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REVIEW

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The unexplored challenge of indaziflam in agroecosystems

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Abstract
Indaziflam is a pre-emergent herbicide increasingly used in agriculture, yet its high toxicity and persistence in soil raise concerns regarding its environmental impact and implications for sustainable production systems. Despite its growing use, scientific knowledge on its environmental behavior and mitigation strategies remains limited. This study presents a systematic review focused on biological processes for reducing indaziflam contamination in agricultural soils. Using the PRISMA protocol, scientific articles published between 2011 and 2025 were retrieved from the Web of Science, Scopus, and SciELO databases. The review identified five relevant studies, most published in recent years and restricted to only two countries, highlighting significant geographic and thematic gaps. The strategies reported include biosorption usingbiochar, phytoremediation with crop-relevant plant species, and microbial biodegradation. However, no study demonstrated direct microbial metabolism or enzymatic degradation of indaziflam. This lack of evidence suggests that the herbicide's recalcitrance may limit microbial activity or that specific degraders have yet to be identified. The current scarcity of research in major agricultural regions likely underestimates the broader ecological risks of indaziflam. Future research should prioritize the isolation and application of microorganisms with metabolic potential, along with the use of tolerant plant species and complementary physicochemical approaches to advance sustainable remediation strategies.

Keywords Bioremediation, Environmental behavior, Herbicide, Soil, Sustainability

1 Introduction

The growing demand for food, driven by the exponential increase in population in recent decades, has been fueling the extensive use of pesticides and fertilizers in agriculture [1–3]. This practice can lead to significant consequences for environmental balance, triggering soil and water resource contamination that will, in turn, negatively impact biodiversity and ecosystems surrounding agricultural areas [4, 5].

In the pursuit of reducing the environmental impacts of pesticides, remediation techniques have been developed and applied, based on different physical, chemical, and/or biological processes [5–7]. However, these approaches have specific advantages and limitations regarding practical and economic feasibility, environmental impact, and effectiveness [8]. Thus, the development of safer, cost-effective, and ecologically sustainable methods to remove pesticides from the environment and reduce their harm is widely explored in the scientific literature [8–15].

In this regard, the herbicide indaziflam (N-[1R,2 S)-2,3-dihydro-2,6-dimethyl-1 H-inden-1-yl]-6-[(1R)-1-fluoroethyl]-1,3,5-triazine-2,4-diamine) is a relatively recent compound, which was first reported in 2010 in the United States for controlling unwanted plants in turf [17]. Its action is systemic typically applied for the pre-emergent control of weeds [16]. Nevertheless, this molecule poses a significant risk due to its high persistence in soil, with a half-life exceeding 150 days and long residual activity, as well as high toxicity [17–19]. Indaziflam belongs to the chemical group of alkylazines and is currently used worldwide in a variety of crops (coffee, sugarcane, citrus, palm, guava, apple, mango, grape) and in commercial areas (lawns and ornamental plants) [20, 21].

Indaziflam acts on cellulose biosynthesis and was considered the most potent cell wall inhibitor ever discovered [17, 19]. However, this mechanism is not yet fully elucidated, but prevent the formation of new plant cells, leading to the cessation of plant growth. Although the formation of cell wall is inhibited, the synthesis of polysaccharides is not affected, which allows for the hypothesis that its inhibitory action occurs at the stage of cross-linking of cellulose microfibrils [20, 21]. Moreover, the herbicide inhibits the crystals deposition in cell wall, which severely affect its formation, division, and elongation and indicate that developed leaves are minimally affected, as their cell walls are already completed. Consequently, effectiveness in post-emergent applications has only been observed up to the two-leaf stage [16]. Plant size, developmental stage, and environmental conditions may also limit the indaziflam action in post-emergence [22].

Chemical characteristics described indaziflam as: (i) lipophilic molecule with low water solubility (2.8 $mg.L^{-1}$); (ii) organic carbon partition coefficient (Koc) less than 1000 $mL.g^{-1}$ with low affinity for organic particles; (iii) half-life higher than 150 days with persistence in soil longer than other pre-emergent herbicides; and (iv) weak acid (pKa = 3.5) with a log Kow of 2.8 (at pH 4.0, 7.0, or 9.0), which presented low to moderate mobility in the soil [17–19].

Due to its long residual activity and broad spectrum of action, indaziflam is applied at low doses. For the control of susceptible annual grasses, the dose potentially reaches 150 g ha^{-1} for more tolerant species [16]. In sugarcane, it varies from 110 to 220 g ha^{-1} depending on the soil characteristics, and a single application generally is sufficient to keep the crop free of invasive plants for 12 months [23].

In agricultural areas, indaziflam can be degraded in soil and intermediate compounds are generated: indaziflam triazine-indanone (ITI), indaziflam-carboxylic acid (ICA), fluoroethyldiaminotriazine (FDAT), indaziflam-hydroxyethyl, indaziflam-olefin, and fluoroethyltriazinanedione (Fig. 1). Indaziflam, ITI, and ICA are cleaved at the N bond to form FDAT (from the triazine portion) and a set of smaller unidentified compounds (from the indazil portion). If there is mineralization of these byproducts, the residues are primarily converted to CO_2 [24].

However, research on treatment strategies for agroecosystems affected by indaziflam remains scarce, despite its considerable potential for environmental harm. Therefore, this study presents a systematic review of the scientific literature focused specifically on

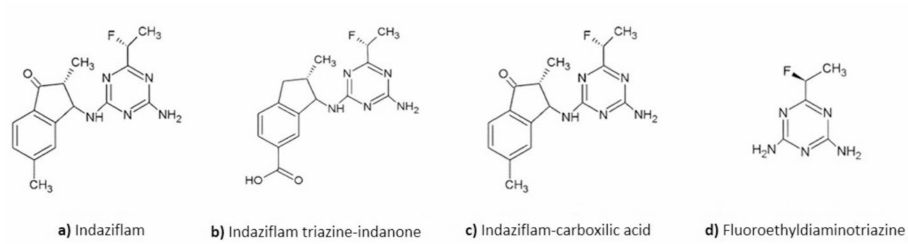

Fig. 1 Chemical structures of **a** indaziflam and its metabolites: **b** indaziflam triazine-indanone, **c** indaziflam-carboxylic acid, and **d** fluoroethyldiaminotriazine

bioremediation methodologies applied to soils contaminated by indaziflam. The review aims to identify the biological approaches explored to date, assess their effectiveness, and highlight existing knowledge gaps. A wide range of recent studies was analyzed, including the most current findings available. Furthermore, the discussion offers a critical evaluation of the feasibility of biotechnological tools and their potential to address the environmental challenges posed by this herbicide.

2 Global pesticide consumption

Global pesticide consumption currently reaches 2.6 million tons per year, with 50% allocated to herbicides, 30% to insecticides, and 17% to fungicides, used to control weeds, insects, and fungi, respectively [25]. This high use of agricultural pesticides is directly linked to the growth in primary crop production, such as wheat, corn, sunflower, and rice, which increased by more than 54% between 2000 and 2021, reaching a record 9.5 billion tons during this period [26]. In addition to the application of these products in established crops, there has been an expansion into new arable land facilitated by technologies such as irrigation [27, 28]. These factors contribute to improved agricultural performance but may also lead to issues related to environmental stress due to intensive production conditions [4, 28–30].

Chemical control in weed management is favored in the current scenario due to its high agronomic performance, short actiontime, and reduced labor costs. In the field, crops of interest and weeds compete for space, light, nutrients, and humidity, which can reduce agricultural production by up to 50%, depending on various biotic and abiotic factors [31].

Therefore, the use of herbicides becomes essential for modern agriculture, as it promotes higher productivity by reducing the harmful effects caused by invasive plants. However, continuous use and improper management of these products lead to various ecological harms. Currently, over 64% of arable land (approximately 24.5 million km^2) is threatened by contamination from at least one herbicide, and 31% is at high risk of pollution [32].

In this context, indaziflam has been widely used in sugarcane cultivation, where it is recognized for its long residual period [33]. However, improper use of indaziflam can trigger various negative effects, primarily due to its environmental persistence [8]. Despite its hazardous nature, there are few reports in the scientific literature assessing the potential impact of this molecule, as it is a relatively new herbicide. Therefore, it is necessary to gather information that characterizes the consequences of indaziflam management in soil and identifies the main bioremediation techniques for contaminated agroecosystems.

3 Environmental impacts of Indaziflam

Soil and water contamination has frequently occurred due to various substances from anthropogenic activities, such as heavy metals, hydrocarbons, and pesticides [34, 35]. Among these potential pollutants, pesticides represent a significant source of contamination due to their high usage worldwide, their dissipation in different environmental matrices, and the indirect impacts from activities related to agricultural applications [36]. Ideally, a pesticide should exhibit selective toxicity to its target organism and not persist in the environment for extended periods. However, the vast majority do not possess these properties and cause various harmful effects even to non-target organisms [37]. This phenomenon justifies the studies on the negative impacts that these xenobiotics can have on agroecosystems.

In this context, indaziflam is categorized as a persistent molecule with high environmental hazard. For example, Brosnan [22] found its activity in controlling *Poa annua* even after 28 weeks of application, and Guerra [38] observed a long residual activity period (ranging from three to five months) for *Eclipta alba*, *Euphorbia maculata* e *Senecio vulgaris*.

Regarding leaching, Jhala, Ramirez, and Singh [18], using *Lolium multiflorum* as a bioindicator in soils with 4% clay and 0.5% organic matter, observed that 73 g ha^{-1} of indaziflam caused leaching up to depths of 15, 20, and 25 cm for precipitation levels of 50, 100, and 150 mm, respectively. This suggests that, under these conditions, indaziflam is considered an herbicide with moderate leaching potential.

An important factor for this herbicide is its leaching potential, which implies contamination of surface and groundwater. Indaziflam exhibits low to moderate mobility in the soil [17, 18], and there is a positive correlation between its sorption and the organic carbon content of various Brazilian soils [27]. However, despite this characteristic being present in the original molecule, its degradation intermediates are more mobile in the soil. Furthermore, since these metabolites are more polar than indaziflam, they exhibit lower sorption and, consequently, a higher potential for leaching and contamination [37, 39].

Regarding its direct effects on non-target organisms, Jones [40] observed that the presence of indaziflam reduced the root biomass of bermudagrass hybrids and decreased the accumulation of macro and micronutrients in their foliar tissues. In animals, Tissot [41] reported a high mortality rate in aquatic bivalves (*Mya arenaria*) and the presence of indaziflam in the tissues of these mollusks when it was present in the water. Additionally, potential harmful effects on humans were presented by Adiguzel [42], whose results revealed that increasing concentrations of indaziflam caused genotoxic effects in HepG2 cells.

Therefore, the negative impacts of continuous pesticide use, such as indaziflam, in agroecosystems have been widely documented. Its deleterious effects directly influence the reduction of biodiversity and the contamination of soil and water, as well as pose threats to non-target organisms and human health. To mitigate these adverse effects, it is crucial to explore sustainable alternatives for the recovery of contaminated areas. In this context, strategies based on the use of biological tools, such as bioremediation, offer promising solutions [10]. These approaches not only aid in the degradation of toxic compounds but also promote ecological restoration, preserving the balance of agricultural ecosystems.

4 Bioremediation as an alternative for contaminated agroecosystems

Bioremediation presents itself as an innovative and promising solution to address adverse environmental impacts in agricultural soils affected by pesticides. This integrated approach applies techniques that use microorganisms, plants, and naturally sourced adsorbent materials to facilitate the degradation, transformation, and mineralization of toxic contaminants into less harmful compounds. Through the metabolic activities of microorganisms and the beneficial interactions between plants and soil, bioremediation not only reduces the toxicity of xenobiotics but also supports soil quality restoration, thereby contributing to the development of healthier and more sustainable agroecosystems [10, 43].

The biodegradation of pesticides through the metabolic activities of microorganisms has become an increasingly recognized solution due to its efficiency, economic viability, and environmental benefits [44]. In this context, approaches employing microorganisms, such as bioaugmentation and biostimulation, have gained prominence. Bioaugmentation involves introducing pesticide-degrading microorganisms into contaminated sites, which may include native (autochthonous), non-native (allochthonous), or genetically modified organisms (GMOs), with the latter option being particularly relevant for harsh environments [10, 11]. Biostimulation aims to enrich the native microbial population by optimizing environmental conditions, such as pH, temperature, and nutrient content. This facilitates the formation of an effective biosystem for remediating areas with high contaminant concentrations [43]. The literature documents the efficiency of microorganisms in remediating environments contaminated by various pesticides, as highlighted in the review study by Lopes [10]. The microbial biodegradation uses pesticides as sources of carbon and nutrients by breaking molecular chemical bonds, which release energy for their metabolism. As a result, the initial contaminants are transformed into less or non-toxic byproducts. Different microorganisms employ a variety of intracellular mechanisms (aerobic, anaerobic, and chemolithotrophic) or extracellular enzymes, which allow an adaptive approach to organic pollutants degradation under different environmental conditions [44].

Besides microorganisms, phytoremediation is an innovative solution using plants to treat area as a low-cost and environmental friendly alternative. In this process, plants stabilize or transfer contaminants, such as heavy metals and pesticides, into their roots and leaves, facilitating the degradation or immobilization of these pollutants [13, 45–47]. Regarding pesticides, Araújo [15] demonstrated the capacity of the plant *Canavalia ensiformis* to phytoremediate soils contaminated with sulfentrazone, ensuring safety for subsequent cultivation of sensitive crops and contributing to the recovery of soil biodiversity. To ensure the effectiveness of this process, the selection of plant species should consider characteristics such as vigor, tolerance to the contaminant, and biomass production capacity [48].

Another relevant approach is biosorption, aphysicochemical process that retains pesticides on solid surfaces, with soil organic matter (SOM) playing a crucial role as an adsorbent. SOM mitigates herbicide leaching through interactions such as covalent bonding and Van der Waals forces [48–50]. However, conserving SOM faces challenges, such as high humidity and temperatures that accelerate its decomposition. Management practices, such as biochar application, are essential to increase organic carbon in the soil and enhance sorptive interaction with herbicides [51–53]. Biochar, produced through biomass pyrolysis in low-oxygen environments, not only sequesters carbon but also improves soil fertility by retaining nutrients and supporting the biosorption of pollutants [54–60]. Studies indicate that biochar can serve as an effective alternative material in remediating herbicide-contaminated areas [9, 61]. For instance, Cara [5] reported in her study that biochar presence significantly reduced carbofuran and chlorpyrifos concentrations in soil, while Ouyang [62] observed that adding 5% biochar increased atrazine removal rates from 27.02 to 76.65%, demonstrating its efficacy. These results were likely due to the macro- and micropores in the substrates, which facilitated the sorption process of pesticide molecules [5, 59, 63].

Thus, as evidenced, bioremediation techniques appear promising for the recovery of contaminated soils, including those affected by indaziflam. Although this herbicide is a relatively recent product on the market, it raises significant concerns due to its remarkable persistence in the environment and its high capacity to pollute soils and impact water resources.

5 Selection of manuscripts in the scientific literature

The methodology for data extraction and the creation of the database followed the PRISMA protocol [64]. The selection of studies was carried out in the online databases Web of Science, Scopus, and SciELO, covering publications from 2011 to 2025. All manuscripts used in this study were obtained through the institutional access to the online system “Periódicos CAPES” - Coordination of Superior Level Staff Improvement, Brazil [65]. To guide the search, three keywords were defined, focusing on articles in English that addressed bioremediation techniques in the context of treating soils contaminated with the herbicide indaziflam. The three strategies used are outlined below:

Strategy 1: Indaziflam.

Strategy 2: Indaziflam AND Soil.

Strategy 3: Indaziflam AND Soil AND Bioremediation.

Using the adopted methodology, with queries in the three databases, a total of 345 articles were retrieved. After removing duplicates (132) and articles without a DOI identifier (6), 207 manuscripts remained. A detailed analysis of titles and abstracts led to the exclusion of 202 articles that did not address the application of bioremediation techniques for the treatment of soils contaminated with the herbicide indaziflam. Moreover, the criteria only selected original research papers; thus, review articles, conference papers, and non-peer-reviewed sources were excluded. Thus, after a thorough content evaluation, only 5 studies that met the criteria established for this work were identified and selected (Fig. 2).

From a critical approach to the literature regarding the 202 articles excluded through detailed analysis of titles and abstracts, it can be observed that the works generally address specific issues related to the movement and dissipation of the herbicide—dynamics of how indaziflam behaves in the soil, either due to pH or texture [66] and how it dissipates in the environment [66, 67] sorption and desorption—how indaziflam and its metabolites are fixed and released in different soil types [9, 16, 39]; weed control—efficacy of indaziflam in controlling various weed species [16] including resistance and tolerance in several crops [68, 69] environmental effects—evaluations of the toxicological potential [42] impact on biodiversity [67], and effects on native species [70] interactions with other herbicides—analysis of mixtures of indaziflam with other chemicals

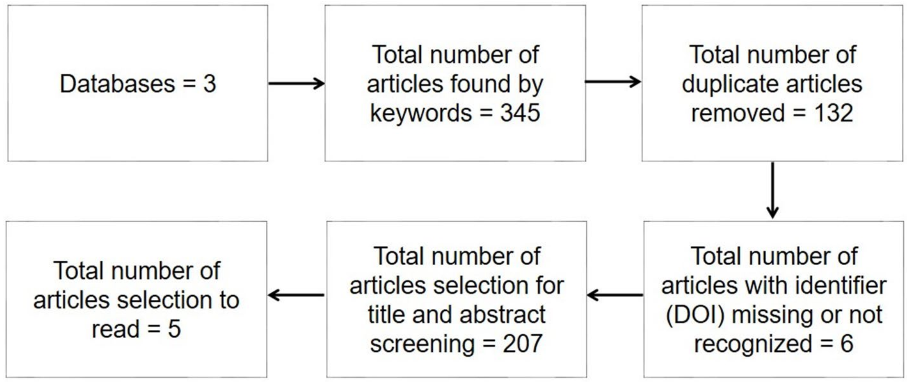

Fig. 2 PRISMA protocol as a methodology for systematic selection of scientific articles

and their effects [71–73] and analytical methods—development and validation of methods such as liquid chromatography coupled with mass spectrometry [74, 75], modified QuEChERS, and UHPLC-MS/MS, to detect and quantify indaziflam residues in different matrices [75].

In contrast to the significant concentration of studies focusing on the management and effects of the indaziflam molecule, there is a need for research based on techniques aimed at inhibiting and/or minimizing the impacts caused by the herbicide. Bioremediation, as previously presented, is a promising strategy that could offer effective solutions for the chemical residues left by herbicides such as indaziflam. Despite the evidence of its environmental impacts, the reviewed literature lacks investigations on how microorganisms, plants, or enzymes can be employed to restore soils contaminated by this herbicide.

5.1 General aspects of the selected manuscripts

The selected manuscripts are detailed in Table 1. From an initial analysis, there is a noticeable recent interest in soil bioremediation with indaziflam, as 4 studies were published in the last 5 years. This highlights the emerging concern within the scientific community regarding treatment alternatives, following the negative impacts observed after the first use of this herbicide in 2010.

It is also noted that studies on the bioremediation of indaziflam are limited to only two countries in the Americas, Brazil and the United States (Table 1). This fact highlights a geographical limitation that reflect the lack of research in other regions. Hence both countries are major consumers of pesticides [76, 77], creating an urgent demand for sustainable solutions. The absence of studies in other countries with vast agricultural regions (such as China and India) can be attributed to differences in research priorities, which focus on food security and agricultural productivity; and to stricter regulations and the use of other pesticides, which reduce the demand for specific approach on indaziflam. Nevertheless, this limitation to only two countries may hinder the transfer of knowledge and the adaptation of effective solutions to varied scenarios. Non-exploitation of different agroecosystems allows the development of new multidisciplinary projects and emphasizes the importance of encouraging such research in diverse conditions, which will enrich the scientific discussion on biological treatment approaches in production systems with indaziflam and promote direct impact on sustainable management practices in a global context.

Table 1 Detailing of the studies selected by the PRISMA protocol on soil bioremediation with Indaziflam

Year	Biotechnological strategy	Soil classification	Other herbicides in association	Key findings	Country	Reference
2014	Biochar (Macadamia nut)	Sandy clay loam and sandy loam	MCPA (2-methyl-4-chlorophenoxyacetic acid); terbuthylazine, nicosulfuron, and fluoroethyldiaminotriazine (FDAT - indaziflam metabolite)	Biochar aging promoted greater surface area and porosity, which reduced sorption of terbuthylazine and MCPA, but increased sorption of indaziflam and FDAT. Nicosulfuron showed low sorption, indicating high leaching potential. Thus, it was suggested that maturation optimize its properties for soil remediation	United States	Trigo [37]
2021	Biochar (Soybean residues, sugarcane bagasse and grape wood chips)	Silty clay loam and Silt loam	Indaziflam triazine-indanone, fluoroethyldiaminotriazine, and indaziflam-carboxylic acid (ITI, FDAT, and ICA; respectively - indaziflam metabolites)	Indaziflam showed higher sorption than the metabolites, whose lowest sorption was found to FDAT and ICA. Biochar sorption process was influenced by soil pH and organic matter. Moreover, hysteresis was observed in the desorption of indaziflam and ITI, indicating strong retention in the soil matrix	United States	Mendes [9]
2023	Plants (*Lupinus albus*, *Canavalia ensiformis* and *Mucuna cinerea)*	Clay	-	Plants species tested were not effective in phytoremediation even after 120 days of herbicide application in two doses (0,75 and 100 g a.i. ha^{-1})	Brazil	Silva [78]
2023	Microorganisms (*Aspergillus niger*; *Penicillium pinophilum*; *Trichoderma* sp. *Bacillus subtilis*; *Pseudomonas* sp.; and *Azospirillum brasiliense*)	-	Sulfentrazone; clomazone; diuron, glyphosate; and s-metolachlor	The microbial species tested were tolerant to indaziflam, but were not able to metabolize this molecule	Brazil	Rabelo [14]
2025	Microorganisms (*Trichoderma* spp.)	-	Metsulfuron-methyl and atrazine	Indaziflam showed a suppressive effect on the development of the *Trichoderma* strains tested	Brazil	Conte [82]

In studies conducted directly on soils, research was found on clay, loam, and silty soils (Table 1). Silva's [78] clay soil is widely found in various regions of Brazil and is extensively used for sugarcane cultivation, one of the country's main crops [79, 80]. On the other hand, the combination of silty clay loam and silt loam soils in Mendes' [9] study, and sandy clay loam and sandy loam soils in Trigo's [37] study, are fundamental for agricultural production in the United States, especially in the Midwestern. In this region, thecharacteristics of these soils, such as their ability to retain moisture and essential nutrients, promote high productivity, making them ideal for corn cultivation [81]. However, this concentration of studies on only a few soil types reveals a significant limitation in the diversity of agricultural systems.

Furthermore, it is worth noting that, among the four identified studies, two explored bioremediation in conjunction with other herbicides (Table 1), indicating a broader approach in the search for sustainable solutions. However, this strategy may complicate the in-depth analysis of the specific effects of indaziflam, potentially compromising the clarity of the results related to this herbicide.

5.2 Biosorption with adsorbent materials

Regarding the studies in the literature that associate biochar with soil bioremediation of indaziflam, two studies were found:

Trigo [37] evaluated the sorption of four herbicides, including indaziflam and its degradation product FDAT, using macadamia nut shell biochar, both fresh and aged for one or two years. This study demonstrated that aging enhanced the biochar's surface area and porosity, resulting in increased sorption of indaziflam and FDAT, although the sorption of other herbicides like terbuthylazine and MCPA was reduced. While important insights into the influence of biochar aging was provided, there was a limitation by the absence of soil matrices and microbial activity analysis, as well as its focus on a single feedstock, which restricts broader applicability.

Mendes [9] examined the impact of biochars produced from soybean residues, sugarcane bagasse, and wood chips on the sorption-desorption behavior of indaziflam metabolites in soils from the Midwestern USA. All biochars improved sorption and reduced desorption, with wood-derived biochar showing the highest effectiveness. Although the inclusion of real soil conditions and multiple biochar sources strengthened the study, it lacked mechanistic analysis of sorption variability and did not explore potential interactions with soil microbial communities.

Overall, these studies suggested that biochar can enhance the immobilization of indaziflam and its metabolites, particularly when aged or derived from specific feedstocks. However, critical gaps remain, including limited understanding of long-term stability, bioavailability, and biochar-microbe-contaminant interactions. Future research should incorporate sorption studies with microbial activity monitoring, employ molecular characterization techniques to elucidate sorption mechanisms, and prioritize long-term field assessments to evaluate the effectiveness and environmental safety of biochar-based remediation strategies.

5.3 Phytoremediation

The treatment strategy with plants has already been widely explored to detoxify environments contaminated by heavy metals, hydrocarbons, dyes and other pollutants [45]. Regarding pesticides, studies showed positive results in soil phytoremediation with the herbicide tebuthiuron [15, 45, 46, 83, 84]. However, this review reinforces the need for research with indaziflam, since there is a great lack of this topic that highlights the concern with decision-making in cases of contamination or excessive use of this molecule-worldwide, thus revealing the gap in research.

The use of plants in the decontamination of environments contaminated with indaziflam was reported only in 2023 by Silva [78]. The authors evaluated the phytoremediation potential of agronomically important crops, such as *Lupinus albus*, *Canavalia ensiformis*, and *Mucuna cinerea*, for the phytoremediation of soils contaminated with indaziflam. In this study, none of the tested doses (75 and 100 g a.i. ha^{-1}) were effective for phytoremediation, and even after 120 days of indaziflam application, the plants did not show the expected capacity to remove or neutralize the contaminants in the soil. This finding raises questions about the viability of using these species for remediation in soils contaminated by indaziflam. The ineffectiveness, in this case, may be attributed to several reasons, such as soil characteristics, including pH and texture, which may have affected the herbicide's availability. Furthermore, the selected plants may not have the necessary mechanisms to metabolize the target molecule, and the dosage or the 120-day period may not have been sufficient for positive environmental treatment outcomes.

These findings underscored the complexity of phytoremediation as a remediation strategy for indaziflam contamination and reveal the necessity for more comprehensive studies. Future research should focus on screening a broader range of plant species, including those known for robust detoxification mechanisms or symbiotic relationships with degrading microbes. Additionally, investigations should systematically assess soil properties and herbicide bioavailability to optimize conditions for plant uptake and/or degradation. Prolonged exposure periods and varied dosages, combined with molecular and physiological analyses of plant responses, will be crucial to elucidate phytoremediation potential. Integrating phytoremediation with complementary approaches (microbial bioremediation and soil amendments) may also enhance overall remediation efficacy.

5.4 Biodegradation

Another thematic with limited literature regarding indaziflam is microbial biodegradation and only two recent studies were found [14, 82].

In 2023, Rabelo [14] studied the tolerance and potential of several microorganisms (*Aspergillus niger*, *Penicillium pinophilum*, *Trichoderma* sp., *Pseudomonas* sp., and *Azospirillum brasilense*) to degrade herbicides. All the species tested were tolerant to indaziflam but did not have the ability to metabolize it. The lack of microorganisms capable of degrading this molecule may be attributed to many factors, which included the complexity of the chemical structure of indaziflam that requires specific enzymes for its degradation. Furthermore, the experimental conditions may not have favored microbial activity as microorganisms may not adapt properly, or the herbicide promoted an inhibitory effect, or there was competition with other substrates in the culture medium. Finally, the incubation time may have been insufficient to microbial action against indaziflam. Therefore, these results can guide other experimental designs that allow new discoveries in relation to this molecule still little explored in the scientific literature.

In 2025, Conte [82] analyzed the potential of *Trichoderma* species in the bioremediation of soil contaminated by herbicides (indaziflam, metsulfuron-methyl, and atrazine) and in promote plant growth in these environments .However, indaziflam and atrazine exhibited a suppressive effect on *Trichoderma* spp., which reduced the mycelial growth in different concentrations (35, 75, and 150 g i.a. ha^{-1}). These results indicated that indaziflam presented a high toxicity to *Trichoderma* even it is a herbicide. Therefore, the lack of studies on indaziflam certainly underestimates the negative effects of this molecule on non-target organisms (such as *Trichoderma* spp.), which is worrying due to its potential damage in agroecosystems.

Possible future approaches that could enable microbial biodegradation include the enzymatic engineering and synthetic biology, as reported in studies for other herbicides. These strategies aim to explore the potential of functional proteins as highly effective catalysts in the biological process [10, 11]. Thus, oxidoreductases, monooxygenases, hydrolases, laccases, peroxidases, lipases, cellulases, and proteases could lead to the herbicide undergoing various reactions, such as oxidation, hydroxylation, denitrification, dehalogenation, demethylation, ammonification, decarboxylation, and hydrolysis. Another strategic approach to be explored for improve microbial action is the addition of limiting nutrients (P, N, C). Biostimulation is a technique widely explored for the nutritional supply of indigenous e exogenous microorganisms, whose association can improve soil quality and stimulate microbial metabolic pathways [10, 44].

5.5 Critical analysis of the selected manuscripts

Regarding the biosorption technique, biochar has already demonstrated its ability to adsorb contaminants in soil and water in several studies [85–90]. Therefore, this important biological material emerges as a promising alternative for the removal of indaziflam in agroecosystems. However, despite the interesting results of biochar in relation to this herbicide, further studies are needed to assess its performance in different soil types and environmental conditions.

The combination of biochar with strategies such as phytoremediation, for example, could maximize the removal of indaziflam, offering an integrated and sustainable approach. In this regard, it would be essential to identify plants with the ability to remediate indaziflam, but the literature also lacks investigations into the phytoremediation potential of different species to mitigate the negative effects of indaziflam. Therefore, this gap in scientific knowledge stands out, highlighting the urgent need for investment in research that explores this topic, whose effectiveness in remediating other pesticides has already been identified [13, 15, 45, 46].

Finally, microorganisms have been extensively studied for the degradation of various pesticides, with demonstrated positive results [10], such as in the case of glyphosate [91, 92]. However, research on the microbial bioremediation of indaziflam is still limited, with only one study found, in which the microbiota did not show efficiency in degrading the molecule. The study concluded that there is a need to explore other microorganisms under varying conditions.

Although advances in the remediation of agroecosystems with pesticides are promising and have been explored by the researchers, the recent emergence, potential impact and high consumption of indaziflam are unfortunately not proportional to its approach by scientific community. Therefore, this herbicide presents specific challenges that require further studies to ensure safe and effective agricultural management and more sustainable production scenarios. Thus, this review demonstrated to society the urgency of investing in research with new perspectives on alternatives that include the development of technologies and combined mechanisms to meet the demand for healthy food based on environmental safety. Results demonstrated the low efficiency of isolated strategies and that the simultaneous application of biological methods, such as biochar, can provide greater efficiency in establishing ecosystem balance.

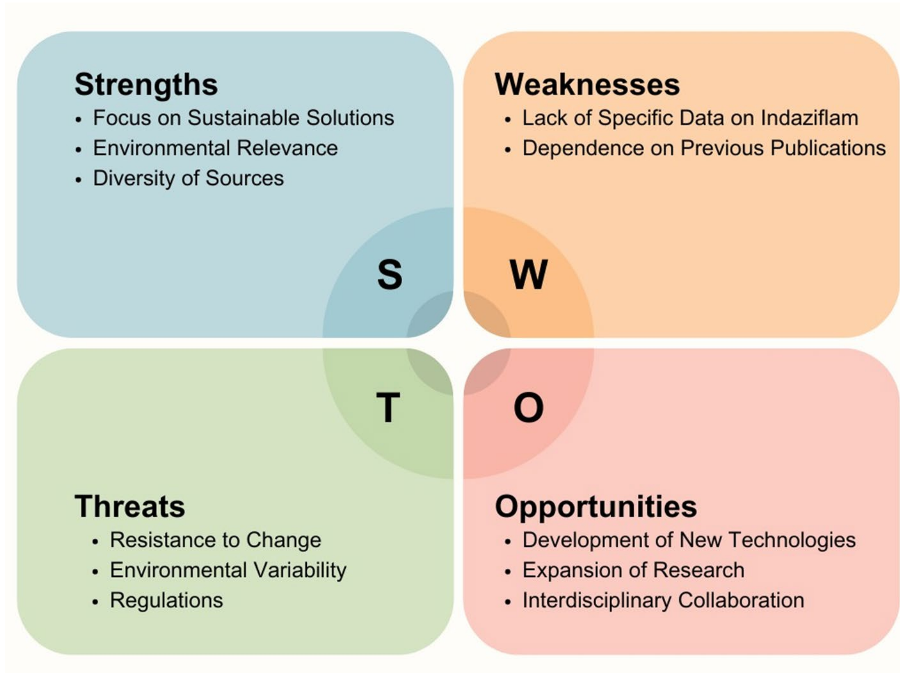

Fig. 3 SWOT analysis for sustainable bioremediation solutions for the herbicide indaziflam

6 Final considerations and future prospects

The herbicide indaziflam is widely used due to its effectiveness in controlling weeds in various crops and commercial areas. Its mechanism of action, which involves the inhibition of cellulose biosynthesis, makes it one of the most potent inhibitors of the plant cell wall. However, the understanding of its environmental behavior is still underexplored by scientists.

It is known that its original molecule has physicochemical characteristics that can cause potential environmental damage, such as high toxicity, high persistence, and an unknown impact on non-target species. Additionally, its degradation intermediates (metabolites) may be even more mobile [37, 39], increasing the risk of contamination and environmental hazard.

Thus, while indaziflam offers significant agronomic benefits, its use requires careful management to mitigate potential adverse ecologicalimpacts. The search for sustainable strategies, such as the bioremediation techniques discussed in this work, can provide solutions to reduce the persistence and negative effects of the herbicide on the environment. In this regard, Fig. 3 presents a SWOT model for this important topic.

The strengths (S) are related to the urgent need to find sustainable solutions for soil contamination caused by herbicides, especially indaziflam. The growing concern about the impacts of this herbicide highlights the importance of investigating bioremediation methods that are not only economically viable but also ecologically sustainable. Additionally, the research benefits from the use of several recognized databases (Web of Science, Scopus, and SciELO), expanding the scope of the information and the credibility of the results.

However, one of the main weaknesses (W) lies in the scarcity of specific scientific data on indaziflam, especially regarding bioremediation, which may limit the depth of conclusions and the development of effective solutions. The reliance on previous publications focused on other herbicides or less detailed scenarios may skew or limit methodologies for treating agroecosystems contaminated with indaziflam.

On the other hand, there are significant opportunities (O) and a fertile ground for scientific advancement. The real possibility of developing new technologies based on existing methodologies could be innovative by expanding them to address indaziflam contamination. Experimental research to validate and extend these findings also strengthens this topic. In this regard, scientific collaboration and interdisciplinarity will provide more integrated and comprehensive solutions to the problem.

Nevertheless, there are threats (T) that may hinder the implementation of these ideas. Resistance to change from farmers and industries could delay the adoption of more sustainable practices. Environmental variability is also a significant challenge, as different conditions directly influence the agronomic efficacy of the molecule and its environmental behavior, limiting the application of biological treatments. On the other hand, changes in agricultural and environmental regulations could benefit the feasibility and implementation of responsible practices, requiring constant adaptations.

Therefore, in light of the ecological challenges presented by indaziflam, future research should focus on the development of safer and more efficient formulations that minimize leaching and persistence in the soil. Advancing knowledge in specific bioremediation techniques and implementing integrated and responsible agricultural practices are equally crucial to ensure that the benefits in weed control are not outweighed by environmental risks. Finally, it is essential that regulatory policies are continuously updated based on new scientific discoveries to ensure a balance between agricultural productivity and environmental preservation.

7 Conclusions

This systematic review underscores the limited but growing body of research addressing bioremediation strategies for indaziflam-contaminated soils. Despite its effectiveness as an herbicide due to low application rates and long residual activity, indaziflam warrant serious concerns due to its likely environmental risks — particularly based on persistence, toxicity, and leaching potential. Biological remediation approaches remain underexplored, with only five studies meeting the inclusion criteria, all from Brazil and the United States. This geographic restriction suggests that the broader global impact of indaziflam may remain underreported and underestimated. Notably, no direct evidence of microbial biodegradation was identified, indicating either the herbicide's inherent recalcitrance or a lack of targeted investigation into suitable microbial strains or enzymatic mechanisms. Similarly, phytoremediation approaches have shown limited success thus far, and while biochar has demonstrated promise as a sorptive amendment, its long-term environmental interactions remain insufficiently explored. Therefore, these findings emphasize the urgent need for interdisciplinary research efforts at understanding the environmental behavior of indaziflam. Future studies should prioritize isolating and characterizing microorganisms capable of degrading indaziflam or its metabolites; identifying tolerant plant species with phytoremediation potential; and integrating biological and physicochemical remediation approaches for greater efficiency. Advancing our understanding of indaziflam's environmental fate and mitigation will be essential for achieving responsible pesticide use, protecting agroecosystem integrity, and promoting sustainability in agricultural practices worldwide.

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Data availability
The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
not applicable.

Consent for publciation
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Competing interests
The authors declare no competing interests.

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