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Overview of Terrestrial Ecotoxicology at UDESC: Advances and Gaps in the Last 10 Years

Panorama da Ecotoxicologia Terrestre na UDESC: Avanços e Lacunas nos Últimos 10 Anos

Gabriela dos Santos Castro *(ORCID 0009-0008-4115-6243), **Leonardo Motta da Costa Silva** (ORCID 0000-0001-7682-8339), **Douglas Alexandre** (ORCID 0000-0001-6093-9990), **Mari Lucia Campos** (ORCID 0000-0003-3250-2067)

State University of Santa Catarina, Lages, SC, Brazil. *Author for correspondence: gbs.castro95@gmail.com

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ABSTRACT

In recent decades, concerns about the environmental impacts of residues and contaminants in soil have driven the growth of studies in terrestrial ecotoxicology. The Santa Catarina State University (UDESC) has stood out in this field, developing research focused on evaluating the effects of different residues on soil organisms. This study provides a ten-year retrospective of UDESC's contributions, systematically cataloging publications that report soil ecotoxicological assays by UDESC-affiliated researchers. With the aim of identifying the main types of residues and materials studied, the advances achieved, and the existing gaps.Through a systematic survey, publications involving soil ecotoxicological assays conducted by researchers affiliated with UDESC were cataloged and analyzed. The results reveal a broad thematic scope, with a predominance of studies on agricultural pesticides and veterinary pharmaceuticals. However, the portfolio lacks investigations into animal-derived pyrolyzed residues (e.g., biochar and ashes), underscoring the need for further research in this area.

KEYWORDS: Bioindicator organisms. Contaminants. Sustainability. Soil health.

RESUMO

Nas últimas décadas, as preocupações com os impactos de resíduos e contaminantes no solo impulsionaram o avanço da ecotoxicologia terrestre. A Universidade do Estado de Santa Catarina (UDESC) tem se destacado nessa área, desenvolvendo pesquisas sobre os efeitos de diferentes resíduos em organismos do solo. Este estudo apresenta um retrospecto de dez anos das contribuições da UDESC, catalogando sistematicamente publicações com ensaios ecotoxicológicos de solo realizados por pesquisadores vinculados à instituição. Com o objetivo de identificar os principais tipos de resíduos e materiais estudados, os avanços alcançados e as lacunas existentes. A partir de um levantamento sistemático, as publicações foram selecionadas e analisadas quanto a classes de contaminantes, organismos-teste, endpoints e cenários edafoclimáticos. Os resultados indicam escopo temático amplo, com predominância de estudos sobre pesticidas agrícolas e fármacos veterinários, além de avanços metodológicos em protocolos adaptados a condições tropicais e subtropicais. Identificou-se, contudo, carência de investigações sobre resíduos pirolisados de origem animal (por exemplo, biochar e cinzas), evidenciando a necessidade de pesquisas futuras que conciliem benefícios agronômicos e avaliação ecotoxicológica em solos tropicais.

PALAVRAS-CHAVE: Organismos bioindicadores. Contaminantes. Sustentabilidade. Saúde do solo.

INTRODUCTION

Soils in agricultural and industrial landscapes receive continuous inputs of pesticides, veterinary pharmaceuticals, poultry litter, swine slurry, and industrial by-products (DALLA ROSA et al. 2019) These inputs can alter the structure and functioning of soil biotic communities responsible for decomposition, nutrient cycling,

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and other key ecosystem processes (SANTOS et al. 2021, MOREIRA & SIQUEIRA 2006). Terrestrial ecotoxicology provides a standardized framework to assess the effects of these inputs on representative soil bioindicator organisms (e.g., *Eisenia andrei*, *Folsomia candida*, *Enchytraeus crypticus*), following OECD (OECD 2004) and ISO (ISO 2007,2008) guidelines adapted to regional edaphoclimatic conditions

At the national level, Brazilian soil ecotoxicology has expanded from a narrow emphasis on acute pesticide testing to a broader framework that couples prospective and retrospective assessments, regulatory interfaces, and methodological adaptations for tropical and subtropical soils. A comprehensive review by NIVA et al. (2016) mapped key actors, themes (pesticides, pharmaceuticals, metals, organic and industrial residues), and regulatory milestones, emphasizing the need for locally calibrated endpoints and climate-relevant designs. Importantly, that review identified Santa Catarina as one of the most active hubs in the country and explicitly listed UDESC among the institutions contributing to the consolidation of terrestrial ecotoxicology in Brazil. This national perspective provides the backdrop against which we position the present synthesis.

Within this landscape, UDESC has built a sustained line of terrestrial ecotoxicology that addresses problems salient to southern Brazil's agro-industrial poultry, swine, and pulp-and-paper, while maintaining adherence to standardized protocols and quality assurance/quality control routines. Over the last decade, the program has investigated synthetic and natural pesticides, veterinary pharmaceuticals, organic amendments, and industrial residues such as pulp-and-paper dregs, alongside more complex exposure systems including biobeds and terrestrial model ecosystems. This portfolio has been shaped both by scientific questions and by stakeholder demand for decision-ready evidence tailored to tropical/subtropical soils.

A pivotal driver of capacity building was the long-standing collaboration with the University of Coimbra (Portugal), coordinated with Prof. Dr. José Paulo Sousa. Through reciprocal visits, short courses, and research stays, eight graduate students and one faculty member from UDESC trained in Coimbra, while Prof. Sousa provided on-site training in Santa Catarina on terrestrial ecotoxicology and environmental risk analysis. This exchange transferred protocols, organism culturing practices, and risk frameworks consistent with European practice, directly supporting the creation of UDESC's terrestrial ecotoxicology research line and the opening of the Terrestrial Ecotoxicology Laboratory (Laboratório de Ecotoxicologia Terrestre – LET).

We adopted a ten-year window (2015–2024) because it captures the consolidation of UDESC's program, maturation of projects, institutionalization of training and QA/QC practices, and alignment with national priorities articulated by NIVA et al. (2016). Despite advances, important knowledge gaps remain, particularly regarding pyrolyzed animal-derived residues (e.g., manure-derived biochar/ashes), mixture effects involving pesticides and veterinary drugs, and long-term or carry-over impacts under realistic use scenarios. Addressing these gaps requires deeper stakeholder integration and transparent communication of risks and benefits.

Accordingly, our objectives are to: (i) synthesize UDESC's contributions to terrestrial ecotoxicology over the past decade, emphasizing organism panels, exposure designs, and climate-relevant conditions; (ii) clarify methods and scope,

including how researchers and studies were identified; (iii) discuss advances, limitations, geographic reach, and beneficiaries (regulators, producer organizations, and extension services); and (iv) outline research priorities and collaboration pathways for the next phase, with particular attention to underexplored residues and mixture effects.

MATERIALS AND METHODS

Study scope and reporting

This synthesis includes UDESC-affiliated terrestrial ecotoxicology studies published between 2015 and 2024. The selected studies involved laboratory, semi-field, or field experiments evaluating soil organisms exposed to contaminants or residues relevant to agricultural or industrial contexts. Reviews without original experimental data and aquatic ecotoxicology studies were excluded.

Faculty identification and scope at UDESC

To delineate the institutional scope, we first mapped the human capital involved in terrestrial ecotoxicology at UDESC. At UDESC/CAV, 3 faculty members from the Department of Soils and Natural Resources affiliated with the Soil Science Postgraduate Program consistently contributed to this line of research during the period. This mapping served only to bound the institutional universe and inform the search strategy; analytical inferences were made at the study level rather than the individual level.

Information sources and search strategy

We used a two-tier strategy:

Researcher-based discovery. We screened Lattes/CNPq curricula and UDESC institutional pages for the faculty listed above to retrieve publication lists and confirm linkage to terrestrial ecotoxicology. Lattes it is a national, publicly searchable CV platform widely used in Brazil to register academic outputs and professional history; it allows filtering by keywords, time windows, and co-authorship, which we used to cross-check affiliations and topical relevance.

Database-based discovery. Using the consolidated researcher list and UDESC as an affiliation filter (including variants; see below), we queried Google Scholar, Scopus, and ScienceDirect for 2015–2024. We combined controlled terms and free text around organisms (e.g., *Eisenia andrei*, *Folsomia candida*, *Enchytraeus* spp.), endpoints (survival, reproduction, avoidance), matrices (tropical/subtropical soils; artificial soils), and exposure agents (pesticides, veterinary pharmaceuticals, poultry litter, swine slurry, industrial dregs, biobeds, terrestrial model ecosystems).

We harmonized institutional strings to capture common variants: “UDESC”, “Universidade do Estado de Santa Catarina”, and unit names (e.g., “Centro de Ciências Agroveterinárias – CAV”), ensuring that UDESC-affiliated outputs were not lost due to naming heterogeneity.

Inclusion and Exclusion Criteria

We included studies that:

(i) tested soil organisms (e.g., *E. andrei*, *F. candida*, *Enchytraeus* spp.) or microbial endpoints under recognized protocols (OECD/ISO or adapted equivalents);

(ii) evaluated contaminants/residues pertinent to agricultural/industrial contexts (e.g., pesticides, veterinary pharmaceuticals, poultry litter, swine slurry, industrial by-products such as pulp-and-paper dregs); and

(iii) listed at least one UDESC author/affiliation.

We excluded: narrative reviews (unless containing original experimental data), purely aquatic tests, and works without soil-biota endpoints. The duplicates were removed manually by checking DOIs, titles, and abstracts across all duplicate sets, and decisions were logged to ensure traceability.

Analysis and Organization of Data

From each eligible study, we extracted and organized the following information in a table: year of publication, main authors, and type of residue evaluated.

Data processing and analysis

The collected data were managed and analyzed using SPSS and MS Excel. Descriptive statistics were applied to calculate frequencies and medians, providing a clear view of the distribution and central tendency of the responses.

Language editing tools were used only for text review. All analyses, data interpretation, and scientific writing were performed by the authors.

RESULTS AND DISCUSSION

General Overview of Ecotoxicology Research at UDESC (2015–2024)

Over the last decade, UDESC has consolidated a broad, methodologically consistent portfolio in terrestrial ecotoxicology that spans agricultural pesticides, veterinary pharmaceuticals, organic agro-residues, industrial by-products, and targeted methodological advances for tropical and subtropical soils (Table 1). The program consistently employs standardized fauna protocols and adapts designs to local edaphoclimatic conditions, thereby improving ecological relevance and cross-study comparability.

UDESC's pesticide research moves from screening of natural products to mechanism-oriented tests with synthetic active ingredients and their metabolites, and to mitigation options in semi-field settings. Early work on natural products evaluated potential non-target soil effects of Bordeaux mixture and neem oil in tropical soils and found context-dependent risks that warranted systematic follow-up (DALLA ROSA et al. 2017). Building on this, andiroba and copaiba oils were tested for repellent efficacy against Musca domestica while tracking environmental effects, indicating a space for lower-hazard alternatives when soil endpoints are explicitly measured (ZORTÉA et al. 2017a).

For synthetic pesticides, fipronil was examined alone, in comparison with neem cake and neem extract, and through targeted assessment of its metabolites in tropical soils, which sharpened the risk profile for springtails under realistic exposure ranges (ZORTÉA et al. 2018a,b).

Neonicotinoid work with imidacloprid used three contrasting tropical soils and then isolated the modifying roles of temperature and soil moisture, showing that toxicity to earthworms and collembolans is sensitive to climate-linked stressors in ways that depend on soil properties (BANDEIRA et al. 2019, BANDEIRA et al. 2020, HENNIG et al. 2020). These results indicate that effect thresholds derived under one soil-climate

combination may misestimate risk under warmer or drier scenarios, and they argue for risk assessment factors that explicitly incorporate edaphoclimatic variance.

The portfolio also includes cypermethrin assays using earthworm reproduction and behavior, which are responsive endpoints for sublethal soil contamination and management guidance (ZORTÉA et al. 2022). Finally, using ecotoxicological parameters, studies demonstrated that biobed effluents were not harmful to soil fauna, offering a mitigation pathway to reduce diffuse pesticide inputs to soils near handling sites (CARNIEL et al. 2020).

Table 1. Articles published by UDESC in the last 10 years (2015-2024).

TITLE	Authors	Year of publication
Ecotoxicological Assessment of Coal Mining Waste	OLIVEIRA FILHO et al.	2015
Ecotoxicological effects of pig manure on *Folsomia candida* in subtropical Brazilian soils.	MACCARI et al.	2016
Ecotoxicological potential of bordeaux mixture and Neem oil on not target soil organisms.	DALLA ROSA et al.	2017
Repellent Effects of Andiroba and Copaiba Oils against *Musca domestica* (Common House Fly) and Ecotoxicological Effects on the Environment.	ZORTÉA et al.	2017a
Toxicity of four veterinary pharmaceuticals on the survival and reproduction of *Folsomia candida* in tropical soils.	ZORTÉA et al.	2017b
Piretous residue causes acute and chronic toxicity in Collembola and Oligochaeta.	OLIVEIRA FILHO et al.	2017
Ecotoxicological effects of fipronil, neem cake and neem extract in edaphic organisms from tropical soil.	ZORTÉA et al.	2018a
Ecotoxicological effect of fipronil and its metabolites on *Folsomia candida* in tropical soils.	ZORTÉA et al.	2018b
Insecticidal Action of Glycerol Monolaurate against the Lesser Mealworm (*Alphitobius diaperinus*) and its Ecotoxicological Effect on *Enchytraeus crypticus*.	TOMASI et al.	2018
Placing arbuscular mycorrhizal fungi on the risk assessment test battery of plant protection products (PPPs).	MALLMANN et al.	2018
Eprinomectin antiparasitic affects survival, reproduction and behavior of *Folsomia candida* biomarker, and its toxicity depends on the type of soil.	SERAFINI et al.	2019
Ecotoxicology as a tool for soil sustainability: Agrochemicals and Veterinary Pharmaceuticals in Brazil.	DALLA ROSA et al.	2019
Toxicity of imidacloprid to the earthworm *Eisenia andrei* and collembolan *Folsomia candida* in three contrasting tropical soils.	BANDEIRA et al.	2019
Effect of temperature on the toxicity of imidacloprid to *Eisenia andrei* and *Folsomia candida* in tropical soils.	BANDEIRA et al.	2020
Toxicity of imidacloprid to collembolans in two tropical soils under different soil moisture.	HENNIG et al.	2020
Effects of fertilizers on the root of *Avena strigosa* and behavior of *Folsomia candida*.	BARETTA et al.	2020
Ecotoxicological effects of swine manure on *Folsomia candida* in subtropical soils.	SEGAT et al.	2020a
Increasing level of liquid pig manure reduces *Eisenia andrei* and *Enchytraeus crypticus* reproduction in subtropical soils.	SEGAT et al.	2020b

Impacts on reproduction of *Enchytraeus crypticus* in fertilized soils with chicken litter treated with synthetic and natural insecticide.	TESTA et al.	2020
The effect of composted and non-composted poultry litter on survival and reproduction of *Folsomia candida*.	MACCARI et al.	2020
Are there any risks of the disposal of pesticide effluents in soils? Biobed system meets ecotoxicology ensuring safety to soil fauna.	CARNIEL et al.	2020
Ecotoxicological test to assess effects of herbicides on spore germination of *Rhizophagus clarus* and *Gigaspora albida*.	MALFATTI et al.	2021
Ecotoxicological effects of untreated pig manure from diets with or without growth-promoting supplements on *Eisenia andrei* in subtropical soils.	MACCARI et al.	2022
Application of Cypermethrin in Soil for the Assessment of Reproduction and Behavior of Earthworms *Eisenia andre*i.	ZORTÉA et al.	2022
Can the increase in atmospheric temperature enhance the toxicity and risk of fipronil for collembolans in tropical soils?	HENNIG et al.	2022b
Role of climatic factors in the toxicity of fipronil toward earthworms in two tropical soils: effects of increased temperature and reduced soil moisture content.	HENNIG et al.	2022a
The Toxicity of The Antiparasitic Amitraz in Tropical Soils on The Reproduction of Edaphic Organisms.	REIS et al.	2023
Ecotoxicity of alkaline residue from the pulp and paper industry to soil faunal organisms.	BIASI et al.	2024

Veterinary pharmaceuticals with soil and climate modifiers

Comparative tests of four veterinary drugs established toxicity baselines for *Folsomia candida* in tropical soils and revealed high sensitivity at low concentrations in some cases, emphasizing the importance of manure-borne actives in soil risk (ZORTÉA et al. 2017b).

Soil-type dependence was demonstrated for eprinomectin, with survival, reproduction and behavior of *F. candida* changing across soil matrices, which operationalizes the concept that sorption and bioavailability govern hazard in practice (SERAFINI et al. 2019).

A notable advance links climate to pharmaceutical and pesticide risk: higher temperatures and reduced soil moisture increased the hazard posed by fipronil to collembolans and earthworms across tropical soils, strengthening the rationale for embedding climate-change scenarios into soil-fauna testing and regulatory margins (HENNIG et al. 2022a,b).

UDESC also documented reproductive impacts of the antiparasitic amitraz in *F. candida* and *Enchytraeus crypticus*, extending the evidence base for veterinary actives beyond macrocyclic lactones (REIS et al. 2023).

Organic residues under real management

UDESC systematically interrogated swine manure and poultry litter across realistic dose and processing gradients. In subtropical soils, pig manure reduced reproduction in *F. candida* and increasing levels of liquid slurry depressed reproduction of *Eisenia andrei* and *E. crypticus,* providing quantitative support for application limits and treatment requirements in livestock-intensive regions (SEGAT et al. 2020a,b).

Poultry-litter studies showed organism-level effects in *E. crypticus* and *F. candida* when litter was treated with synthetic or natural insecticides and when composted versus non-composted materials were compared, underscoring that both litter chemistry and stabilization stage control bioavailability and hazard (TESTA et al. 2020, MACCARI et al. 2020).

Field realism was further increased by testing untreated pig manure derived from diets with and without growth-promoting supplements, which affected earthworm endpoints in subtropical soils and highlights feed-to-field linkages in terrestrial ecotoxicology (MACCARI et al. 2022).

Together, these bodies of work show that soil hazard depends jointly on dose, processing state, and the receiving soil, with clear implications for nutrient management policies and on-farm best practices.

Industrial residues and special materials

Beyond agro-residues, UDESC evaluated mining and pyritous residues and documented acute and chronic effects on springtails and oligochaetes, including avoidance patterns relevant to acidification risks. These findings justify the application of ecotoxicological criteria in mining-waste management for tropical soils (OLIVEIRA FILHO et al. 2015, OLIVEIRA FILHO et al. 2017).

Pulp-and-paper alkaline dregs also showed negative effects on soil fauna, which is salient given rising cellulosic by-product volumes in the region (BIASI et al. 2024).

As an alternative control tool, glycerol monolaurate was tested for insecticidal action and its ecotoxicity was evaluated using Enchytraeus crypticus, illustrating how efficacy studies can be aligned with soil-safety screening in a single pipeline (TOMASI et al. 2018).

Fertilizer impacts on *Avena strigosa* roots and *F. candida* behavior, added agronomic inputs to the assessment scope and caution against assuming neutral soil effects from common amendments (BARETTA et al. 2020).

Methodological contributions

Methodologically, UDESC expanded the terrestrial test battery by integrating arbuscular mycorrhizal fungi into plant-protection product risk assessment. This work identified AMF species suitable for germination tests under ISO protocols and proposed protocol refinements, which increase ecological realism by linking soil fauna with plant–microbe symbionts (MALLMANN et al. 2018). UDESC also applied Terrestrial Model Ecosystems to observe responses of native soil communities under controlled semi-field conditions. TME increases environmental realism while retaining experimental control and represents a community-level exposure system rather than a mitigation device (MALFATTI et al. 2021). In parallel, biobeds were evaluated as biological filters that degrade and retain agrochemical residues from point sources, which constitutes a mitigation measure rather than a community test (CARNIEL et al. 2020). Together, these contributions advance methodological realism, connect invertebrate, microbial and plant endpoints, and align with regulatory modernization for tropical soils (MALLMANN et al. 2018, MALFATTI et al. 2021, CARNIEL et al. 2020).

Synthesis of UDESC's contribution

Across 2015–2024 UDESC delivered twenty-eight studies with direct regional relevance and strong links to local industry and communities. The concentration of

outputs in agricultural pesticides and veterinary drugs mirrors widespread use in Southern Brazil and underlines the program's applied orientation. At the same time, the portfolio covers critical waste streams, including poultry litter, swine slurry and industrial dregs, and introduces mitigation strategies and new endpoints. The institutional role is therefore twofold: production of decision-relevant effect data for tropical soils, and training of ecotoxicologists in standardized, climate-aware testing. A persistent gap is the scarcity of trials with animal-derived pyrolyzed materials such as biochar, which appears as a clear opportunity aligned with regional waste-to-value strategies (survey summary and gaps)

The classification and frequency of the residue types assessed in these studies is summarized in Table 2. This table makes clear the predominance of research involving pesticides and veterinary pharmaceuticals, while other residue categories, such as poultry litter, industrial by-products, and pyrolyzed materials, appear less frequently. This distribution is further illustrated in Figure 1, which visually highlights the contrast among residue categories.

Table 2. Frequency with which the different waste materials were studied at UDESC.

INPUTS/RESIDUES	FREQUENCY
Poultry litter	2
Alkaline dregs (pulp and paper)	1
Pesticides (natural and/or synthetic)	14
Pig manure	4
Veterinary pharmaceuticals	6
Mineral and organic fertilizer	1
Glycerol monolaurate (GML)	1
Pyritous mining residue (coal-pyrite mix)	2

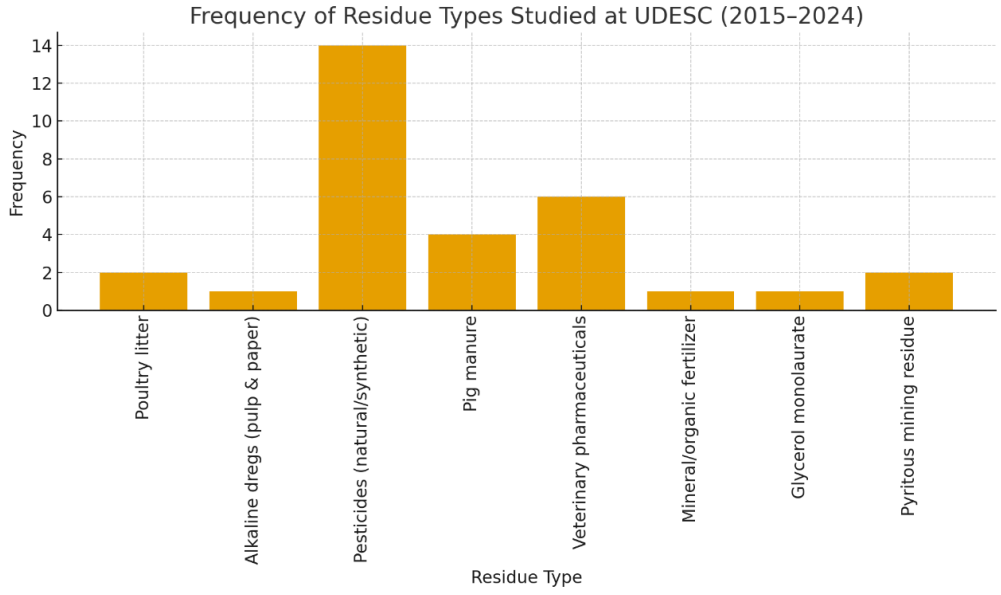


Figure 1. Frequency of residue types studied in terrestrial ecotoxicology research at UDESC (2015–2024).

Limitations, gaps, and directions for future work

Climate-sensitive toxicity and new thresholds. The climate sensitivities observed for fipronil and imidacloprid indicate that legacy thresholds may need to be re-benchmarked for warmer, drier scenarios. Future designs should cross soil texture, organic matter, and moisture–temperature regimes to derive climate-adjusted hazard thresholds for tropical and subtropical soils (BANDEIRA et al. 2020, HENNIG et al. 2022a,b).

Life-cycle perspective for manures and litter. Processing state and upstream dietary inputs propagate to soil toxicity. Environmental permits and extension guidance in livestock-dense regions should integrate feed and litter management, alongside application limits informed by soil-fauna endpoints (SEGAT et al. 2020a,b; MACCARI et al. 2022).

Primary gap: pyrolyzed animal-derived residues. UDESC has not yet addressed biochars or ashes produced from animal-derived residues, including manure, poultry litter, carcasses, hatchery and egg-processing wastes, and slaughterhouse by-products. Although agronomically promising, these materials can carry PAHs, concentrated metals, and high alkalinity that may alter toxicity pathways and soil functions. Priority studies should pair agronomic performance with ecotoxicological endpoints across contrasting tropical soils.

Mixtures and interactions. Evidence on mixtures is scarce. Beyond cases such as poultry litter with insecticide additives (TESTA et al. 2020, MACCARI et al. 2020), few factorial designs test interactions among contaminant classes or waste types. Future work should include mixtures of contaminants to map additivity, antagonism, or synergy.

Methods to increase environmental realism. Terrestrial Model Ecosystems and other semi-field designs should be more widely employed to quantify community-level responses under controlled conditions, thereby increasing ecological realism in tropical and subtropical soils.

CONCLUSION

This survey highlights UDESC's consistent contribution to terrestrial ecotoxicology in Brazil over the last decade. The portfolio addresses a broad set of residues and contaminants that mirror the main soil pressures in Southern Brazil and applies internationally recognized bioindicators with protocol adaptations suited to tropical and subtropical conditions.

The analysis also identifies strategic gaps, particularly the absence of studies on animal-derived pyrolyzed residues, which is timely given the growing use of pyrolysis for organic waste. Future research should expand bioindicator diversity, include long-term designs, examine contaminant mixtures and interactions, and integrate climate-sensitivity through moisture and temperature regimes. The study underscores the value of sustaining and expanding UDESC's research lines to ensure that scientific advances translate into safer, more sustainable soil management.

NOTES

AUTHOR CONTRIBUTIONS

Conceptualization, methodology, and formal analysis, Mari Lucia Campos, Douglas Alexandre and Gabriela dos Santos Castro; investigation, Gabriela dos Santos Castro; resources and data curation, Mari Lucia Campos; writing-original draft preparation, Gabriela dos Santos Castro; writing-review and editing, Douglas Alexandre, Leonardo Motta da Costa Silva and Mari Lucia Campos;supervision, Mari Lucia Campos and Douglas Alexandre; project administration, Mari Lucia Campos; funding acquisition, Mari Lucia Campos. All authors have read and agreed to the published version of the manuscript.

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INSTITUTIONAL REVIEW BOARD STATEMENT

Not applicable for studies not involving humans or animals.

INFORMED CONSENT STATEMENT

Not applicable because this study did not involve humans.

DATA AVAILABILITY STATEMENT

The data can be made available under request.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest.

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