

# Ecotoxicity of *Phyllanthus niruri*: A Review of Its Effects on Selected Soil and Aquatic Organisms

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Received: 2nd Mar, 2026 | Revised: 14th Mar, 2026 | Accepted: 4th Apr, 2026 | Available Online: 20th Apr, 2026

## ABSTRACT

*Phyllanthus niruri* L. (Euphorbiaceae), commonly known as Bhumi Amla or stone breaker, is a tropical medicinal plant with extensive traditional use in Ayurvedic, Chinese, and Malay medicine. The escalating global demand for this herb, driven by its proven hepatoprotective, antiviral, antidiabetic, and antiurolithiatic properties, has resulted in increased cultivation and subsequent waste generation, raising significant ecotoxicological concerns. This comprehensive review critically evaluates the ecotoxicological impact of *Phyllanthus niruri* on selected water and soil organisms, synthesizing current scientific evidence on its phytochemical composition, therapeutic applications, and environmental safety profile. The review encompasses acute and chronic toxicity studies on aquatic organisms including zebrafish (*Danio rerio*), Nile tilapia (*Oreochromis niloticus*), and *Daphnia magna*, as well as terrestrial ecosystem impacts on soil microorganisms and invertebrates. While mammalian toxicity studies indicate a favorable safety profile with an acute LD<sub>50</sub> exceeding 5,000 mg/kg body weight, aquatic toxicity assessments reveal species-specific effects requiring careful evaluation. The analysis highlights the "herbal paradox" wherein therapeutic botanicals perceived as safe for human consumption may pose environmental risks through bioactive phytochemical discharge and heavy metal accumulation. This review identifies critical research gaps in chronic toxicity data, bioaccumulation potential, and ecosystem-level impacts, emphasizing the need for standardized ecotoxicological protocols and sustainable waste management strategies for the herbal pharmaceutical industry.

**Keywords:** *Phyllanthus niruri*, ecotoxicology, aquatic toxicity, soil organisms, phytochemicals, environmental safety, herbal medicine waste.

**How to cite this article:** Mishra PA, Singh EA, Apte KG, Bodhankar M. Ecotoxicity of *Phyllanthus niruri*: A Review of Its Effects on Selected Soil and Aquatic Organisms. *Int J Drug Deliv Technol.* 2026;16(34s):207-216. DOI: 10.25258/ijddt.16.34s.26

**Source of support:** Nil.

**Conflict of interest:** The authors declare no conflict of interest.

## 1. Introduction

### 1.1 Background and Context

*Phyllanthus niruri* L., belonging to the family Euphorbiaceae, represents one of the most extensively studied medicinal plants in traditional medicine systems across tropical and subtropical regions. Commonly referred to as Bhumi Amla in Ayurveda, Chanca Piedra in Brazil, and Dukong Anak in Malaysia, this annual herb has garnered substantial scientific attention due to its remarkable therapeutic properties and its emerging role in modern pharmacology (Lee, Nathanael YS, et al.). The plant's widespread

distribution across Asia, Africa, and South America has facilitated its integration into diverse ethnomedicinal practices, where it has been traditionally employed for treating liver diseases, kidney stones, diabetes, and various infectious conditions (Paithankar, V. V., et al).

The global herbal medicine market has witnessed unprecedented growth over the past two decades, with the World Health Organization estimating that approximately 80% of the world's population relies on traditional medicine for primary healthcare [3]. This surge in demand has catalyzed intensive cultivation of medicinal plants, including

# Ecotoxicity of *Phyllanthus niruri*: A Review of Its Effects on Selected Soil and Aquatic Organisms

*Phyllanthus niruri*, resulting in significant increases in production volumes and associated waste generation. The environmental implications of this expansion have only recently begun to receive systematic scientific attention, particularly regarding the ecotoxicological consequences of bioactive phytochemical discharge into aquatic and terrestrial ecosystems (Mishra P et al).

## 1.2 The Herbal Paradox

The concept of the "herbal paradox" encapsulates the contradiction between the perceived safety of natural medicinal products and their potential environmental hazards. While *Phyllanthus niruri* has demonstrated an excellent safety profile in human and mammalian studies, with established therapeutic benefits across multiple organ systems, its ecological impact remains inadequately characterized (Asare GA, Addo P, Bugyei K, et al). This paradox is particularly relevant given that bioactive compounds exhibiting therapeutic efficacy in biological systems may similarly affect non-target organisms, potentially disrupting ecosystem functions and biodiversity.

The ecotoxicological assessment of medicinal plants requires a paradigm shift from traditional pharmacological evaluation to comprehensive environmental risk assessment. Unlike synthetic pharmaceuticals, botanical extracts contain complex mixtures of bioactive compounds including alkaloids, flavonoids, tannins, and lignans, whose individual and synergistic effects on environmental organisms remain largely unexplored (Dhar S, Gupta K, Talapatra SN). Furthermore, the accumulation of heavy metals from cultivation soils and pharmaceutical processing residues introduces additional dimensions to the ecotoxicological profile of herbal waste.

## 1.3 Scope and Objectives

This review aims to provide a systematic evaluation of the ecotoxicological impact of *Phyllanthus niruri* on selected water and soil organisms, synthesizing current scientific evidence regarding:

1. The phytochemical composition and therapeutic applications of *Phyllanthus niruri* that inform its biological activity profile
2. Acute and chronic toxicity data from aquatic organisms including fish, amphibians, and invertebrates
3. Terrestrial ecotoxicological effects on soil microorganisms, invertebrates, and plant communities

4. Mechanistic insights into toxicity pathways and bioaccumulation potential

5. Identification of critical research gaps and recommendations for future investigations

The review adopts an integrative approach, combining traditional ecotoxicological methods with contemporary molecular techniques, to provide a comprehensive assessment of the environmental safety of this globally significant medicinal plant.

## 2. Literature Review

### 2.1 Botanical and Phytochemical Profile of *Phyllanthus niruri*

#### 2.1.1 Taxonomy and Distribution

*Phyllanthus niruri* is an annual herb characterized by its distinctive phyllanthoid branching pattern, with small, alternate, elliptic-oblong leaves arranged along slender stems. The plant typically grows to 30-60 cm in height and produces small, axillary, monoecious flowers that develop into depressed-globose capsules containing trigonous seeds [7]. Taxonomic identification relies on microscopic examination of leaf epidermal features, pollen morphology, and anatomical characteristics.

The species exhibits considerable morphological and phytochemical variation across its geographic range, with distinct chemotypes identified in Indian, Malaysian, Brazilian, and Chinese populations. This variability has implications for both therapeutic efficacy and ecotoxicological profiles, as different extraction methods and plant parts yield distinct phytochemical compositions [8].

#### 2.1.2 Phytochemical Constituents

The phytochemical complexity of *Phyllanthus niruri* underlies both its therapeutic efficacy and potential environmental impact. Comprehensive phytochemical analyses have identified multiple classes of bioactive compounds [9]:

**Lignans:** The most extensively studied constituents include phyllanthin, hypophyllanthin, and niranthin. These dibenzylbutyrolactone lignans demonstrate hepatoprotective, antiviral, and cytotoxic activities. Phyllanthin exhibits potent inhibitory effects against hepatitis B virus replication and displays significant antioxidant capacity [10].

**Flavonoids:** Quercetin, rutin, astragalins, and various quercetin glycosides constitute the major flavonoid fraction. These compounds contribute to the antioxidant, anti-inflammatory, and antimicrobial properties of the plant extract.

The total flavonoid content varies significantly with extraction method, geographic origin, and

# Ecotoxicity of *Phyllanthus niruri*: A Review of Its Effects on Selected Soil and Aquatic Organisms

harvest time [11].

**Alkaloids:** The presence of alkaloids including securinine, norsecurinine, and dihydronorsecurinine contributes to the plant's pharmacological activities. These compounds may also mediate toxicological effects in sensitive organisms.

**Tannins:** Hydrolysable and condensed tannins represent a substantial fraction of the extractable compounds, with documented protein-precipitating and antimicrobial activities.

**Other Constituents:** The plant additionally contains fatty acids, triterpenes (lupeol, phyllanthol), phenolic acids (gallic acid, ellagic acid), and corilagin, all contributing to its complex biological activity profile [12].

The quantitative composition of these compounds varies substantially with extraction methodology. Supercritical fluid extraction with ethanol-water modified carbon dioxide has been optimized to yield standardized extracts with consistent phytochemical profiles, enabling reproducible ecotoxicological assessments [13].

## 2.2 Therapeutic Applications and Pharmacological Mechanisms

### 2.2.1 Hepatoprotective Activity

The hepatoprotective potential of *Phyllanthus niruri* represents one of its most extensively validated therapeutic applications. In-depth mechanistic studies have demonstrated that phyllanthin and hypophyllanthin exhibit potent hepatoprotective activity against carbon tetrachloride (CCl<sub>4</sub>)-induced hepatotoxicity in clone-9 and HepG2 cell lines [14]. The protective mechanisms involve:

• **Antioxidant enzyme modulation:** Restoration of superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx) activities

• **Lipid peroxidation inhibition:** Reduction of malondialdehyde (MDA) levels and prevention of membrane damage

• **Anti-inflammatory action:**

Suppression of pro-inflammatory cytokine production and NF- $\kappa$ B pathway inhibition

• **Apoptosis regulation:** Modulation of Bax/Bcl-2 ratio and caspase activation

Clinical studies have demonstrated that *Phyllanthus niruri* supplementation improves liver function parameters in patients with non-alcoholic fatty liver disease (NAFLD), although effects on chronic hepatitis require further investigation [15].

### 2.2.2 Antiviral Activity

The antiviral properties of *Phyllanthus niruri* were first systematically investigated by Venkateswaran and colleagues, who demonstrated that the aqueous extract inhibits hepatitis B virus (HBV) DNA polymerase and reduces woodchuck hepatitis virus surface antigen (WHsAg) expression in vivo [16]. Subsequent studies have elucidated multiple mechanisms of antiviral action:

• **HBV inhibition:** Interference with viral DNA synthesis and inhibition of HBsAg secretion

• **Hepatitis C suppression:** Inhibition of HCV replication in hepatocyte cultures

• **Quorum sensing disruption:** Inhibition of bacterial cell-to-cell communication in aquatic pathogens

These antiviral properties have significant implications for aquaculture applications, where *Phyllanthus* spp. extracts demonstrate potential for disease control in fish and shrimp production [17].

**2.2.3 Antidiabetic and Antihyperlipidemic Effects**  
*Phyllanthus niruri* demonstrates significant antihyperglycemic and hypolipidemic activities in experimental diabetes models. Administration of aqueous extracts to streptozotocin-induced diabetic rats resulted in reduced fasting blood glucose levels, improved insulin sensitivity, and amelioration of diabetic nephropathy [18]. The mechanisms include:

•  **$\alpha$ -glucosidase inhibition:** Delayed carbohydrate absorption and postprandial glucose reduction

• **AMPK activation:** Enhanced glucose uptake in peripheral tissues

• **Antioxidant protection:** Reduction of oxidative stress in pancreatic  $\beta$ -cells and renal tissue  
Kidney function studies demonstrate that *Phyllanthus niruri* administration prevents deterioration of renal function in diabetic rats through amelioration of histopathological changes, reduced oxidative stress, inflammation, fibrosis, and apoptosis [19].

### 2.2.4 Antiurolithiatic Activity

The traditional use of *Phyllanthus niruri* as a "stone breaker" has been validated through multiple clinical and preclinical studies. The plant extract interferes with multiple stages of calcium oxalate crystal formation and aggregation, modifies crystal structure and composition to increase fragility, and induces ureteral relaxation facilitating stone passage [20]. Clinical trials demonstrate that standardized extracts, combined with magnesium and vitamin B<sub>6</sub>, reduce the risk of recurrent urinary stones.

# Ecotoxicity of *Phyllanthus niruri*: A Review of Its Effects on Selected Soil and Aquatic Organisms

## 2.3 Ecotoxicological Studies on Aquatic Organisms

**2.3.1 Zebrafish (*Danio rerio*) Embryo Toxicity Studies** The zebrafish embryo toxicity test (ZFET) has emerged as a standardized method for evaluating the ecotoxicological potential of pharmaceutical and herbal compounds. Studies utilizing *Phyllanthus niruri* extracts have revealed important insights into developmental toxicity [21]:

**Acute Toxicity Findings:** The fish embryo toxicity test (FETT) with *Phyllanthus niruri* extract demonstrated embryo mortality at high extract concentrations ( $\geq 500$   $\mu\text{g/mL}$ ), with an  $\text{LD}_{50}$  of 505.71  $\mu\text{g/mL}$ , indicating relatively low acute toxicity [13]

**Developmental Parameters:** Embryos treated with *Phyllanthus niruri* extract at concentrations up to 1000  $\mu\text{g/mL}$  exhibited normal development without morphological abnormalities. Heartbeat rates remained within normal ranges, and developmental milestones were achieved comparable to negative controls.

**Teratogenicity Assessment:** A separate study investigating the toxic and teratogenic effects of *Phyllanthus niruri* leaf water extract on zebrafish embryos after 36 hours of exposure reported effects on heartbeat at certain concentrations, necessitating careful evaluation of exposure levels [22].

**Antidiabetic Activity:** Zebrafish models have also been employed to evaluate the antidiabetic activity of *Phyllanthus niruri*, demonstrating potential therapeutic applications alongside safety considerations [23]

**Aquaculture Applications:** The therapeutic potential of *Phyllanthus* spp. in sustainable aquaculture has been systematically reviewed, highlighting applications in growth promotion, immune stimulation, disease control, and water quality improvement [17]. These applications emphasize the importance of understanding both therapeutic benefits and potential environmental impacts when *Phyllanthus niruri* extracts enter aquatic ecosystems.

### 2.3.2 Invertebrate Toxicity Studies

***Daphnia magna*:** The water flea *Daphnia magna* represents a standard test organism for aquatic ecotoxicology. QSAR (Quantitative Structure-Activity Relationship) modeling of *Phyllanthus niruri* phytochemicals using the T.E.S.T. software has predicted acute toxicity ( $\text{LC}_{50}$ ) values for major constituents in *D. magna* [26].

Lignans (phyllanthin, hypophyllanthin) and flavonoids (quercetin, rutin) showed varying toxicity profiles, with some compounds

demonstrating potential mutagenicity in predictive models.

***Artemia salina*:** Brine shrimp (*Artemia salina*) lethality assays have been employed to screen the cytotoxic potential of *Phyllanthus niruri* extracts, with results correlating with antitumor activity and providing preliminary data on acute toxicity to aquatic invertebrates.

## 2.4 Terrestrial Ecotoxicological Assessment

### 2.4.1 Soil Microorganism Impacts

The impact of *Phyllanthus niruri* cultivation and waste discharge on soil microbial communities remains inadequately characterized. However, studies on related medicinal plants provide relevant insights [27]:

**Heavy Metal Accumulation:** *Phyllanthus niruri* demonstrates accumulation of heavy metals including lead, cadmium, and chromium from contaminated soils. While this phytoremediation capacity suggests potential for soil decontamination, the accumulation of metals in plant biomass poses risks when plant residues are incorporated into soil or enter food chains.

**Organic Amendment Studies:** Research on organic fertilizers (chicken manure, rice husk biochar) for *Phyllanthus niruri* cultivation indicates that soil amendments significantly influence biomass yield and heavy metal content. Optimized organic fertilization can reduce heavy metal accumulation in plant tissues while enhancing bioactive compound production [28].

**Microbial Community Effects:** Bioactive compounds from medicinal plants, including aristoloxazines and other phytochemicals, can significantly reduce soil microbial populations and inhibit general plant growth, indicating potential for ecosystem disruption [4].

### 2.4.2 Earthworm and Soil Invertebrate Studies

While specific studies on *Phyllanthus niruri* effects on earthworms (*Eisenia fetida*) are limited, research on related medicinal plant residues demonstrates variable effects on survival, reproduction, and gut microbiome composition. Some residues may enhance growth, while others inhibit reproduction at sublethal concentrations [4].

### 2.4.3 Phytoremediation Potential

*Phyllanthus niruri* has been evaluated for phytoremediation of heavy metal-contaminated soils. Comparative studies with *Eclipta prostrata* and *Scoparia dulcis* exposed to lead-contaminated soil revealed that while *Phyllanthus niruri* accumulated lead in a concentration-dependent manner, it proved susceptible to lead toxicity,

# Ecotoxicity of *Phyllanthus niruri*: A Review of Its Effects on Selected Soil and Aquatic Organisms

indicating limitations for phytoremediation applications compared to more tolerant species [29].

## 2.5 Mechanisms of Ecotoxicological Action

### 2.5.1 Oxidative Stress Pathways

The antioxidant properties of *Phyllanthus niruri* that confer therapeutic benefits may paradoxically contribute to environmental effects. In aquatic organisms, the modulation of reactive oxygen species (ROS) production and antioxidant enzyme activities can disrupt normal cellular redox homeostasis [30]. Studies on Nile tilapia demonstrate that while *Phyllanthus niruri* supplementation did not significantly alter oxidative stress biomarkers in muscle tissue, the potential for ROS-mediated effects requires further investigation [24].

### 2.5.2 Bioaccumulation Potential

The lipophilic nature of certain *Phyllanthus niruri* constituents, particularly lignans and triterpenes, raises concerns regarding bioaccumulation in aquatic food chains. While direct bioaccumulation studies are lacking, the physicochemical properties of major constituents suggest potential for bioconcentration in non-target organisms.

### 2.5.3 Endocrine Disruption Potential

The antidiabetic and hypolipidemic activities of *Phyllanthus niruri* imply potential interactions with metabolic and endocrine pathways in non-target organisms. The effects on fish glucose metabolism observed in Nile tilapia studies suggest that exposure to *Phyllanthus niruri* compounds may influence energy homeostasis in aquatic species [24].

## 2.6 Standardization and Quality Control

The standardization of *Phyllanthus niruri* extracts is essential for reproducible ecotoxicological assessment. Quality control parameters include [31]:

**Phytochemical Standardization:** Total flavonoid determination, HPLC analysis of phenolic compounds, and quantification of marker compounds (phyllanthin, hypophyllanthin, corilagin) ensure consistent extract composition.

**Extraction Method Optimization:** Supercritical fluid extraction, aqueous extraction, and solvent extraction methods yield distinct phytochemical profiles with implications for ecotoxicological properties.

**Safety Evaluation:** The zebrafish embryo toxicity test has been validated as a method for safety evaluation of *Phyllanthus niruri* extracts, demonstrating that standardized extracts at appropriate concentrations are safe for consumption [13]. However, ecotoxicological data

for other aquatic and terrestrial species or organisms remain insufficient.

## 3. Materials and Methods

### 3.1 Literature Search Strategy

This review employed a comprehensive systematic literature search strategy to identify relevant studies on the ecotoxicological assessment of *Phyllanthus niruri*. The search was conducted across multiple electronic databases including PubMed, Scopus, Web of Science, Google Scholar, and specialized ecotoxicology databases. Search terms included combinations of "Phyllanthus niruri", "ecotoxicology", "aquatic toxicity", "soil toxicity", "environmental impact", "fish toxicity", "zebrafish", "Daphnia", and "heavy metals".

### 3.2 Study Selection Criteria

Inclusion criteria were established to ensure the relevance and quality of included studies:

1. **Study Types:** Original research articles, review articles, and systematic reviews published in peer-reviewed journals

2. **Language:** English language publications

3. **Time Period:** No specific time restriction, with emphasis on recent publications (2010-2026)

4. **Relevance:** Studies investigating ecotoxicological effects, environmental fate, or bioaccumulation of *Phyllanthus niruri* or its constituents

5. **Taxonomic Scope:** Studies on aquatic organisms (fish, amphibians, invertebrates, algae) and terrestrial organisms (soil microorganisms, invertebrates, plants)

### 3.3 Ecotoxicological Assessment Methods

#### 3.3.1 Aquatic Toxicity Testing

**Zebrafish Embryo Toxicity Test (ZFET):** Conducted according to OECD Test Guideline 236, evaluating mortality, developmental abnormalities, and teratogenic effects at various concentrations.

**Fish Acute Toxicity Tests:** Standardized protocols following OECD Test Guideline 203 for acute toxicity testing in fish, determining LC<sub>50</sub> values and behavioral observations.

**Invertebrate Toxicity:** *Daphnia* immobilization tests (OECD TG 202) and *Artemia*

Lethality assays for screening acute toxicity.

#### 3.3.2 Terrestrial Toxicity Assessment

**Soil Microorganism Impact:** Evaluation of microbial biomass, enzyme activities (dehydrogenase, urease), and community structure using molecular techniques.

**Earthworm Toxicity:** Standardized tests following

# Ecotoxicity of *Phyllanthus niruri*: A Review of Its Effects on Selected Soil and Aquatic Organisms

OECD TG 207 for earthworm survival and reproduction.

**Phytoremediation Studies:** Plant growth assays in contaminated soils with measurement of heavy metal accumulation and translocation factors.

### 3.3.3 Analytical Methods

**Phytochemical Analysis:** HPLC-DAD, LC-MS/MS for identification and quantification of bioactive compounds.

**Heavy Metal Analysis:** Atomic absorption spectroscopy (AAS) and inductively coupled plasma mass spectrometry (ICP-MS) for metal quantification in plant tissues and environmental samples.

**QSAR Modeling:** Computational prediction of toxicity using T.E.S.T. software and other molecular modeling approaches.

## 4. Results

### 4.1 Phytochemical Composition and Variability

The comprehensive analysis of *Phyllanthus niruri* phytochemical composition reveals significant variability influenced by geographic origin, cultivation practices, and extraction methodology. The primary bioactive compounds identified include:

**Lignans:** Phyllanthin (0.5-2.0% dry weight), hypophyllanthin (0.3-1.5%), niranthin (0.1-0.8%)

**Flavonoids:** Total flavonoid content 2.5-8.0% dry weight, with quercetin and rutin as major constituents

**Tannins:** Total tannin content 5-15% dry weight

**Phenolic acids:** Gallic acid and ellagic acid (0.5-2.0%)

Heavy metal content in cultivated *Phyllanthus niruri* varies with soil contamination levels, with documented accumulation of lead (5-50 mg/kg), cadmium (0.1-2.0 mg/kg), and chromium (1-10 mg/kg) [28]

### 4.2 Aquatic Toxicity Findings

#### 4.2.1 Zebrafish Studies

The zebrafish embryo toxicity test demonstrated that *Phyllanthus niruri* extract exhibits relatively low acute toxicity compared to reference compounds. Key findings include:

**LC<sub>50</sub>:** 505.71 µg/mL for embryo mortality

**No Observed Effect Concentration (NOEC):**

<500 µg/mL for morphological abnormalities

**Heartbeat:** Normal rates maintained up to 1000 µg/mL

**Development:** No

significant developmental delays at sublethal concentrations

These findings indicate that *Phyllanthus niruri* extracts are classified as relatively safe for aquatic environments at low concentrations, though higher concentrations may pose risks.

#### 4.2.2 Fish Species Responses

Studies on Nile tilapia and common carp demonstrated variable responses to dietary *Phyllanthus niruri* supplementation:

• **Nile Tilapia:** No significant effects on stress biomarkers (cortisol, glucose) or immune parameters at tested concentrations. Blood glucose levels were slightly lower in supplemented groups without adverse effects [24].

• **Common Carp:** No significant alterations in liver enzyme profiles (ALT, AST) or hematological parameters at dietary inclusion levels up to 5% [25].

#### 4.2.3 Invertebrate Sensitivity

QSAR modeling predictions for *Daphnia magna* indicate variable toxicity of individual constituents:

• **High Toxicity:** Certain lignan derivatives (predicted LC<sub>50</sub> <1 mg/L)

• **Moderate Toxicity:** Flavonoid compounds (predicted LC<sub>50</sub> 1-10 mg/L)

• **Low Toxicity:** Tannin fractions (predicted LC<sub>50</sub> >10 mg/L)

### 4.3 Terrestrial Ecotoxicological Effects

#### 4.3.1 Heavy Metal Accumulation

*Phyllanthus niruri* demonstrates concentration-dependent accumulation of heavy metals from contaminated soils:

**Lead:** Bioaccumulation factor (BAF) 0.5-2.0 in above-ground tissues

**Cadmium:** BAF 1.0-3.0, with preferential accumulation in leaves

**Chromium:** BAF 0.3-1.5, with limited translocation to aerial parts

The accumulation of heavy metals in plant biomass raises concerns regarding the environmental fate of *Phyllanthus niruri* waste, particularly when plant residues are used as organic amendments or disposed in landfills.

#### 4.3.2 Soil Microbial Impact

Limited direct studies on *Phyllanthus niruri* effects on soil microorganisms were identified. However, related studies on medicinal plant residues indicate:

**Microbial Biomass:** Potential reduction in bacterial and fungal biomass with high

# Ecotoxicity of *Phyllanthus niruri*: A Review of Its Effects on Selected Soil and Aquatic Organisms

concentrations of bioactive compounds

**Enzyme Activities:** Variable effects on dehydrogenase and phosphatase activities depending on compound concentration and soil type.

## 4.4 Ecotoxicological Risk Assessment

Based on the synthesized data, the ecotoxicological risk profile of *Phyllanthus niruri* can be summarized as follows:

Organism Group	Risk Level	Key Findings
Zebrafish embryos	Low	LC <sub>50</sub> >500 µg/mL; normal development at sublethal concentrations
Aquatic invertebrates	Low-Moderate	Variable sensitivity; some constituents potentially toxic
Soil microorganisms	Unknown	Insufficient data; requires further investigation
Soil invertebrates	Unknown	Insufficient data; requires further investigation

## 5. Discussion

### 5.1 Synthesis of Ecotoxicological Findings

The ecotoxicological assessment of *Phyllanthus niruri* reveals a complex picture characterized by apparent safety at environmentally relevant concentrations but potential risks at higher exposure levels. The zebrafish embryo toxicity studies provide the most robust evidence for aquatic safety, demonstrating that *Phyllanthus niruri* extracts exhibit lower toxicity compared to individual isolated compounds such as gallic acid and corilagin [13]. This finding suggests that the complex mixture of compounds in the whole extract may exhibit antagonistic or mitigating effects on toxicity, a phenomenon well-documented in botanical pharmacology but underappreciated in ecotoxicology.

The fish studies on Nile tilapia and common carp demonstrate tolerance to dietary *Phyllanthus niruri* inclusion, with no significant adverse effects on growth, stress parameters, or immune function at practical feeding levels [24, 25]. These findings are particularly relevant given the increasing interest in *Phyllanthus* spp. as functional feed additives in sustainable aquaculture [17]. The lack of adverse effects in these studies suggests that *Phyllanthus niruri* could be safely incorporated into aquaculture feeds at appropriate concentrations, though chronic exposure studies are warranted.

### 5.2 The Herbal Paradox Revisited

The concept of the "herbal paradox" is particularly

relevant when considering *Phyllanthus niruri* environmental impacts. While the plant demonstrates excellent safety in mammalian systems and human clinical trials, with an acute LD<sub>50</sub> exceeding 5,000 mg/kg body weight in rats [5], the ecotoxicological data reveal a more nuanced picture. The therapeutic mechanisms that underlie its efficacy antioxidant activity, enzyme inhibition, and metabolic modulation may similarly affect non-target organisms, potentially disrupting normal physiological functions.

The QSAR modeling predictions for *Daphnia magna* indicate that certain *Phyllanthus niruri* constituents, particularly some lignan derivatives, may exhibit toxicity at concentrations relevant to environmental exposure scenarios [26]. This finding highlights the importance of distinguishing between whole extract effects and individual constituent effects. While the complex extract may be relatively safe due to compound interactions, isolated constituents released into the environment through improper waste disposal or industrial discharge may pose greater risks.

### 5.3 Heavy Metal Considerations

The accumulation of heavy metals by *Phyllanthus niruri* from contaminated soils presents a dual concern: the potential for human exposure through medicinal use of contaminated plant material, and the environmental fate of metal-laden plant waste. The documented accumulation of lead, cadmium, and chromium in plant tissues [28] suggests that cultivation site selection and soil quality monitoring are essential for both product safety and environmental protection.

The phytoremediation potential of *Phyllanthus niruri* for heavy metal-contaminated soils appears limited compared to more tolerant hyperaccumulator species [29]. While the plant can accumulate metals, its susceptibility to metal toxicity restricts its utility for remediation applications. This characteristic has implications for waste management, as plant residues from contaminated sites may require specialized disposal rather than incorporation into agricultural soils.

### 5.4 Implications for Aquaculture and Water Quality

The therapeutic applications of *Phyllanthus* spp. in aquaculture, including growth promotion, disease control, and water quality improvement [17], must be balanced against potential environmental impacts. The current evidence suggests that at concentrations used for therapeutic purposes, *Phyllanthus niruri* poses minimal risk to cultured fish species. However, the discharge of

# Ecotoxicity of *Phyllanthus niruri*: A Review of Its Effects on Selected Soil and Aquatic Organisms

aquaculture effluents containing *Phyllanthus niruri* compounds into receiving waters requires further evaluation.

The potential for *Phyllanthus niruri* to modulate microbial communities in aquaculture systems, while beneficial for disease control, raises questions about impacts on receiving water microbial ecology. The suppression of harmful algal blooms and pathogenic bacteria in culture systems could theoretically affect natural aquatic ecosystems if effluent management is inadequate.

## 5.5 Research Gaps and Limitations

Significant knowledge gaps persist in the ecotoxicological assessment of *Phyllanthus niruri*:

1. **Chronic Toxicity Data:** Most available studies focus on acute toxicity endpoints. Long-term exposure effects on reproduction, growth, and population-level parameters are largely unknown.

2. **Bioaccumulation Studies:** Direct evidence of bioaccumulation and bio magnification in food chains is lacking. The lipophilic nature of certain constituents suggests this warrants investigation.

3. **Ecosystem-Level Effects:** Studies on community-level impacts, including interactions between species and effects on ecosystem functions, are absent.

4. **Soil Ecotoxicology:** The impact on soil organisms, including microorganisms and invertebrates, remains poorly characterized.

5. **Mixture Toxicology:** The ecotoxicological effects of *Phyllanthus niruri* constituents in combination with other environmental contaminants have not been evaluated.

6. **Field Studies:** Most available data derive from laboratory studies under controlled conditions. Field monitoring of environmental concentrations and effects is lacking.

## 5.6 Regulatory and Management Implications

The current regulatory framework for herbal medicine waste is inadequate to address the specific ecotoxicological concerns associated with *Phyllanthus niruri* and similar medicinal plants. Key recommendations include:

1. **Standardized Testing:** Development of standardized ecotoxicological testing protocols specifically for herbal medicine products, incorporating whole extract testing alongside individual constituent evaluation.

2. **Environmental Risk Assessment:** Mandatory environmental risk assessment for herbal products, including evaluation of waste generation and disposal pathways.

3. **Waste Management Guidelines:** Development of industry-specific waste management guidelines for herbal pharmaceutical manufacturing, including treatment and disposal protocols for spent biomass and extraction residues.

4. **Cultivation Best Practices:** Promotion of good agricultural practices (GAP) for medicinal plant cultivation, including soil quality monitoring and heavy metal testing.

## 6. Conclusion

The ecotoxicological profile of *Phyllanthus niruri* (Bhumi Amla) currently has significant data gaps and incomplete evidence. This makes it hard to fully understand its long-term effects on ecosystems. Although early studies indicate low immediate toxicity at certain concentrations, the absence of standard environmental monitoring and regulatory oversight could pose a risk to biodiversity. The available evidence indicates that:

1. **Aquatic Toxicity:** *Phyllanthus niruri* extracts exhibit relatively low acute toxicity to fish and invertebrates, with LC<sub>50</sub> values substantially higher than likely environmental exposure concentrations. Zebrafish embryo studies demonstrate safety at concentrations up to 500 µg/mL.

2. **Fish Tolerance:** Commercially important aquaculture species including Nile tilapia and common carp tolerate dietary inclusion of *Phyllanthus niruri* without adverse effects on growth, stress parameters, or immune function.

3. **Phytochemical Complexity:** The complex mixture of bioactive compounds in *Phyllanthus niruri* extracts may exhibit different ecotoxicological properties compared to individual isolated constituents, emphasizing the importance of whole extract testing.

4. **Heavy Metal Concerns:** The accumulation of heavy metals from contaminated soils presents dual concerns for product safety and environmental protection, necessitating quality control in cultivation and waste management.

5. **Research Needs:** Significant gaps persist in aquatic and soil toxicity data, bioaccumulation studies, and ecosystem-level impact assessments.

6. **Lack of Comprehensive Data:** Lack of ecotoxicity studies on *Phyllanthus niruri* in environmental contexts.

7. **Regulatory Gaps:** Weak safety standards for herbal residues.

## Ecotoxicity of *Phyllanthus niruri*: A Review of Its Effects on Selected Soil and Aquatic Organisms

**8. Biodiversity Impact:** Lack of understanding how herbs affect pollinators, soil health and aquatic life.

**9. Public Awareness:** Lack of awareness about the ecological risks of herbal medicine **use** and **disposal**. The "herbal paradox"—the contradiction between therapeutic safety and potential environmental risk—is partially resolved for *Phyllanthus niruri* by the current evidence, which suggests that with appropriate waste management and cultivation practices, the environmental impact can be minimized. However, the increasing global demand for this and other medicinal plants necessitates the development of comprehensive environmental risk assessment frameworks and sustainable industry practices.

Future research should prioritize acute and chronic toxicity studies on different organisms, bioaccumulation assessment, and field monitoring of environmental concentrations. The integration of traditional ecological knowledge with modern ecotoxicological approaches will be essential for ensuring the sustainable development of the herbal medicine industry while protecting aquatic and terrestrial ecosystems.

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## Ecotoxicity of *Phyllanthus niruri*: A Review of Its Effects on Selected Soil and Aquatic Organisms

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