Brief Report

A Novel In-Home Disposal Kit to Mitigate Drug Misuse and Environmental Risk

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Brief Report

A Novel In-Home Disposal Kit to Mitigate Drug Misuse and Environmental Risk

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Abstract: Unused prescription opioids in homes contribute to drug misuse. ICET, Inc. created a disposable, eco-friendly disposal kit that deactivates opioids through catalytic oxidation at room temperature, reducing concentrations by over 99% within two hours. The patented formulation includes permonosulfate, catalysts, and solidifying agents. LC-MS confirmed effective degradation of DEA Schedule I–IV substances. The kit is suitable for home, hospice, and clinical use, addressing public health and environmental concerns by preventing drug diversion and minimizing ecological impact. It also has potential for hormonal, antidepressant, and antibiotic deactivation.

Keywords: Prescription opioid disposal; chemical deactivation; drug misuse prevention; permonosulfate; environmental safety

1. Introduction

Improper storage and disposal of unused prescription medications in residential settings pose significant risks of diversion, misuse, and environmental contamination. In particular, opioids retained in households are frequently accessed by individuals other than the intended recipient, contributing to the growing incidence of opioid use disorder (OUD). According to data from the U.S. National Institute on Drug Abuse (NIDA), approximately 14.3 million individuals aged 12 and older misused prescription psychotherapeutic medications in 2021, with a substantial proportion obtaining drugs from friends or family members [1,2].

Despite this public health crisis, the United States lacks a standardized protocol for the disposal of unused opioids. Current disposal methods—such as drug take-back programs, the FDA's flush list, or mixing medications with household waste—are either inaccessible, environmentally unsound, or fail to ensure the chemical inactivation of active pharmaceutical ingredients (APIs). Drug drop-off kiosks are often underutilized due to geographic, transportation, and accessibility barriers [3.4].

In 2018, Public Law 115-271 provided U.S. Food and Drug Administration (FDA) authority to mandate a Risk Evaluation and Mitigation Strategy (REMS) for safe disposal packaging or safe disposal solutions for opioid analgesic medications. A safe in-home disposal system with every opioid prescription is ideal and is being evaluated by the US FDA [5] and could impact pharmacies, medical professionals, pharmaceutical manufacturers and pharmaceutical companies [6]. Pharmacists and consumers must consider cost, effectiveness, and environmental impact when recommending and selecting products for medication disposal at home.

Moreover, the environmental implications of improper disposal are concerning. Flushing medications can lead to pharmaceutical contamination of surface water and drinking water, as conventional wastewater treatment systems are not equipped to filter out pharmaceutical compounds. Similarly, discarding drugs in household trash may result in soil and groundwater pollution, and poses ongoing risks of diversion and misuse.

There remains a critical unmet need for a fast-acting, validated narcotic medication disposal solution that meets regulatory standards and is supported by third-party efficacy and safety verification.

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1.1. Limitations of Current Disposal Technologies

Cost, weight, and environmental sustainability are pressing concerns in the development and deployment of drug disposal systems. Existing products like activated carbon pouches and colloidal carbon solutions do not chemically deactivate drugs and may pose environmental contamination risks. Hypochlorite-based kits can convert drug components into more toxic or carcinogenic substances. Most rely on passive mechanisms such as activated carbon adsorption or swellable polymers, with one product utilizing bleach, raising concerns about chlorination of organic compounds. These methods typically lack selectivity, involve long contact times, and show inconsistent efficacy—particularly in chemically altering or irreversibly degrading active pharmaceutical ingredients (APIs). This underscores the need for a product that chemically alters controlled substances to inactivate them. A 2017 independent review commissioned by the San Francisco Department of the Environment critically assessed eight consumer-targeted medication disposal products [6]. The report concluded that none of these systems satisfied the U.S. Drug Enforcement Administration's (DEA) "non-retrievable" standard for the disposal of controlled substances.

1.2. Environmental and Cost Concerns

Disposal technologies using carbon powder or granular utilize large quantities (70–100 g) of activated carbon per pouch. The carbon is packaged within durable, heavy-duty plastic to contain fine particulates and prevent leakage, contributing to significant packaging bulk and increased plastic waste. Furthermore, the production of activated carbon, especially from coconut shells, involves energy-intensive processes associated with high greenhouse gas emissions. One life cycle analysis reported an average of 6.6 kg CO_2-equivalent emissions per kilogram of activated carbon produced, alongside severe risks of local human toxicity and environmental acidification [7].

This is particularly troubling given that many countries exporting raw biomass for carbon production, such as wood or coconut shell waste, are economically disadvantaged and bear the environmental burden of manufacturing. Moreover, the widespread use of activated carbon in remediation is now increasingly accompanied by carbon regeneration and hazardous waste stripping technologies, further underscoring the unsustainability of single-use carbon products.

2. Development of a Safe, Environmentally Friendly Opioid Disposal System

Advantages of the ICET Kit

The ICET system employs a catalytic oxidation mechanism using a combination of iron-TAML (tetra-amido macrocyclic ligand) catalysts and peroxymonosulfate. This approach chemically and irreversibly degrades the drug's active components into inert byproducts. The oxidation proceeds rapidly at room temperature under mild, non-corrosive pH conditions. Additionally, the pouch is lightweight (~10–15 g), uses inexpensive, environmentally benign components, and eliminates the bulk waste associated with activated carbon-based systems.

ICET addresses both environmental and regulatory concerns by:

- Utilizing minimal material mass with high efficacy.
- Avoiding the release of toxic chlorinated byproducts.
- Ensuring irreversible degradation of controlled substances.
- Producing no retrievable parent compounds, as verified through LC-MS and TLC analysis.

A safe, chemically reactive disposal kit has been developed by ICET, Inc., to address these challenges. The formulation leverages peroxymonosulfate, a powerful oxidizing agent, in combination with proprietary catalysts and solidifying agents. Upon addition of water and pharmaceutical tablets or capsules, the kit starts a room-temperature catalytic reaction, leading to over 99% reduction in parent opioid concentration within two hours.

LC-MS analyses were employed to assess degradation efficacy across a range of DEA Schedule I–IV substances and commercial formulations, including immediate-release and extended-release

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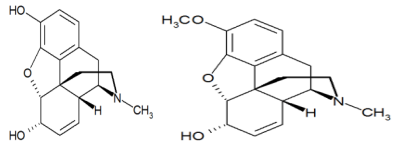
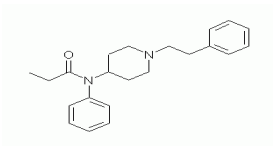
opioids. The system is free from activated carbon and chlorine-based compounds, thereby eliminating the potential for harmful by-products and reactivation.

2.1 Target Molecule Properties and Oxidation Mechanisms

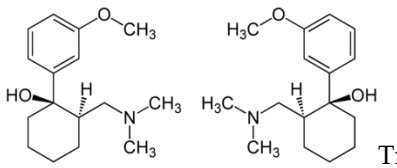
Pharmaceutical opioids are commonly formulated as water-soluble salts (e.g., hydrochloride, sulfate, tartrate, citrate), which enhance bioavailability but also facilitate environmental mobility upon improper disposal. The oxidative strategy targets key structural moieties critical for opioid receptor binding—namely the phenolic/alcoholic hydroxyl group, the tertiary amine, and the aromatic ring—thus ensuring pharmacological inactivation.

Previous structural studies have demonstrated that the nitrogen lone pair in opioid molecules is oriented above the C-ring. Based on these findings, Coop and colleagues proposed that an oxidizing metal species could be coordinated to the nitrogen lone pair, thereby positioning it favorably for redox interaction at the oxidation-prone site. The tertiary amine moiety in the opioid structure could thus serve as an amino ligand to facilitate complex formation. In their experimental investigations, a range of transition metal-based oxidants were tested against opioid substrates, and the formation of complex mixtures of oxidation products was observed. This was attributed to the lack of selectivity in the oxidation process, likely due to competing reactivity across multiple loci within the opioid framework.

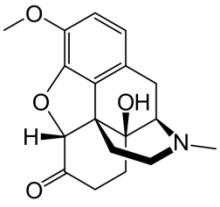




Morphine Codeine Fentanyl



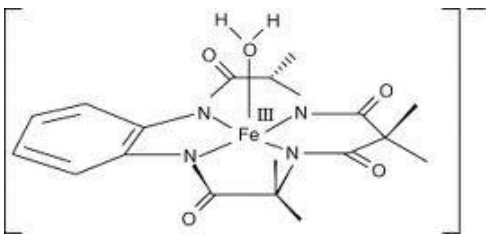
Tramadol



Oxycodone

2.2. Catalytic activator and Oxidant

In our pursuit of a highly effective catalytic system for opioid deactivation, we investigated the potential of an iron-based tetra-amido macrocyclic ligand (Fe-TAML) catalysts, developed and commercialized by Green Ox Catalysts, LLC (http://greenoxcatalysts.com). These catalysts were selected over conventional iron salts due to their superior activity at neutral to highly basic pH conditions and their effectiveness at remarkably low concentrations, ranging from micromolar to nanomolar levels [12].



Tetra-amido macrocyclic ligand (TAML)-based iron catalyst (Fe-TAML)

Fe-TAMLs represent the first generation of highly successful synthetic analogs of peroxidase enzymes. When combined with hydrogen peroxide, Fe-TAMLs catalyze the formation of high-valent iron-oxo species that initiate rapid oxidation of a broad spectrum of organic pollutants. These

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catalysts function optimally at ambient temperatures and maintain activity over a wide pH range (from pH 7 to >14), offering a robust and scalable platform for advanced oxidation processes [13].

Previous studies have demonstrated the efficacy of Fe-TAML/hydrogen peroxide systems in degrading recalcitrant pharmaceutical compounds, including fluoxetine, estradiol-based hormones, atorvastatin, and sertraline [14]. For example, degradation of atorvastatin under Fe-TAML catalysis yielded 26 identified oxidation products, as separated by high-performance liquid chromatography (HPLC), accompanied by partial mineralization. Similarly, sertraline underwent demethylation and extensive molecular fragmentation. Of particular relevance to opioid deactivation is the presence of tertiary N-methylamine groups within opioid structures—a functional motif common to many biologically active alkaloids such as atropine, scopolamine, and cocaine [16,17]. Due to the instability of hydrogen peroxide systems, more stable persulfate radical-based advanced oxidation technologies (SR-AOTs) have garnered increasing attention for their capacity to degrade persistent organic pollutants in aqueous systems. Sulfate radicals ($SO_4^{\bullet -}$) exhibit a high redox potential, and their generation through transition metal activation of precursors such as peroxymonosulfate (PMS) is particularly effective due to the slow consumption rate and high stability of the oxidant [18–20].

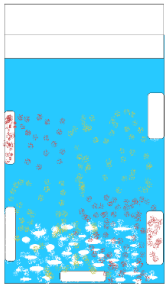
Peroxymonosulfate or Permonosulfate: Oxone™ is a, swimming pool non-chlorine shock treatment compound for organics destruction, with a 70 years of use safely record. Oxone® which contains potassium peroxymonosulfate, KHSO5 as the oxidizing species, is commercially available as the triple salt 2KHSO5·KHSO4·K2SO4. Today, Oxone® is the most widely used chlorine-free oxidizer [21] were selected for their beneficial properties

- It provides stable and potent oxidation under ambient storage conditions.
- It offers non-chlorinated oxidative degradation, avoiding toxic halogenated by-products.
- Its breakdown products are generally recognized as safe (GRAS).
- It exhibits excellent shelf life, making it viable for household and institutional use.

2.3. System Description and Experimental Methodology

Choosing the proper stable, safe oxidant/activator system for such "Green chemistry" was our key discovery in maximizing the efficacy of the oxidation of the functionalities such as the tertiary amine and phenolic /alcohol moieties in opioid molecules.

This system operates under buffered, non-corrosive (neutral to slightly alkaline) aqueous conditions and effectively deactivates opioid molecules via sulfate radical-mediated oxidation.



The deactivation system described herein, protected under U.S. Patent No. 10,137,325, utilizes a synergistic combination of an oxidizing agent, a transition metal-based catalyst, and an immobilizing matrix to chemically degrade active pharmaceutical opioid ingredients upon activation with water. These components are pre-loaded into a sealable, waterproof pouch that weighs approximately 10–15 grams (see schematic on the left) and is designed for convenient home or clinical use. When a pharmaceutical dosage form is introduced into the pouch and water is added, a rapid chemical oxidation process is initiated. Simultaneously, the immobilizing agent offers a gel-like slurry that encapsulates both the reactive components and the degradation products. This containment prevents further environmental exposure following disposal into municipal waste streams.

The present study describes the first successful application of Fe-TAML catalysis in conjunction with peroxymonosulfate for the chemical deactivation of various opioid medications. The developed

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system achieves degradation rates exceeding 98% within 2–4 hours at room temperature in neutral or alkaline pH, non-corrosive aqueous conditions. This work has culminated in a patented process and the development of prototype home-use disposal kits aimed at reducing pharmaceutical misuse and environmental contamination.

2.4. Reagents and Materials

Controlled research quantities of pharmaceutical-grade compounds—including pure acetaminophen, codeine, morphine, and oxycodone salts—were obtained under DEA authorization from Spectrum Chemical Manufacturing Corp. Commercially available medications (Tylenol® #3 and Percocet® equivalents) were sourced from New England Medical Supply, while additional opioid formulations, including fentanyl patches and combination tablets, were acquired through Patterson Veterinary Supply.

The iron-based catalyst, Fe-TAML (tetra-amido macrocyclic ligand complex), was generously provided Dr. Steve Horwitz at GreenOx Catalysts LLC. Potassium peroxymonosulfate (PMS) was used as the oxidizing agent and procured from commercial suppliers.

2.5. Analytical Methodology

All analytical testing and method development were conducted in collaboration with Creagen Biosciences Inc., Woburn, MA, USA, using ICET deactivation kits.

TLC Analysis

Conducted by Creagen BioSciences, Inc., Woburn, MA

All samples, both reacted and unreacted, were simultaneously analyzed by thin-layer chromatography (TLC). The following general experimental protocol was employed:

- **TLC Plate:** Silica gel 60 Å, 250 µm thickness, F-254 coated
- **Eluent System:** Dichloromethane : Methanol : Triethylamine (DCM:MeOH:TEA = 80:20:1, v/v)
- **Visualization:** Plates were air-dried post-elution and visualized under UV light (254 nm), followed by exposure to iodine (I_2) vapor, and staining with phosphomolybdic acid (PMA) solution with subsequent heating.

All TLC runs were performed in duplicate. Images were recorded for documentation and comparison. Liquid chromatography-mass spectrometry (LC-MS) analyses were performed using a Shimadzu LC-10AD VP instrument equipped with an Agilent ZORBAX SB-C18 column (4.6 mm internal diameter, 250 mm length). A linear gradient elution protocol was applied, ranging from 5% to 95% acetonitrile in water, each solvent containing 0.1% formic acid to facilitate ionization. This instrumentation setup allowed for accurate quantification of residual parent compounds and degradation products over time, enabling precise characterization of the oxidation kinetics for various pharmaceutical substrates under simulated home disposal conditions.

Both unreacted and reacted samples were applied directly, and also after solvent extraction, to evaluate residual presence of opioid compounds. The results demonstrated the absence of detectable opioids in all reacted samples and their respective extracts, in contrast to the unreacted controls, thereby confirming complete or near-complete degradation as verified by TLC.

To assess the efficacy of our formulation, a series of time-course degradation experiments were performed using liquid chromatography-mass spectrometry (LC-MS) to monitor the degradation of active pharmaceutical ingredients (APIs). We have produced test data for tablets and pure forms of Oxycodone 10mg / acetaminophen 325mg(tablets), Codeine (30mg/acetaminophen 350mg (tablets), Hydrocodone 30mg/ 325 acetaminophen(tablets), Fentanyl patches 5mg, 10mg/patch, 5-10patches/kit and Morphine salts. Fentanyl was degraded very quickly within an hour.

Three representative common prescription drug formulations were selected for the study: Oxycodone/Acetaminophen (O/AN), Codeine/Acetaminophen (C/AN), and Acetaminophen-only (AN). These drugs represent commonly prescribed combinations and allow for evaluation of both opioid and non-opioid substrates. Each formulation was tested over a 48-72-hour period using two independent trials with prototype kits

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3. Results and Discussion

3.1. Evaluation of Opioid Deactivation via LC-MS

We assessed the system's activity by examining opioid concentrations between 1.5 mg/mL and 10 mg/mL in a 150 mL kit, as pure substances and with acetaminophen up to 32.5 mg/mL (Table 1). The kits were coded, reaction time at room temperature was less than 4 hours, and results are summarized in Table 2.

Table 1. Initial Concentration pure Drug Components Used in the Study.

S.No	Sample Type	Sample Code	Conc. (mg/mL)
1	Unreacted	C (Codeine)	10.0
2	Unreacted	M (Morphine)	10.0
3	Unreacted	O (Oxycodone)	10.0
4	Unreacted	AN (Acetaminophen)	32.5
9	Reacted	C (Codeine)	10.0
10	Reacted	M (Morphine)	10.0
11	Reacted	O (Oxycodone)	10.0
12	Reacted	AN (Acetaminophen)	32.5

Abbreviations: M – Morphine; C – Codeine; O – Oxycodone; AN – Acetaminophen.

Table 2. LC-MS Analysis of Pure and Reacted Drug Samples.

S.No	Sample Type	Sample Code	Expected Mass (M)	UV, tR (min)	Found (M+1)	Found (M-1)	Notes (LC-MS & TLC)
1	Pure (Before Rxn)	C (Codeine)	299.2	5.63	300.3	300.3	Clear parent peak; reproducible baseline
2	Pure (Before Rxn)	M (Morphine)	285.1	4.20	286.2	284.3	Clear parent peak; reproducible baseline
3	Pure (Before Rxn)	O (Oxycodone)	315.2	5.89	316.3, 653.6 (2M+Na)	—	Clear parent peak; reproducible baseline
4	Pure (Before Rxn)	AN (Acetaminophen)	151.1	5.20	152.1	150.1	Clear parent peak; reproducible baseline
9	Reacted	C (Codeine)	299.2	1.75, 5.20	—	—	Parent peak absent; confirmed by TLC
10	Reacted	M (Morphine)	285.1	1.67	—	—	Parent peak absent; confirmed by TLC
11	Reacted	O (Oxycodone)	315.2	1.66	—	—	Parent peak absent; confirmed by TLC
12	Reacted	AN (Acetaminophen)	151.1	5.19	—	—	Partial degradation; parent peak reduced, TLC confirmed.

Table 3. Comparison of peak areas from unreacted control at 0 hours to reacted samples up to 72 hours. Rates as decreasing ratios compared to acetaminophen shown in the last column.

Sample ID	Time point, Hours	Description, volume of water added/kit 20mL	M Area (ES+)			Rate
			AN (152.1)	O (316.3)	C (300.3)	

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Trial 1						
ICET-5-01	0 (control)	O/AN Oxycodone (O) /Acetaminophen(AN);	180,592,560	218,879,580		1.2120
	4	O/AN (10 tabs) 10/325	102,275,072	1,015,818		0.0099
	24	O/AN(10 tabs) 10/325	190,000,112	44782		0.0002
	48	O/AN(10 tabs) 10/325	53,102,768			0.0000
ICET-5-02	0	C/AN Codeine(C) /Acetaminophen	183,216,720		191,759,944	1.0466
	4	C/AN 10 tabs (30/350)	105,490,640		2,371,398	0.0225
	24	C/AN10 tabs (30/350)	137,165,104		24,841	0.0002
	48	C/AN10 tabs (30/350)	162,100,512		1,339,499	0.0083
ICET-5-03	0	AN	246,869,168			
	4	AN 6.5 tablets (500mg)	140,162,016			
	24	AN6.5 tablets (500mg	171,163,152			
	48	AN6.5 tablets (500mg	64,644,916			
Trial 2						
ICET-5-05	0	O/AN	180,592,560	218,879,580		1.2120
	4	O/AN(10 tabs) 10/325	130,867,128	2,366,433		0.0181
	24	O/AN(10 tabs) 10/325	156,362,256	40,000		0.0003
	48	O/AN(10 tabs) 10/325	36,177,868	83185		0.0023
	72	O/AN(10 tabs) 10/325	82,877,240	17686		0.0002
ICET-5-06	0	C/AN	183,216,720		191,759,944	1.0466

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	4	C/AN (10 tabs(30/350)	80,334,520		2,091,722	0.0260
	24	C/AN(10 tabs(30/350)	155,816,992		54,495,324	0.3497
	48	C/AN(10 tabs(30/350)	13,183,815		12,582	0.0010
	72	C/AN (10 tabs(30/350)	68,366,056		287,906	0.0000
ICET-5-07	0	AN only	246,869,168			
	4	AN 6.5 tablets (500mg)	139,846,336			
	24	AN6.5 tablets(500mg	80,593,232			
	48	AN6.5 tablets (500mg	17,009,258			

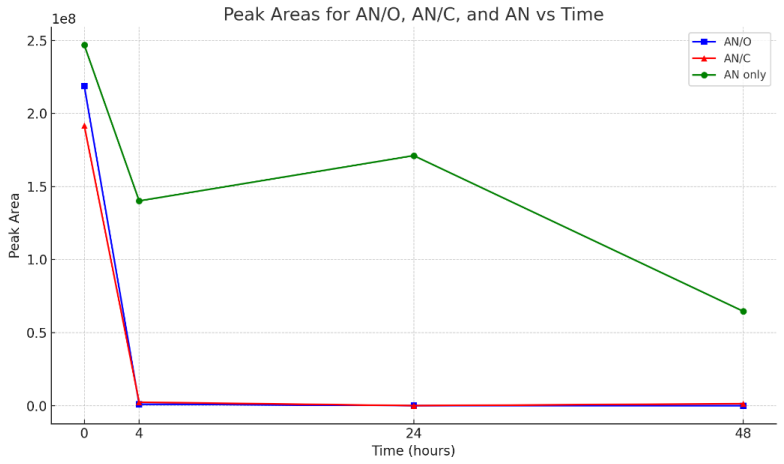

Figure 1. Rate trends for the disappearance of parent opioids and acetaminophen in pills.

The deactivation kinetics were evaluated by monitoring the decrease in LC-MS signal intensity over time. For O/AN, a significant reduction in the ES+ peak area—greater than 99%—was observed within 24 hours in both trials, with most of the degradation occurring within the first 4 hours, indicating rapid oxidative deactivation.

In the case of C/AN, Trial 2 displayed a transient increase in signal intensity at 24 hours, possibly due to the formation of intermediates or delayed catalytic activation. Nonetheless, over 99% degradation was achieved by 72 hours. The AN-only formulation demonstrated a slower but steady degradation profile.

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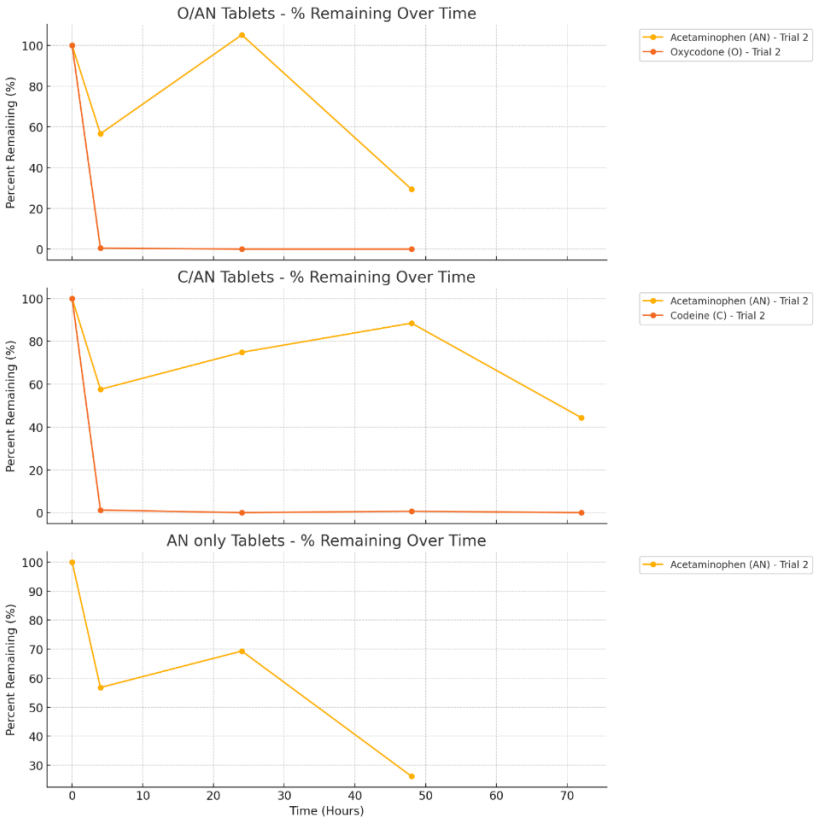

Figure 2. Active Compounds Percent Remaining.

Quantitative assessment was performed by calculating the percentage of each API remaining relative to its initial concentration at time zero. The overall pattern of significant decline in peak areas over time, clearly shows that both O/AN and C/AN Oxycodone (O)and codeine(C) in combinations with Acetaminophen (AN) degraded rapidly and completely than AN alone. These findings confirm the robust and reproducible degradation capacity of the ICET formulation across diverse pharmaceutical matrices.

4. Safety to the User and Risk Assessments

The dissolution/opioid destruction reaction generates no gases or violent reactions. The kit contains no EPA-listed toxic chemicals (F, P, K, U) or RCRA chemicals and is neither ignitable nor corrosive. The kit uses agents with a safe history, such as permonosulfate, an EPA-registered swimming pool treatment chemical. GreenOx has US EPA permits for using the TAML® catalyst in destroying biocides and for commercial laundry applications. EPA registration includes extensive toxicological and environmental assessments.

Acute oral toxicity of permonosulfate is 2000 mg/kg in rats, and dermal toxicity is 11,000 mg/kg. The neutralized permonosulfate is not corrosive. Potassium sulfate's oral toxicity (LD50) is 6600 mg/kg in rats. As low-volume household waste holding destroyed medications, this product waste is likely exempt under section 261.4(b). Preliminary tests [22]on the post-reaction product using Fe-TAML catalyst, PMS, and oxycodone-acetaminophen tablets indicated comparable toxicity to unreacted controls, both within 80% control tissue growth, confirming they are not toxic. The reaction product was a concentrated mud like slurry used as is.

5. Applications and Implications

The ICET kits have been demonstrated to degrade pharmaceutical opioid compounds quickly and irreversibly, addressing concerns related to drug diversion, accidental ingestion, and environmental contamination. Its use as a home-use disposal solution offers a new method for

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reducing prescription drug misuse while protecting aquatic and terrestrial ecosystems from pharmaceutical pollutants.

Since opioid disposal via drop-off boxes is inconvenient and infrequently used, home-based solutions for opioid disposal are necessary. This intervention will reduce or eliminate potential sources of non-medical opioid use and associated morbidity and mortality in patients and their families. The ICET kit is suitable for use in homes, hospices, and outpatient clinics. Its ease of use, rapid deactivation kinetics, and environmentally friendly formulation make it suitable for public health initiatives targeting prescription drug misuse and pharmaceutical waste reduction. Future work includes broader API testing, and collaboration with regulatory agencies to support adoption in clinical and community settings.

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Data Availability: Upon reasonable request.

Conflicts of Interest: None.

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