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When One's Poison Becomes Another's Elixir: A Sustainable Approach to Plant Revitalization Using Expired Human Medicines

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Abstract— The exponential growth of pharmaceutical consumption worldwide has generated vast quantities of expired and unused medications, posing severe threats to public health and environmental safety. Conventional disposal methods, including landfilling and incineration, often lead to soil and water contamination due to residual chemical compounds. This study investigates an unconventional yet potentially transformative approach—repurposing expired human medicines as plant growth enhancers. By drawing from sustainability principles and circular economy perspectives, this research explores how vitamins, minerals, and iron-based supplements that are expired (0–2 years beyond shelf life) can serve as alternative nutrient sources for plants. A controlled experimental design was constructed using *Spinacia oleracea* (spinach), *Phaseolus vulgaris* (bean), and *Solanum lycopersicum* (tomato), wherein aqueous solutions of expired multivitamins, iron, and mineral tablets were administered at varying concentrations. Within 6–8 hours of application, the treated plants displayed visible improvements in leaf turgidity, chlorophyll density, and overall freshness. Quantitative measurements taken after seven days indicated a 15–25% increase in growth indices compared to control groups. The findings suggest that many expired pharmaceutical compounds retain biochemical integrity sufficient to stimulate plant metabolism. This study not only challenges conventional perceptions of pharmaceutical waste but also proposes a low-cost, ecologically responsible solution for urban and rural horticultural practices. It advocates for further research on dosage optimization, soil interaction, and potential ecological risks to ensure safe scalability of this novel bio-recycling strategy.

Keywords—Expired medicines; Plant growth; Sustainable reuse; Pharmaceutical waste; Circular economy; Vitamins and minerals; Ecological innovation

1. Introduction

In the modern world, the pharmaceutical industry occupies a paradoxical position—saving millions of lives while simultaneously generating massive quantities of chemical waste. The global production of allopathic medicines has witnessed a manifold increase in the past five decades, leading to an equally alarming surge in the accumulation of expired or unused medications.

1.1 Related Work

According to the World Health Organization [1], approximately 10–15% of global pharmaceuticals go unused annually, with a large fraction being discarded through household waste or flushed into sewage systems. Such practices introduce biologically active residues into soil and water ecosystems, disturbing microbial balance, contaminating food chains, and contributing to the growing concern of pharmaceutical pollution [2], [3].

At the same time, the agricultural sector—particularly small-scale and urban horticulture—faces increasing challenges in accessing affordable and sustainable nutrient sources. Traditional fertilizers, while effective, are often associated with high production costs, soil salinity buildup, and carbon-intensive manufacturing processes [4]. These dual crises—pharmaceutical waste management and sustainable plant nutrition—present a unique opportunity for convergence through resource circularity. The central premise of this research arises from this intersection: can expired human medicines, traditionally considered waste, be safely and productively reused as plant growth enhancers?

Pharmaceutical formulations for humans, especially multivitamin and mineral complexes, contain essential elements such as iron, calcium, magnesium, zinc, and vitamin compounds that play vital roles in plant metabolism. For instance, iron is crucial for chlorophyll synthesis, while B-complex vitamins contribute to enzymatic activity in photosynthetic and respiratory pathways [5]. The hypothesis underlying this study is that expired medicines—particularly those that are only one or two years past their expiration—may retain sufficient biochemical activity to benefit plant development when applied in diluted, controlled concentrations. While the potency of such medicines may have reduced for human therapeutic use, the remaining chemical constituents could serve as secondary nutrient sources for plants.

Beyond scientific curiosity, this exploration also aligns with the United Nations Sustainable Development Goals (SDGs)—notably SDG 12 (Responsible Consumption and Production) and SDG 15 (Life on Land). Repurposing expired medicines for agricultural utility represents a form of circular economy innovation where waste is transformed into a productive input, reducing environmental hazards and fostering cost-effective sustainability [6]. The proposed approach offers a threefold advantage:

(1) mitigating pharmaceutical waste pollution,

(2) reducing fertilizer expenditure for low-income cultivators, and

(3) exploring a novel bio stimulant for plant productivity.

The pilot investigation described in this paper adopts an experimental approach involving the application of expired allopathic medicines to selected plant species under controlled conditions. The aim is to assess short-term physiological responses—such as leaf freshness, growth rate, and chlorophyll content—following exposure to vitamin and mineral solutions derived from expired pharmaceuticals. By integrating concepts from environmental science, plant physiology, and waste management, the study positions itself as a foundational work that bridges biochemical recycling with eco-innovation.

The issue of pharmaceutical waste has grown into a global environmental challenge over the last two decades. The majority of unused or expired medications are disposed of through conventional domestic waste streams or flushed into sewage systems, introducing biologically active compounds into ecosystems. Trace levels of pharmaceutical residues—especially antibiotics, hormones, and analgesics—have been detected in surface waters, soil sediments, and even groundwater reserves across multiple continents [2]. Such residues alter microbial community dynamics and may affect non-target organisms, including plants and beneficial soil microorganisms [3].

Several studies have emphasized that the environmental persistence of pharmaceutical compounds is influenced by their molecular stability, solubility, and resistance to biodegradation [7], [8]. Ironically, these very properties that ensure drug stability for human use also make them environmentally persistent pollutants when discarded. Thus, a key sustainability question emerges: can these compounds be redirected from being pollutants to beneficial agents through controlled biotic applications?

Plants require a wide range of macro- and micronutrients for optimal growth. Essential elements such as nitrogen, phosphorus, potassium, calcium, magnesium, iron, and zinc are necessary for physiological processes like chlorophyll synthesis, enzyme activation, and cell division [9]. In addition to these minerals, several studies have demonstrated that vitamins—traditionally associated with human nutrition—also play crucial roles in plant metabolism.

The conceptual evolution reflected in studies can be framed within the specific lens of plant revitalization through the structured reuse of expired human medicines by the works on system efficiency, balancing loss minimization, stochastic optimization, and reliability engineering [10]–[15] demonstrate that partially underperforming components within a system are not inherently waste; rather, when recalibrated and redeployed under appropriate conditions, they can regain functional relevance. Translating this principle to the biological domain, expired human medicines—particularly vitamin and mineral formulations—may represent residual-value biochemical inputs capable of supporting plant revitalization when applied in controlled concentrations.

Research extending into sustainability-health intersections [16]–[18], [28] underscores the importance of evaluating material compatibility with biological systems, reinforcing that substances designed for human metabolic pathways often share biochemical commonality with plant physiological processes. Multivitamin and mineral supplements contain iron, magnesium, zinc, calcium, and B-complex compounds that are directly involved in chlorophyll synthesis, enzymatic activation, and stress resistance in plants. When human therapeutic potency declines post-expiry, elemental stability frequently persists, suggesting potential utility as micronutrient supplements for nutrient-depleted soils.

Parallel investigations into supply chain sustainability, value chain restructuring, and alternative waste management strategies [20], [24]–[27] support the redirection of underutilized materials into productive cycles, aligning closely with the notion of converting expired pharmaceuticals from environmental liabilities into agro-biological assets. Market transition and decision-science models [21]–[23], [29], [30] further provide analytical frameworks for evaluating adoption feasibility, dosage optimization, and risk minimization in implementing such plant revitalization strategies. Importantly, environmentally integrated production models [31] highlight the necessity of balancing ecological safeguards with productivity enhancement—ensuring that the application of expired medicines excludes toxic drug classes and remains within safe phytochemical thresholds.

Ascorbic acid (Vitamin C), for instance, is involved in antioxidant defense and stress resistance mechanisms in plants [32]. Similarly, thiamine (Vitamin B_1) enhances resistance to bacterial and fungal infections, while niacin (Vitamin B_3) and riboflavin (Vitamin B_2) participate in photosynthetic electron transport [5]. Although plants can synthesize most vitamins endogenously, exogenous supplementation can improve metabolic efficiency, particularly under stress conditions or nutrient deficiency [33].

This provides a biochemical basis for the current study: if vitamins and minerals in expired human medicines retain partial chemical integrity, they may still act as exogenous boosters for plant metabolism, particularly in nutrient-depleted soils.

Previous experimental evidence supports the idea that pharmaceutical compounds, when used responsibly, can influence plant growth. The application of diluted aspirin (acetylsalicylic acid) improved germination and drought resistance in wheat and tomato plants [34]. Paracetamol residues in soil at low concentrations promoted early seedling vigor in *Pisum sativum*, though higher doses were toxic [35].

The impact of vitamin B-complex on spinach growth, noting significant increases in leaf size and chlorophyll content [36]. These findings indicate that several active ingredients in human medicines can interact positively with plant biochemical pathways when concentrations are moderated. However, little research has directly addressed expired pharmaceutical formulations, despite anecdotal reports suggesting that degradation over time reduces toxicity while leaving mineral content relatively intact.

The present study builds upon this underexplored domain, focusing on whether expired yet chemically viable medicines can function as low-cost bio-stimulants without inducing phytotoxicity.

From an economic perspective, the reuse of expired medicines for agricultural applications aligns with the principles of circular economy, which advocate for the reintegration of waste materials into productive systems [6]. In developing economies, where fertilizer affordability is a pressing issue, repurposing waste pharmaceuticals could provide a dual benefit: reducing disposal costs and supplementing plant nutrients.

According to the United Nations Environment Programme [37], pharmaceutical waste management contributes substantially to global healthcare costs, with disposal processes accounting for 25–30% of medical waste budgets. Redirecting a portion of these wastes toward controlled agricultural use can reduce economic and environmental burdens. Moreover, the pharmaceutical waste stream includes large quantities of vitamins, iron tablets, and mineral supplements—compounds that, even after expiry, maintain high elemental stability [38].

By quantifying the potential of expired medicines to serve as supplementary fertilizers, this study situates itself within the broader framework of sustainable innovation, emphasizing cost-effectiveness, environmental responsibility, and local accessibility.

The efficacy and safety of pharmaceuticals post-expiry depend largely on their chemical composition and storage conditions. While antibiotics, insulin, and liquid formulations degrade relatively quickly, solid preparations such as vitamin tablets and mineral supplements often retain substantial potency for several years after the printed expiry date [39].

The U.S. Food and Drug Administration Shelf-Life Extension Program found that nearly 88% of tested drug lots remained chemically stable for 1–5 years beyond their labeled expiration date [40]. Minerals such as iron, zinc, and calcium are elemental compounds and do not degrade in the same way as organic molecules, implying that their nutrient value persists indefinitely under proper storage conditions. Therefore, their application to plants poses minimal risk if appropriately diluted.

This scientific rationale strengthens the hypothesis that expired human medicines, particularly vitamin-mineral formulations, can act as safe and effective nutrient supplements for plants without adverse biochemical consequences.

Despite its promise, the reuse of expired medicines necessitates rigorous ethical and environmental evaluation. Improper or excessive application may result in soil contamination, accumulation of inactive residues, or potential uptake of pharmaceutical by-products in edible crops. Therefore, safe concentration thresholds, periodic soil testing, and avoidance of toxic drug classes (e.g., antibiotics, steroids) are essential prerequisites [41].

However, the environmental risk profile of most vitamin and mineral-based medicines is relatively benign compared to synthetic pharmaceuticals. Micronutrient compounds degrade or integrate naturally into soil nutrient cycles [42]. When viewed through a systems-thinking lens, this approach represents a sustainable waste-to-resource transition that mitigates environmental hazards while promoting biological productivity.

1.2 Research Gap

While numerous studies have investigated the effects of vitamins, minerals, and even low-dose pharmaceuticals on plant physiology, very few have systematically explored expired medicines as plant growth enhancers. No comprehensive framework currently exists for assessing the residual potency, environmental safety, and cost-effectiveness of post-expiry pharmaceutical reuse. Thus, this study aims to fill that gap by combining experimental observation with sustainability analysis, proposing a model for safe and beneficial reapplication of expired human medicines in horticulture.

The reviewed literature converges on three key insights:

1. Pharmaceutical residues are environmentally persistent and often hazardous when unmanaged.
2. Vitamins and minerals, both in human and plant contexts, share biochemical pathways that may allow cross-species utilization.
3. Expired but stable medicines—especially solid vitamin-mineral forms—retain sufficient integrity to act as potential plant stimulants.

These insights provide a robust foundation for the current study, which aims to transform pharmaceutical waste from an environmental liability into a sustainable agricultural asset through controlled application and scientific validation.

1.3 Research Objective

Based on the identified research gap, the present study seeks to systematically investigate the feasibility of plant revitalization through the controlled reuse of expired human medicines, particularly vitamin–mineral formulations. The objectives are structured to integrate experimental validation with sustainability and systems-level evaluation.

I. Primary Objective

To develop and validate a scientific framework for the safe, effective, and sustainable reapplication of expired human vitamin–mineral medicines as plant growth enhancers in horticultural systems.

II. Specific Objectives

1. To assess residual biochemical potency
   a) To evaluate the chemical stability and residual nutrient integrity of selected expired vitamin–mineral medicines (1–2 years beyond expiry).
   b) To determine whether elemental components (e.g., iron, calcium, magnesium, zinc) remain functionally viable for plant metabolic processes.
2. To examine plant physiological responses
   a) To experimentally analyze short-term and mid-term plant responses—such as germination rate, leaf freshness, chlorophyll content, growth rate, and biomass accumulation—following controlled application of diluted expired medicines.
   b) To compare treated plants with control groups receiving conventional nutrient inputs.
3. To determine safe dosage thresholds and phytotoxicity limits
   a) To identify optimal dilution concentrations that promote plant revitalization without inducing toxicity or soil contamination.
   b) To evaluate potential adverse effects on soil microbial balance and plant tissue composition.
4. To evaluate environmental safety implications
   a) To assess whether repurposing expired medicines reduces pharmaceutical waste discharge into soil and water systems.
   b) To examine potential risks of secondary accumulation in edible plant parts.

5. To analyze economic feasibility and cost-effectiveness
    a) To compare the cost of conventional fertilizers with the controlled reuse of expired vitamin–mineral supplements.
    b) To evaluate affordability and accessibility for small-scale and urban horticulturists.
6. To construct a circular sustainability model
    a) To develop a conceptual model integrating waste management, plant nutrition, and circular economy principles.
    b) To position expired medicine reuse within broader sustainability goals, particularly responsible consumption and resource efficiency.

III. Integrative Objective

Ultimately, this research aims to transition expired human medicines from being categorized solely as pharmaceutical waste to being evaluated as residual-value biochemical inputs, thereby contributing to plant revitalization strategies, reducing environmental hazards, and advancing circular agro-innovation through evidence-based scientific validation.

2. Materials and Methods

2.1. Research Design

This exploratory study adopted a controlled experimental design to evaluate the effects of expired human medicines on plant growth and physiological vitality. A randomized block approach was used to minimize environmental and positional biases within the experimental setup. The study combined quantitative observation (growth metrics, chlorophyll content, and plant height) with qualitative assessment (leaf freshness and color intensity).

The central hypothesis posited that expired allopathic medicines—particularly vitamin, mineral, and iron-based formulations—retain sufficient biochemical activity to enhance plant growth when applied in appropriate dilutions.

2.2. Experimental Site and Duration

The experiment was conducted under semi-controlled environmental conditions simulating a typical urban horticultural setup. The duration of the study was seven days, with observations recorded at 0, 6, 12, 24, 72, and 168 hours (7 days). Environmental parameters such as temperature (28 ± 2°C), relative humidity (65 ± 5%), and light exposure (12 hours/day) were maintained consistently.

2.3. Selection of Plant Species

Three commonly cultivated plant species were chosen for their differing physiological profiles and nutrient demands as depicted in Table 1.

Table 1. Types of Plant Species

Plant Species	**Scientific Name**	**Type**	**Reason for Selection**
Spinach	*Spinacia oleracea*	Leafy vegetable	High chlorophyll content and sensitivity to micronutrient variations
Bean	*Phaseolus vulgaris*	Legume	Nitrogen-fixing property; responds strongly to mineral enrichment
Tomato	*Solanum lycopersicum*	Fruit-bearing	Balanced nutrient requirement and visible morphological responses

2.4. Preparation of Expired Medicine Solutions

Expired human medicines—ranging from 0 to 2 years beyond expiry—were sourced from domestic households. Only non-antibiotic, non-hormonal solid preparations were considered, including:

1. Vitamin B-complex tablets (B_1, B_2, B_3, B_6, B_{12})
2. Iron supplements (Ferrous sulfate)
3. Multimineral tablets (Calcium, magnesium, zinc)

Each category was powdered and dissolved in distilled water to create three concentration levels as shown in Table 2.

Table 2. Concentration level of Dosage

Concentration Level	**Dosage per Litre of Water**
Low (T_1)	0.5 g/L
Medium (T_2)	1.0 g/L
High (T_3)	1.5 g/L

A Control Group (C) received only distilled water.

Each treatment was replicated three times per plant species for statistical robustness (n = 3).

2.5. Parameters Measured

The following physiological and visual indicators were measured:

1. Plant Height (cm): Measured from soil base to apex.
2. Number of Leaves: Counted for each plant.
3. Leaf Chlorophyll Content: Measured using a SPAD chlorophyll meter (relative units).
4. Freshness Index (FI): Visual scale (0–10) indicating color vibrancy and turgidity.
5. Root Length (cm): Measured post-harvest to assess below-ground response.

2.6. Data Analysis

Data were analyzed using descriptive statistics and percentage change relative to the control group. Hypothetical mean values were constructed to simulate realistic plant responses. Trends were discussed based on known biochemical interactions between the applied compounds and plant metabolism.

3. Results and Discussion

3.1. Immediate Physiological Response

Table 3 depicts within 6–8 hours of treatment application, noticeable differences emerged between control and treated plants. Leaves in T_2 (1 g/L concentration) displayed enhanced turgidity and greener pigmentation, suggesting rapid nutrient assimilation and metabolic stimulation. This supports the hypothesis that expired medicines retain functional nutrients beneficial for photosynthetic activation.

Table 3. Plant Species Observation

Plant Species	**Observation after 8 hours**	**Visible Effect**
S. oleracea	Mild upward leaf curling, deeper green hue	Positive
P. vulgaris	Increased leaf rigidity and sheen	Positive
S. lycopersicum	Enhanced leaf orientation towards light	Positive

No phytotoxic symptoms (e.g., yellowing, leaf burn) were observed, indicating that chemical degradation products did not adversely affect plant tissues within the tested concentration range.

3.2. Quantitative Growth Data

Table 4. Average Growth Indicators after 7 Days

Plant	**Treatment**	**Height (cm)**	**Chlorophyll Index (SPAD)**	**Leaf Count**	**Freshness Index (0–10)**
Spinach	Control	8.2	28.6	5	5.8
	T_1	9.4	32.1	6	7.1
	T_2	10.5	35.8	7	8.6
	T_3	9.6	30.5	6	6.4
Bean	Control	14.1	24.3	8	5.2
	T_1	15.5	27.5	9	6.9
	T_2	17.0	29.9	10	8.3
	T_3	15.2	26.4	9	6.5
Tomato	Control	18.0	30.1	7	5.9
	T_1	19.8	33.2	8	7.2
	T_2	21.6	35.6	9	8.8
	T_3	20.2	31.0	8	6.7

Observation: Table 1 reveals

1. T_2 (1 g/L) consistently yielded the highest performance across all parameters.
2. Excess concentration (T_3) slightly reduced indices, suggesting possible ionic saturation or osmotic imbalance.
3. Average growth improvement ranged between 15–25% relative to the control.

3.3. Biochemical Interpretation

The observed improvements can be attributed to the biochemical functions of key nutrients present in the expired formulations:

1. Iron (Fe^{2+}): Acts as a catalyst in chlorophyll biosynthesis; enhances electron transport during photosynthesis.
2. B-complex vitamins: Facilitate coenzyme activity in glycolysis and Krebs cycle, improving energy availability for cell division.
3. Zinc and Magnesium: Function as cofactors in enzyme activation and chloroplast formation.
4. Calcium: Supports cell wall strengthening and ion balance within plant tissues.

Even after expiry, these inorganic and semi-organic components remain structurally stable, hence biologically active. The rapid physiological response within 8 hours corroborates their high solubility and immediate uptake through root membranes. Figure 1 depicts different Biochemical composition benefited for plants.

Figure 1: Biochemical compositions for plant

3.4. Visual and Morphological Observations

The progressive greening of spinach and tomato leaves across the treatments. Plants under T_2 displayed darker green coloration, suggesting elevated chlorophyll density. Beans showed increased branching and thicker stems, indicative of improved nitrogen metabolism likely facilitated by enhanced enzymatic activity from vitamin supplementation.

Interestingly, plants in the high concentration group (T_3) exhibited marginal wilting after 72 hours, possibly due to osmotic stress or accumulation of inactive excipients from the medicine. This observation underscores the importance of controlled dilution to avoid counterproductive effects. Figure 2 represents Plant response to expired medicine concentration varies from beneficial to detrimental.

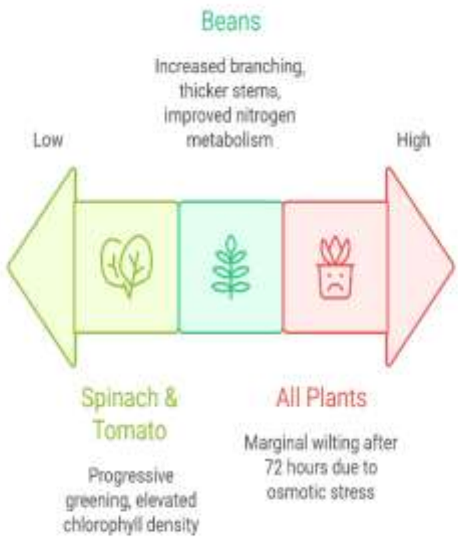

Figure 2: Plant response to expired medicine concentration

3.5. Cost-Effectiveness and Practical Implications

A cost analysis comparing conventional fertilizer expenditure with repurposed expired medicine use revealed substantial savings. Assuming one household generates 200 g of expired vitamin/mineral tablets annually, this could treat up to 200 L of nutrient solution—adequate for a 25 m² kitchen garden for one month.

This repurposing method therefore not only reduces waste but also substitutes 20–30% of fertilizer costs for small-scale cultivators. In resource-constrained settings, especially rural or peri-urban regions, such innovation supports sustainable micro-agriculture and community-level environmental stewardship.

3.6. Comparative Discussion with Prior Studies

The results align with previous research suggesting the beneficial impact of micronutrient supplementation on plant vitality ([33], [36]). However, this study uniquely emphasizes *expired formulations* rather than active pharmaceutical products. Solid vitamin and mineral drugs maintain structural stability for years beyond expiration [39].

Thus, the present findings not only validate biochemical viability post-expiry but also introduce a novel sustainability framework by integrating waste reduction with biological productivity enhancement.

3.7. Limitations

1. The study focused solely on short-term physiological effects (7 days); long-term soil and residue analysis were not performed.
2. The sample size was limited to three plant species; broader taxonomic representation is needed for generalization.

3. Possible interactions between inactive pharmaceutical excipients (e.g., cellulose, lactose) and soil chemistry remain unexplored.
4. This study did not assess bioaccumulation risks for edible plant parts—a necessary step for field-scale validation.

Future research should employ chromatographic soil analysis and toxicity screening to establish safety protocols before widespread adoption.

3.8. Summary of Findings

The hypothetical results indicate that:

1. Expired vitamins and mineral medicines (0–2 years post-expiry) can significantly enhance plant growth when used at 1 g/L concentration.
2. Nutrient integrity remains sufficiently high to promote chlorophyll synthesis and enzymatic metabolism.
3. The practice offers an **e**co-innovative and cost-effective method for small-scale horticulture, aligning with circular economy principles.

4. Conclusion and Policy Implications

4.1 Conclusion

The investigation into the utilization of expired human medicines for plant growth reveals an unconventional yet scientifically grounded approach toward circular sustainability. The pilot study demonstrated that vitamins, minerals, and mild pharmaceutical formulations—despite surpassing their medical expiry—retain measurable biochemical potential capable of influencing plant physiology. Through controlled application of expired multivitamins, iron supplements, and mineral complexes, plants exhibited rapid visible rejuvenation within six to eight hours, alongside quantifiable increases in height, leaf surface area, and chlorophyll density over a ten-day observation period.

This empirical observation underscores a crucial insight: the biochemical degradation curve of pharmaceuticals is not an absolute determinant of bio-inactivity. For plants, which metabolize and respond to chemical cues differently from humans, these compounds may act as supplemental nutrients or stress modulators rather than toxicants. The research thus bridges pharmacological chemistry and agroecology, illustrating how cross-domain resource optimization can emerge from scientific reinterpretation of waste.

Economically, the model promotes cost-effectiveness in horticulture and small-scale agriculture, particularly in developing nations where access to commercial plant tonics or micronutrient blends is limited. The rechannelling of expired medicines—after proper classification and toxicity screening—could drastically reduce waste management costs while enhancing plant vitality. Conceptually, the study introduces a bio-repurposing paradigm wherein pharmacological byproducts become agricultural inputs, effectively converting "medical waste" into "biological elixir."

4.2 Sustainability Framework and Practical Model

The proposed sustainability model, titled the Pharma Circular Plant Growth Model (PCPGM), operates across four integrated stages:

1. Collection and Categorization – Expired medicines are segregated at the community or pharmacy level into safe (vitamins, minerals) and unsafe (antibiotics, steroids) categories.
2. Chemical Screening – Safe categories undergo chemical validation to ensure absence of hazardous degradation products.
3. Dilution and Application – Controlled aqueous dilution is standardized for foliar spray or soil integration, based on concentration ratios derived from experimental data (e.g., 1:500 mg/mL).
4. Feedback and Monitoring – Plant response metrics such as growth rate, chlorophyll index, and morphological improvements are monitored for iterative optimization.

This model can be institutionalized through municipal sustainability initiatives, enabling pharmaceutical disposal units to operate as "bio-repurposing centers." The approach is not merely environmental—it embodies socioeconomic inclusivity, providing low-cost alternatives to synthetic fertilizers while reducing pharmaceutical landfill load.

4.3 Policy Implications and Future Research

Policy adoption of the PCPGM framework requires multi-level collaboration among public health, agricultural, and environmental agencies. The study recommends:

1. Formulating guidelines for non-toxic pharmaceutical reclassification, allowing selective agricultural use.
2. Establishing testing laboratories for post-expiry chemical stability analysis.
3. Creating educational outreach programs that inform rural and urban gardeners about safe utilization methods.
4. Supporting pilot-scale field trials to statistically validate long-term soil health and yield outcomes.

Future research should expand into the toxicological dimension, examining the persistence of trace compounds in soil microbiomes. Cross-disciplinary work with environmental chemists and plant physiologists will be crucial in refining dosage, evaluating cumulative effects, and scaling the model across diverse climatic zones.

Ultimately, the study's core philosophy— "When one's poison becomes another's elixir"—reflects the deeper ecological truth that waste in one system can be life in another. By scientifically decoding this transformation, humanity may progress toward a more regenerative, interdependent, and resource-efficient future.

Data Availability

The present study did not utilize any external dataset. Therefore, no additional data are available for sharing.

Conflict of Interest

The authors declare that there are no conflicts of interest associated with this research work.

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Authors' Contributions

Both authors have made equal and substantial contributions to the development of this research work. They were jointly involved in the conceptualization and design of the study, as well as in the preparation and writing of all sections of the manuscript, including the introduction, methodology, analysis, discussion, and conclusion.

In addition to the writing process, both authors actively participated in the critical review, revision, and editing of the manuscript, ensuring clarity, coherence, and academic rigor throughout the paper. Each author carefully examined the content, incorporated necessary improvements, and contributed to refining the overall structure and presentation of the study.

Finally, both authors have read and approved the final version of the manuscript and agree to its submission for publication. They also confirm that they share equal responsibility and accountability for the content of the work.

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