Science Societies

The fate of fentanyl

Current knowledge, critical environmental monitoring and research needs

By Kaine Korzekwa

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Scientists are beginning to study how fentanyl and its by-products enter and persist in the environment with early findings suggesting it does not easily break down in soil and can be detected in water, wastewater, and even transit systems. While current environmental levels are far below those that pose direct safety risks to humans, little is known about the drug's metabolites, degradation products, and long-term impacts on ecosystems and food chains. Researchers emphasize that more monitoring, better detection methods, and multidisciplinary collaboration are urgently needed to understand fentanyl's environmental fate and potential risks.

Fentanyl likely brings to mind the United States' struggle with drug addiction and overdose deaths. But some scientists are looking to track it throughout the environment to understand how it breaks down and where it may end up.

While studies have found fentanyl throughout the environment, little is known about what happens to the drug and its components. The vast majority of levels detected are far from posing safety concerns, but scientists say more research is needed now to understand how the drug may be accumulating in the environment.

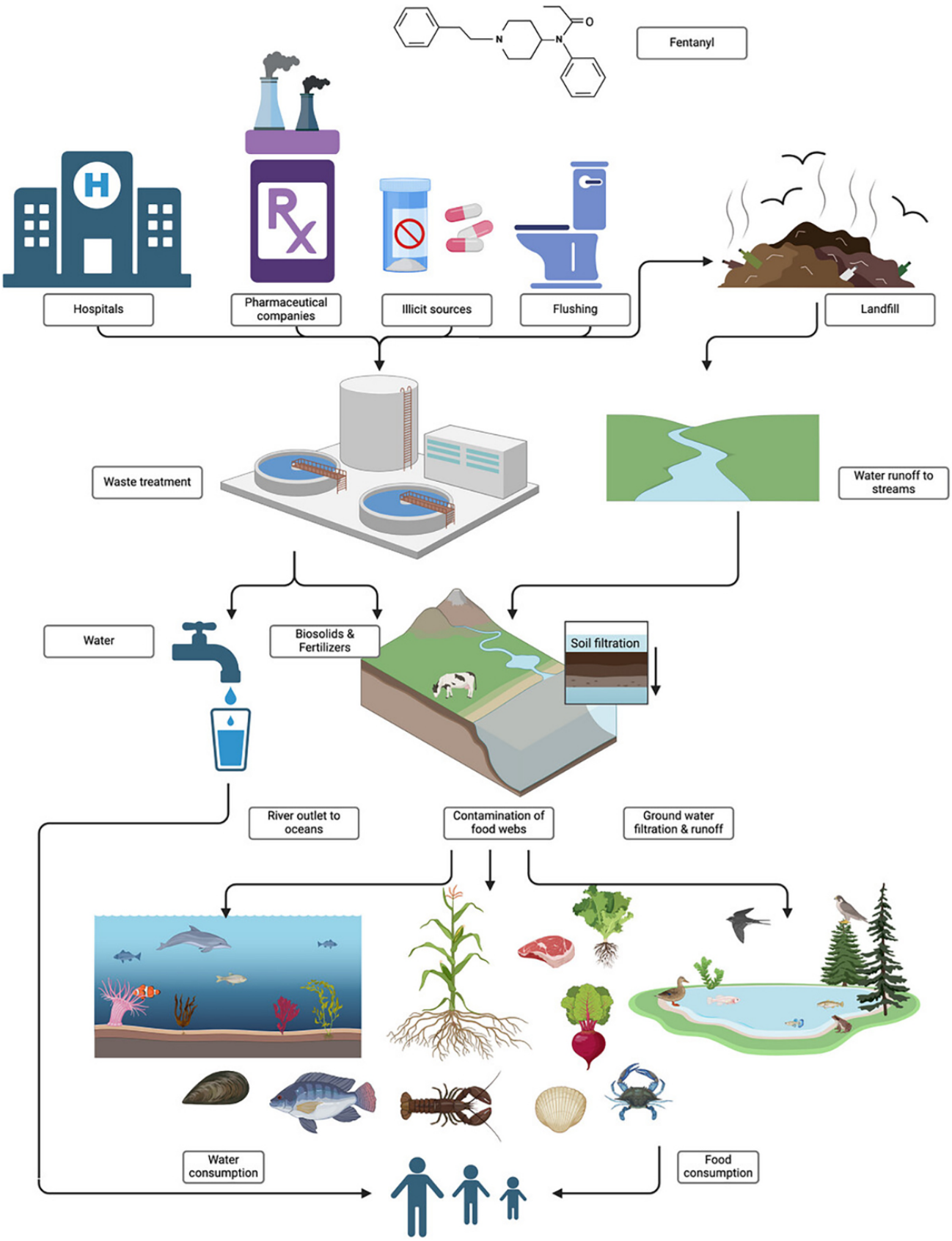
A review and analysis in the *Journal of Environmental Quality* authored by a team of researchers from the Pacific Northwest National Laboratory (PNNL) sought to understand the life cycle of fentanyl in the hopes of catalyzing more research in this

area.

Researcher Loreen Lamoureux describes how their research into how fentanyl degrades in soil became challenging due to a lack of literature on the topic. Her group's work was investigating what happens to fentanyl, where it goes in the environment, and if it is accumulating or not. Their results began to suggest it was not breaking down readily in soils.

"As a scientist you're reviewing a body of literature, and you realize there is a very clear gap," says Lamoureux, a biomedical scientist at PNNL. "We knew the next step was to write a review to try to get others interested in doing this research along with us. We wanted to highlight the importance of monitoring fentanyl over time and bring to the forefront that further research is necessary to understand the breakdown, such as how long it takes and what does it break down into and how toxic or nontoxic are those components and metabolites."

Fentanyl enters the environment through multiple avenues, including households, pharmaceutical companies, illicit producers, and health care facility waste products. The production of fentanyl, both legal and not, is a source of environmental fentanyl. While many hear about illicit use of the drug, it is also administered legitimately in hospitals and to patients as a prescription in the form of a patch. The drug is often flushed down the toilet as a way of safe disposal, yet this is one way it enters the environment. In addition, after someone uses fentanyl, their body breaks it down into metabolites that are excreted and flushed.



Environmental fentanyl originates predominantly from households, pharmaceutical companies, illicit producers, and healthcare facility waste products. Solid and liquid

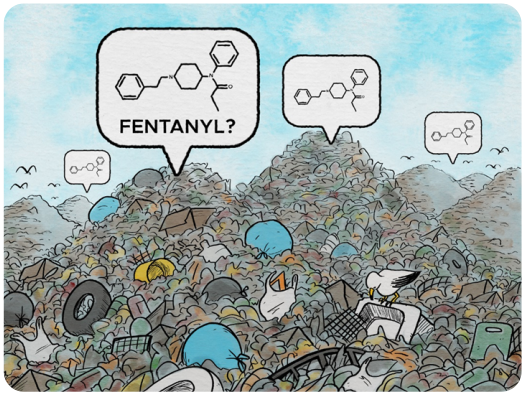
remnants used in production end up in landfills or as fertilizers. Ultimately, water runoff and waste treatment plants distribute the contaminant into the water table, where it contaminates agriculture and livestock, making its way into the food chain. This illustration, from Reid et al. (2025), was created in BioRender; https://BioRender.com/.

"The metabolites and degradation products are one of the biggest open questions right now," Lamoureux says. "If someone takes fentanyl either legally or illegally, a certain percentage of that is metabolized and very likely to end up in wastewater. What are these metabolites? What are they doing, if anything, when they get into the environment, and are there organisms breaking them down further? While these end products may not be directly harmful to humans, we really do not know much about their toxicity to environmental organisms. This is something to consider."

Low levels detected, but questions remain

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Once in the environment, studies highlighted in the review illustrate how fentanyl has been detected in water, wastewater, rivers, oceans, agricultural environments, biosolids, and biochar. Through many of these avenues, very minute amounts of fentanyl may find their way into groundwater, municipal water systems, and the food web, ultimately ingested by animals and people. Two milligrams of fentanyl can kill the average person, but the levels detected in these studies are considered orders of magnitude lower than this amount. In some countries, biosolids are broadly distributed as fertilizers, not only on crops, but in forest remediation and Christmas tree farms. Even when the end product is not being ingested, it's still an open question about what happens to the fentanyl in the soil and nature.



Fentanyl frequently ends up in landfills because of discarded pharmaceutical or illicit products. Illustration by Sara Levine, Pacific Northwest National Laboratory.

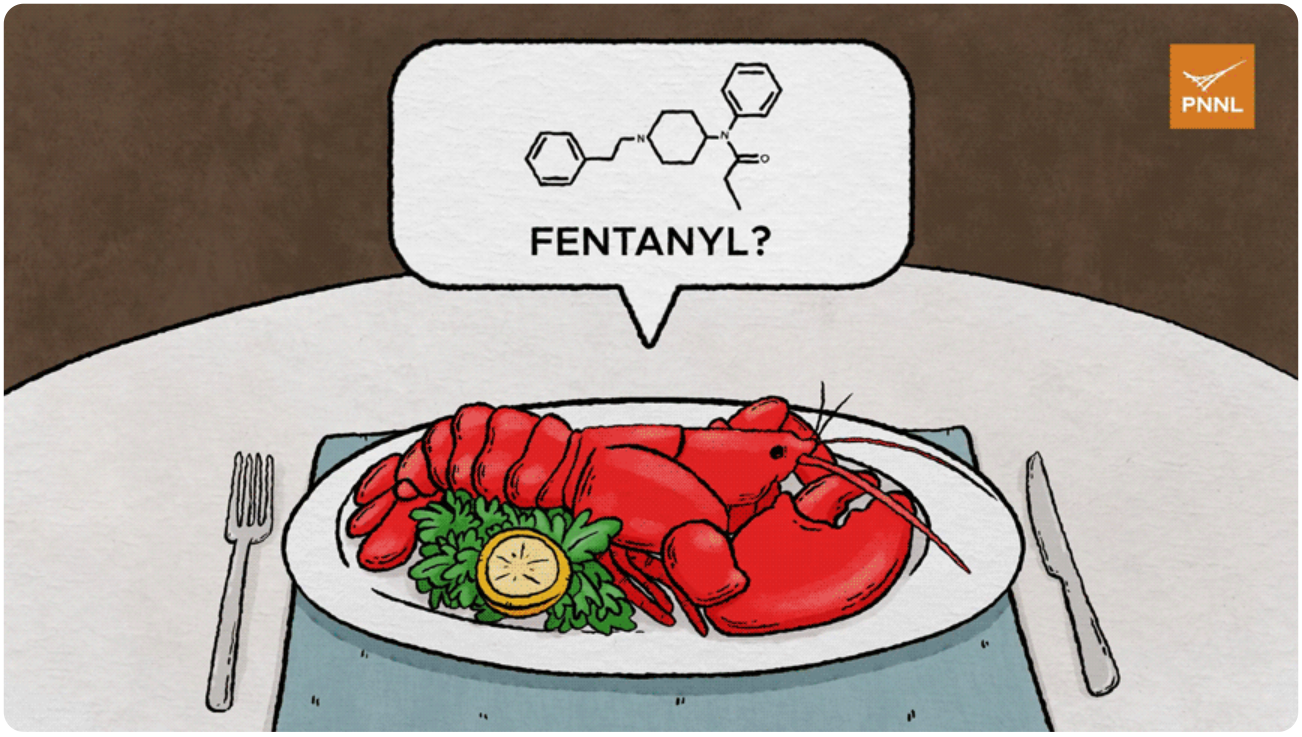
"Our main message in this review is that, yes, it has been detected in the environment, and we should continue to keep an eye on it, but at the current levels, it is not causing harm," says Deseree Reid, a chemist at PNNL. "We simply need more information to understand the impact on nature and people, and to do that, we need additional monitoring and more research."

The national lab researchers add that work on the makeup and toxicity of fentanyl's precursors, metabolites, degradation products, and analogs is also lacking. Each of these has characteristics and risks, many of which are understudied. During their research on how fentanyl degrades in soil, they combed the literature in hopes of

finding what these degradation products and analogs were to help them detect it in their soil study, but they were largely unable to find much information.

Exposure of transit workers in Pacific Northwest

In their work on the review, the team at the national lab did not find many researchers looking for evidence of how fentanyl may be accumulating in the food chain or tissues of animals or crops. One study they came across was led by Marissa Baker, an associate professor and occupational hygienist at the University of Washington School of Public Health.



We don't know if fentanyl is ending up in the food chain or in what quantities, but it is important to be asking this question. Animation by Sara Levine, Pacific Northwest National Laboratory.

Her work broadly focuses on measuring environmental exposures to understand how someone's work and occupation impact their health. In one study, thought to be the

first of its kind, they partnered with five transit agencies in the Pacific Northwest to assess fentanyl and methamphetamine on public transportation. Their goal was to characterize exposures that the operators of the buses and trains would be experiencing. They sampled the air and surfaces to approximate what the drivers would be exposed to over a full work shift.

“We found fentanyl in about a quarter of the samples that we took,” Baker explains. “In our study, we did have some cases where samples exceeded health-based exposure guidelines set by the American Conference of Governmental Industrial Hygienists. While we found there is a risk of exposure, the levels we found were not high enough to be consistent with bus drivers or even passengers experiencing overdoses unless they were directly using the drug. But it does suggest we should be pushing to learn more about exposures even if we may not yet know the full extent of the scientifically established risk.”

Baker’s work did find a social facet of the environmental impacts of fentanyl. While the levels found in the transit vehicles would not cause acute harm, the bus drivers were scared, mad and frustrated that they were being exposed as part of doing their job. This can lead to worried and distracted drivers, which is a real concern, Baker says.



One study in the Pacific Northwest sought to characterize exposures that the operators of buses and trains would be experiencing. Fentanyl was found in about a quarter of the samples. Photo courtesy of Flickr/Vincent Macaluso. CC BY-NC 2.0.

As parts of the country make efforts to decriminalize drugs and ensure people who use drugs receive the help they need, Baker explained, the research on what it may mean

for human health and the environment has lagged behind.

She added that having a review available is an excellent place to start to help identify what the research gaps are and what kind of work others may be doing.

“When you have a topic that is emerging and trying to figure out how to organize and prioritize ongoing research, a review like this one is the perfect place to start to compile that kind of information,” Baker says. “What data are out there and what may be missing? What methods are being used and in what contexts? Who is doing this research that I may be able to collaborate with? Are there populations that are being under-emphasized in the research? Is the body of evidence tilting one way or the other? These are all open questions in this area of work right now that we can start piecing together from this review and hopefully further work.”

Collaboration key in making progress on fentanyl research

The review authors say they hope their review sparks more research by scientists, but also helps members of the public understand more about fentanyl and how complex the issue of fentanyl use and research can be.

"[People] may ask why we can’t just stop making the drug. But the reality is it’s a very complicated problem because it comes from all these different sources and because there are

legitimate uses for it."

"For scientists, it can be useful to see how this complex problem can be broken down into pieces that research can help address," Lamoureux says. "For others who are more exposed to the fentanyl crisis in the media, they may ask why we can't just stop making the drug. But the reality is it's a very complicated problem because it comes from all these different sources and because there are legitimate uses for it."

It is also extremely complex to monitor an environmental system for fentanyl because of the expansiveness of the water, crops, and animals. As a chemist, Reid has focused on detection methods for not only fentanyl, but its numerous precursors, metabolites, degradation products, and analogs.

> "From a technical standpoint, unless you're highly involved with developing detection methods, you may not be familiar with the multitude of factors that can impact the sensitivity and selectivity of your detection method and how that can greatly affect your ability to monitor this issue," she says. "It may be surprising to many people that some of the detection methods we would need to fully understand the environmental impacts of fentanyl have not yet been developed or are prohibitively complex or expensive."
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> And it is not just fentanyl that must be monitored. It's the mind-boggling array of components for pre-cursors of fentanyl, as well as the breakdown products, that would each need a specific detection method and long-term monitoring throughout the environment in everything from soil and water, to people, animals, fish, and insects. Identifying and being able to detect these beginning and end components is an

important next step in elucidating how long fentanyl takes to break down and understanding where it is residing in the environment.



Dr. Loreen Lamoureux inspects a vial of soil during extraction of fentanyl. Photo by Andrea Starr, Pacific Northwest National Laboratory.

Reid believes an important step forward will be more rapid and reliable detection methods and that there has been a lot of effort put into this area. With a better method, researchers and others could collect local samples much easier, even, for example, enlisting local farmers to test their crops. Yet each type of sample, such as water, soil, vegetation, and animal tissue, must have its own extraction method.

> “You have to be able to process samples, and we went through multiple processes for developing an extraction method for soil,” Reid says. “All samples are different in their matrix and complexity, so it’s a very hard problem. While water has a relatively robust method, many other facets of this issue face problems with detection, particularly at these incredibly low amounts. It very often comes back to whether your testing method is working in your sample. We are only as good as the tools we have available.”

Like most wicked problems in science, the review authors point out that to better understand fentanyl will take multidisciplinary work from researchers across many areas of expertise. From the chemistry and detection side to the interactions with the environment and humans, the issue spans numerous scientific concepts.

“Our work, for example, had components of chemistry, assay development, microbiology, mass spectrometry, data analytics, and an incredible soil scientist who helped us understand how to sample soils and the different processes and standards required to work with different soils,” Lamoureux says. “We have to aggregate the best people together to solve these really hard problems.”

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Dig deeper

Reid, D. J., Patel, K. F., Melville, A. M., Bailey, V. L., Omberg, K. M., & Lamoureux, L. R. (2025). Environmental life cycle of fentanyl: from the cradle to an unknown grave. *Journal of Environmental Quality*, *54*, 513–527. https://doi.org/10.1002/jeq2.70016

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