Breaking Lock-Ins to Enable Environmentally Safe and Sustainable Pharmaceuticals

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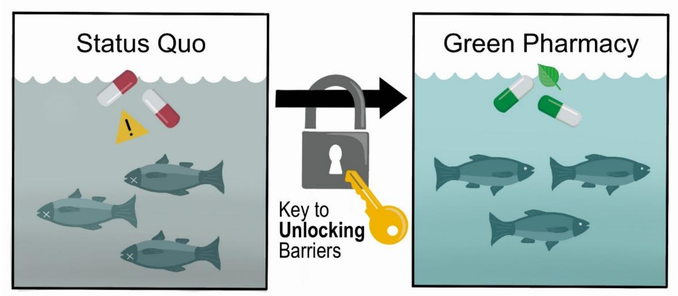
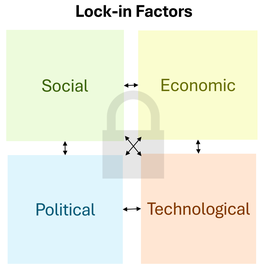
KEY TAKEAWAYS

- **Hazardous pharmaceuticals** released to environment
- **"Lock-in" framework** used to identify barriers to implementing green drug design
- We recommend **actionable measures** for key stakeholders



BACKGROUND

- **Widespread environmental pollution** of pharmaceuticals[1]
- **Toxic effects** in non-target organisms[1,2]
- Need creative solutions to maintain patient access while reducing pollution
  - "**Benign-by-design**" and "**ecopharmacovigilance**" [3,4]
- **Lock-in**[5] results in barriers



RESEARCH QUESTIONS

1. What are the **systemic barriers** preventing us from implementing environmentally "benign-by-design" drugs?
2. How can we **break lock-ins** towards safe and sustainable pharmaceuticals?

LOCK-IN 1: RESOURCE TIMING MISALIGNMENT

- Environmental safety and sustainability considerations are **most effective in early stages** of drug development, while necessary resources become available in the late stages

A

Key Actors

Academia and biotech start-ups

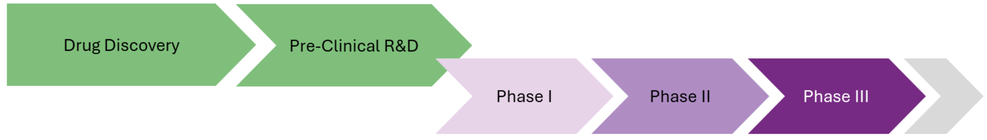
Economic factors:
- Low economic risk, high potential reward if bought out by big pharma

Social factors:
- In academia, failure in high-risk drug development is acceptable. Focus is knowledge generation and degree attainment

Big Pharma

Economic factors:
- Access to adequate funding for clinical trials
- Lower risk to invest in drugs which have already proven some degree of efficacy
- Large pool of drug candidates to choose from

Technological factors:
- Experience, knowledge, and technical capacity to conduct clinical trials and upscaling for commercialization



B

Factors hindering integration of environmental safety and sustainability

1. In Early Drug Development

Economic factors:
- Market + patent time pressure
- High cost of testing

Social factors:
- Limited timeframe for PhDs, start-ups
- Lack of training in environmental safety

Political factors:
- Little to no legal incentive to consider environmental safety before clinical trials

Technological factors:
- Focus on using existing drug design and methods (e.g., fluorinated drugs) rather than risking time and resources to develop more sustainable alternatives
- Lack of access to environmental safety screening tools

2. In Late Drug Development

Economic factors:
- Cheaper to leverage existing supply chains and commercialization network

Political factors:
- Too late to modify chemical structure due to drug approval and patent processes
- Little to no legal incentive to consider environmental safety in drug approval

Technological factors:
- Existing drug production infrastructure

LOCK-IN 2: NEGLECTING EXISTING DRUGS

- Redesign of existing drugs often dismissed as an option in drug development → efforts to improve their environmental safety and sustainability are **sidelined**
- **Re-design of existing drugs discouraged** by:
  - High costs, no guaranteed return
  - Lengthy re-approval processes
  - No reward with existing patent systems
  - Disruption of supply chains
  - Existing competition

- **More incentive for novel drug discovery,** especially in rare disease and oncology, due to:
  - Reduced competition
  - Government subsidies
  - Market exclusivity with new patents

BREAKING LOCK-INS

- Strategic approach based on Meadows (1999) **leverage points in complex systems**[6]

Policymakers

- Additional market exclusivity, priority regulatory review, subsidies for green drugs
- Mandatory early-stage environmental safety testing
- Polluter-pays-principle
- Educational curricula

Academia

- Educational curricula
- Certification criteria for safe and sustainable drugs
- "Benign by design" principles
- Open-access data for in-silico tox models
- Ready-to-integrate tools for environmental safety testing

Big pharma

- Bridge the resource gap for academia and start-ups
- Open-access data for in-silico tox models
- Green molecular design in merger & acquisitions

Financial institutions

- Pollution impact in financial assessments
- Positive and negative reinforcement reflected in policies
  - e.g., insurance, interest rates
- Subsidies

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Icons from Flaticon (2025)

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