; Manjula, G. Automatic waste management and segregation system using IoT. Int. J. Eng. Res. Technol. 2021, 9, IJERTCONV9IS12031.
105. Yaashikaa, P. R.; Senthil Kumar, P.; Priya, A. K.; Karunanithi, T.; Vo, D. -V. N.; Yaashikaa, P. B. Role of microbes in bioremediation of heavy metals contaminated soil: a short review. Front. Plant Sci. 2024, 15, 1420408.
106. Rathi, N.; Kumar, R.; Pathak, J.; Bhatt, P.; Kumar, A.; Sharma, S.; Kumar, D. Multi-omics approaches in microbial-mediated bioremediation: current status and future prospects. Front. Microbiol. 2018, 9, 1132.
107. Circular economy. Wikipedia. Available online: https://en.wikipedia.org/wiki/Circular_economy.
108. Lacy, P.; Rutqvist, L. 5 opportunities of a circular economy. World Resources Institute, 26 October 2022. Available online: https://www.wri.org/insights/5-opportunities-circular-economy.
109. Nasir, M. A.; Hussain, M.; Asif, H. M.; Javed, A. R.; Ahmad, R. F.; Shah, S. F. Waste management 2.0 leveraging IoT for an efficient and eco-friendly smart city solution. Environ. Sci. Pollut. Res. 2024, 31, 115166-115189.