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Review

Agroecological impacts of crop residue burning: A qualitative systematic review of direct and inferred evidence

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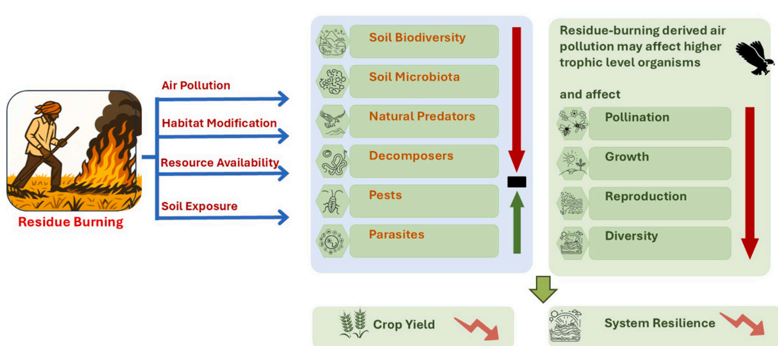
HIGHLIGHTS

- Crop residue burning reduces soil microbial diversity.
- Burning increases the pest population in agricultural fields.
- Residue burning depletes soil nutrients, threatening long-term crop productivity.
- Air pollution from burning may disrupt the ecological functions of arthropods and birds.
- Residue burning leads to erosion of ecosystem services, negatively affecting agricultural sustainability.

GRAPHICAL ABSTRACT



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ABSTRACT

The widespread adoption of mechanized crop harvesting in cereal-based production systems and limited turnaround time between cropping seasons have made crop residue burning a prevalent time-saving practice. Despite its well-documented environmental and health consequences, how residue burning affects agrobiodiversity and ecosystem functions remains underexplored. This qualitative systematic review includes a total of 250 peer-reviewed studies, of which 41 examined the direct effects of residue burning, and 209 focused on broader air pollution impacts as inferential evidence, of which 134 publications focused on arthropods and 75 on birds. From the 233 recorded trait instances across the studied species, about 40 % showed a negative response to residue burning, indicating improved biodiversity responses to alternative residue management practices, such as retention, incorporation, and manual or mechanical removal. Residue burning negatively affected natural predators but favored parasitic nematodes and rodent pests. More studies are required to better characterize the functional responses of important species across various agroecosystems. The decline in soil biodiversity and beneficial species due to residue burning significantly diminishes the ecosystem services these biodiversity components provide, ultimately threatening long-term system productivity. Arthropods and birds, which play critical ecological roles in agroecosystems, may also be adversely affected by residue burning. However, very few air pollution studies have explicitly examined the impact of residue burning on higher taxa. Findings from broader air pollution studies, used here as secondary evidence, offer valuable inferential insights into the

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potential ecological impacts of crop residue burning on birds and arthropods, mediated through changes in air quality. Despite these documented consequences, agrobiodiversity considerations are largely absent from policy discussions on residue management. Our findings highlight the urgent need for a comprehensive assessment of the ecological impacts of crop residue burning on biodiversity and associated ecosystem services to inform biodiversity conservation and climate mitigation efforts to ensure sustainability of agricultural systems.

1. Introduction

The intensification of agriculture, particularly since the Green Revolution, has played a crucial role in addressing global food demand, enhancing food security, and reducing poverty (Gollin et al., 2021). However, this shift has also driven the widespread adoption of input-intensive and mechanized farming practices, some of which are now understood as unsustainable due to their deleterious environmental and climatic consequences. Excessive use of chemical inputs, intensive tillage, over-irrigation, and large-scale burning of crop residues have degraded soil health and contributed to environmental pollution (Onder et al., 2011). The widespread adoption of mechanized crop harvesting in cereal-based production systems and the need to minimize time between the harvest of one crop and the planting of the next has led to crop residue burning as a common management strategy (Cordeiro et al., 2024). It is a low-cost method for rapidly clearing fields, particularly prevalent in South Asia, despite proven negative environmental and health consequences (Yang et al., 2008). Biomass burning, including agricultural residue burning and forest fires, contributes to about 37 % of global black carbon emissions, exacerbating climate change (Bond et al., 2013). Moreover, burning depletes soil nutrients and, over time, lowers crop yields. For instance, paddy straw burning results in complete loss of soil nitrogen, 25 % of soil phosphorus, and between 5 % and 60 % reductions in soil sulphur (Dobermann and Fairhurst, 2002).

The persistence of residue burning is driven by a multitude of factors, including short turnaround times between crops, limited access to alternative management technologies, and economic constraints faced by smallholder farmers (Keil et al., 2021; Krishna and Mkondiwa, 2023). Despite government initiatives promoting sustainable residue management options (e.g., mechanized zero tillage planting with residue retention), many farmers continue to resort to burning due to habit, ease, low cost, and time efficiency compared to alternative options, often perceived as labour-intensive and expensive (Reddy and Chhabra, 2022). Limited time between crops and low demand for straw reduce its value for farmers, making burning a preferred disposal method. Short planting windows leave little time for residue management, and delays in planting reduce crop yields. In addition, the composition of certain crop residues (e.g., high silica content) can limit their use as fodder or other byproducts, further reducing their economic value (Singh et al., 2014).

Crop residue burning is also associated with well-documented adverse health effects on human beings. Burning residues emit large quantities of greenhouse gases (GHGs) and air pollutants – including carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur oxides (SO_x), hydrocarbons and particulate matter (PM), – worsening air quality (Chanana et al., 2023; Ravindra et al., 2019). GHGs are atmospheric pollutants, such as CO_2, methane (CH_4), and nitrous oxide (N_2O), that absorb and trap infrared radiation emitted by Earth's surface, thereby contributing to the greenhouse effect by preventing heat from escaping into space (Filonchyk et al., 2024). While some research has been conducted on the effects of crop residue burning on human health, its effects on local agrobiodiversity and non-human organisms remain underexplored, especially in the Global South, and hence largely unaccounted for by policymakers, farmer advisories or environmentalists.[1] A synthesis that draws together this fragmented evidence is therefore timely and necessary.

Residue burning affects agrobiodiversity through multiple interlinked pathways, including air pollution, micro-climate alteration, habitat destruction, soil degradation, and ecological imbalances. Further details of the impact pathways are provided in Supplementary Material S1. Air pollution, a consequence of residue burning, affects entire ecosystems by impairing respiration, increasing physiological stress, and disrupting key biological processes such as growth, reproduction, and development of various species (Barton et al., 2023; Ryalls et al., 2024; Sanderfoot and Holloway, 2017). In addition to direct air pollution effects, residue burning results in altered habitat structure, reduced resource availability, and disruption of ecological interactions, largely because of fire that alters surface soil thermal properties (structure and composition), and the reduced availability of detritus. Soil biodiversity – including beneficial microorganisms, decomposers, and natural predators – deteriorates significantly as a result of residue burning (Reddy and Chhabra, 2022; Sul et al., 2013). Arthropods, a crucial group within agroecosystems, are particularly affected, yet their responses to residue burning, as well as those of higher trophic-level organisms such as birds and mammals, which play key roles as both predators and pests in agroecologies, remain understudied.

Current studies and policy discussions on crop residue burning have mainly focused on its effects on gaseous emissions, soil health, crop yields, and human health, while failing to systematically address the disruption of biological communities and the ecosystem services they provide. On the other hand, the effects of crop residue burning on agricultural biodiversity are highly context-specific, varying across crop types, cropping seasons, regional ecology, and intensity of farming practices, necessitating a comparison of existing studies to identify common ecological patterns and broader implications. Identifying this as a critical research gap, we conducted a qualitative systematic review to examine how crop residue burning influences various components of agrobiodiversity and associated ecosystem functions. Our study is structured around two main objectives:

(1) To synthesize existing evidence from studies that directly examine the impact of crop residue burning on agrobiodiversity across different taxa and ecosystem functions; and
(2) To assess the potential ecological consequences of burning, mediated through altered air quality, on higher taxa, particularly arthropods and birds, where direct evidence is currently limited.

While most existing impact studies of residue burning have focused on soil biota or microbial communities, the ecological effects on higher trophic organisms (e.g., birds) remain poorly understood. To address this research gap, the second objective draws on inferences from broader air pollution studies and uses them as secondary evidence of the potential biodiversity impacts of residue burning, particularly on birds and arthropods, through pollution-mediated ecological pathways. By doing

[1] The term "agrobiodiversity" refers to the variety and variability of animals, plants, and microorganisms that are used directly or indirectly for food and agriculture. It includes cultivated crop varieties, livestock breeds, and non-harvested species such as soil microbes, pollinators, natural enemies, and higher organisms like birds and mammals that support ecosystem functions essential to agricultural production (FAO, 1999).

so, this review uniquely positions the decline in agrobiodiversity as a key concern, alongside adverse impacts on the environment and human health, in the discourse on crop residue management. While some earlier reviews have addressed agronomic or environmental effects, to our knowledge, no prior synthesis has explicitly combined direct and indirect evidence across multiple taxa, including often-overlooked higher trophic levels. By highlighting these pathways, we aim to generate insights relevant for biodiversity-informed agricultural policy, carbon market design, and sustainable food system planning, while providing a foundation for cross-sectoral interventions that align climate, conservation, and development goals.

2. Methodology

A qualitative systematic review was conducted between July and October 2024 to identify published research on the agrobiodiversity impacts of crop residue burning globally and to use these studies to assess the effects of residue burning as examined through direct estimation (primary evidence) and indirectly through examining the impact of air quality on species. This review had two key objectives. We describe the first approach as "primary evidence generation" for the rest of this paper. In the second approach, because studies specifically examining the impact of residue burning on important arthropods (such as pollinators) and higher taxa (such as birds or mammals) were limited, we developed and resorted to a concept called "Secondary Evidence linking Residue Burning and Biodiversity" (SERB). The term refers to indirect evidence drawn from broader air pollution studies, considered as the most explored consequence of residue burning, which we apply here to infer the potential ecological consequences of residue burning. Specifically, this approach helps us explore how species such as arthropods, birds, and vertebrates might be indirectly impacted by residue burning through pathways mediated by air pollution. This approach will be indicated as SERB in the remaining sections of this paper.

2.1. Study selection

2.1.1. Primary evidence generation: Impacts of crop residue burning

To ensure a rigorous and comprehensive approach, the guidelines of PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses; Moher et al., 2009) were followed for the first objective. The systematic review followed a carefully structured search strategy, guided by clear inclusion and exclusion criteria and a multi-stage screening process. We explored publications assessing the effects of crop residue burning on non-harvested agrobiodiversity (including microbes, arthropods, nematodes, and other fauna). To minimize publication bias and capture a broad range of evidence, the search included both peer-reviewed articles and grey literature. We focused on studies published in English between 1995 and July 2024. Reports and books were excluded from the final selection because they lacked data or did not report any measured species traits. Only research that directly compared residue burning as a management practice against non-burning alternatives was retained. Studies dealing with non-agricultural fires (e.g., in natural vegetation) were omitted unless the burning was related to land clearing for agriculture. Finally, we excluded publications that assessed biodiversity outcomes unrelated to residue burning or examined burning practices without linking them to biodiversity impacts.

A detailed literature search was conducted using Google Scholar, PubMed, SpringerLink, and ScienceDirect databases to identify research published globally in journals that directly reported on the impacts of crop residue burning on non-harvested agrobiodiversity. The search employed a combination of keywords with Boolean operators and truncation, incorporating terms related to agriculture, combustion and biodiversity: (crop OR agriculture* OR stubble) AND (combustion OR fire OR burning) AND (diversity OR biodiversity OR microb* OR animal* OR arthropod*). Although higher taxa such as birds and bats were included in the keyword search, no studies addressing these groups in the context of residue burning were identified.

The primary search yielded a large number of publications – for example, Google Scholar returned 378,000 results. However, most of these results were excluded as they did not examine the impact of residue burning on any component of biodiversity or were unrelated to the research objective. To manage the focus of the review, databases were pragmatically scanned, and the search results were sorted by relevance. If 100 consecutive search results did not yield a single relevant study, the search within that database was terminated. This procedure aligns with the SAFE (Screening After a Fixed number of Exclusions) heuristic, which recommends halting screening after a set number of consecutive irrelevant records, particularly when combined with other criteria like screening a minimum percentage of the dataset. This approach balances review thoroughness with efficient resource use (Boetje and van de Schoot, 2024) and is consistent with the search strategy outlined by Bramer et al. (2017).

The initial search results from all databases were compiled after screening them by title and abstract, duplicates removed, and 142 studies were shortlisted for full text review. We excluded 73 publications after the initial screening because their full texts were unavailable. Some links were inaccessible or nonresponsive, and several records, particularly from the CABI database, provided only English abstracts while the full texts were either unreachable or in non-English languages, making them unsuitable for inclusion. We contacted the corresponding authors where possible, and those full texts we could obtain were included in the final review. A second-stage screening involved examining the reference lists of the remaining 69 publications to identify additional relevant research leading to the addition of 17 articles. The next step led to the exclusion of 45 articles from the total 86 due to repetition, lack of focus on residue burning as a management practice or investigating burning impacts in non-agricultural systems. Ultimately, 41 publications met the eligibility criteria and were included in the final review, as detailed in Fig. 1.

2.1.2. Secondary evidence linking residue burning and biodiversity

The second objective is to examine how air pollution, specifically resulting from crop residue burning, affects arthropods and birds, which are key taxa in agroecosystems. Since direct evidence on the biodiversity impacts of residue-burning-derived air pollution is limited, we use secondary evidence (SERB) to examine the impact of air pollution on birds and arthropods, emphasizing their role in agroecosystems. We are not elaborating on the extent of air pollution from crop residue burning, as there is a large body of literature (e. g., Lin and Begho, 2022; Deshpande et al., 2023; Pinakana et al., 2024) and it is outside the scope of our review. Birds were selected for this analysis because (1) they are widely recognized as bioindicators due to their sensitivity to environmental changes, (2) they play a crucial role as dominant predators of arthropods in agricultural systems, and (3) the combined response (of birds and arthropods) to residue burning offers valuable insights into changes within trophic systems. Additionally, the response of arthropods to air pollution was examined to enable a direct comparison with the findings from the primary evidence. Our qualitative review of literature on air pollution impacts on arthropods and birds followed the approach outlined by Barton et al. (2023). Since this area has been extensively studied, the latest and most comprehensive review papers were selected as a starting point. For arthropods, Ryalls et al. (2024) was employed, while Barton et al. (2023) and Sanderfoot and Holloway (2017) served as the basis for birds. Relevant studies were identified through an examination of the reference lists in these reviews. Additionally, Google Scholar was used to conduct a supplementary search to capture any studies that might have been missed in the initial reviews. The search employed keywords combined with Boolean operators and truncation to target relevant studies. For arthropods, keywords used are ("air pollution" OR pollutants OR "air quality") AND (insect OR arthropod* OR ant OR butterfl* OR bug* OR species), while for birds, ("air pollution" OR

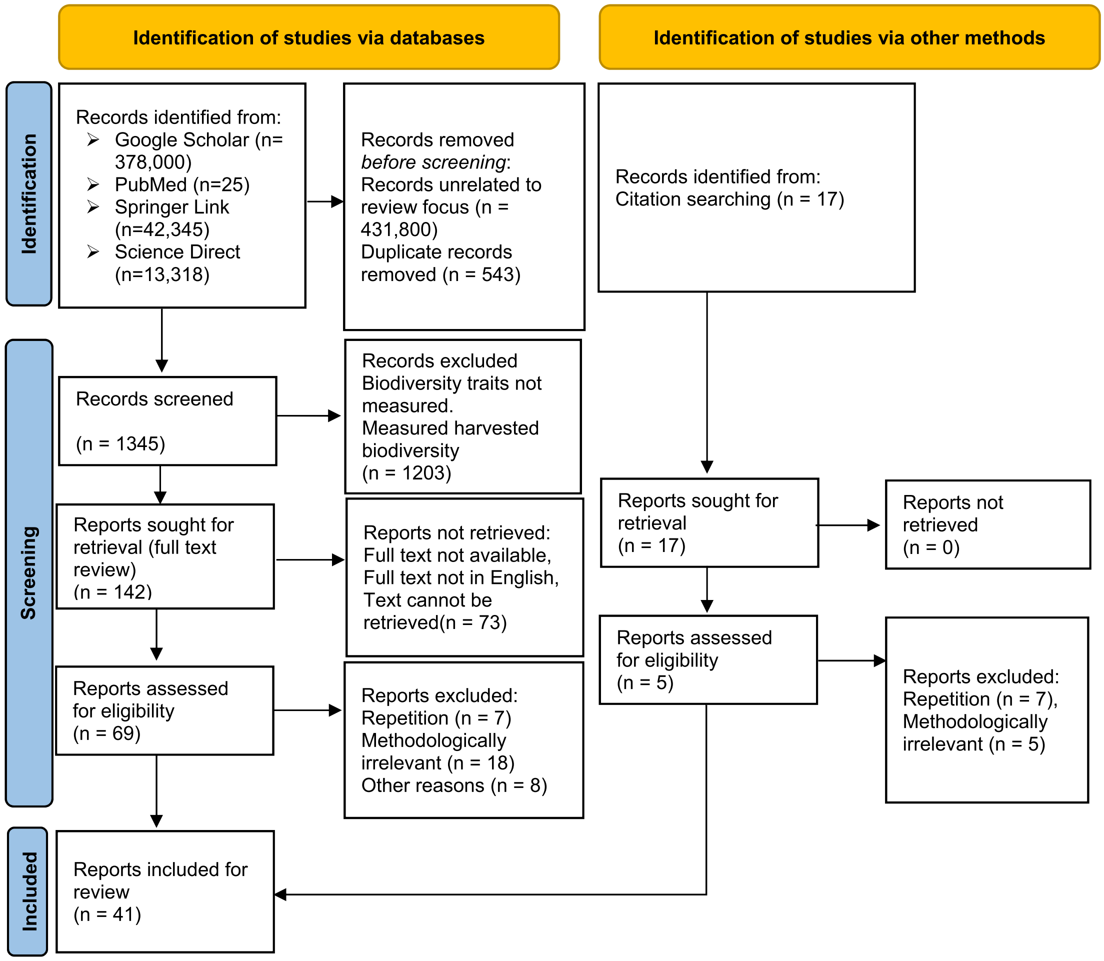

Fig. 1. Study selection criteria for primary evidence generation and inclusion in the systematic review.
Notes: The PRISMA flow diagram details the database search results, including the number of studies obtained and screened in each step. "Studies from other sources" include the results of the reference search of the 69 studies.

pollutants OR "air quality") AND (bird* OR avian OR avifauna*) were applied.

To ensure consistency in study selection, clearly defined inclusion and exclusion criteria were applied. Only studies involving wild and free-ranging birds were included, while studies focusing on captive or farmed birds were excluded. Research examining the impact of urbanization, proximity to roads, and vehicular traffic was included, as these factors are closely associated with combustion-related air pollutants, particularly NO_x. For studies investigating heavy metals, only those explicitly linking atmospheric deposition via aerosols, such as emissions from smelters or mining operations, were considered relevant. In case of arthropods, both field-based studies and controlled experiments, including those integrating both approaches, were included, given that most studies on arthropods are experimental in approach. For birds, only field-based studies were selected, except where wild birds were captured to assess the effects of air pollution, or when field-derived data were incorporated into modelling analyses.

The studies identified through the review references and database searches were compiled, and duplicates were removed. Only studies published in English till July 2024 were considered. Following the predefined study selection criteria, 134 studies on arthropods and 75 studies on birds were included in the final review, focusing on the SERB.

2.2. Data extraction

2.2.1. Primary evidence

From the shortlisted publications, data were systematically extracted and entered into Microsoft Excel. Key details recorded included study characteristics (title, authors, publication year, location, and study approach), cropping system details (type of system and residue management methods), and biodiversity-related information (taxa studied, microhabitats, taxonomic classifications such as species name, phylum, and functional group). Particular attention was given to the response of biodiversity traits under non-burning practices compared to burning. Non-burning methods included residue incorporation, removal, partial or full retention, and other alternative practices. If the type of non-burning practices was not clearly mentioned, it was recorded as a generic unburned practice.

Since the objective of the systematic review was to understand the response of biodiversity and its attributes to residue burning, the direction of response of biodiversity traits to non-burning practices compared to residue burning was classified based on the interpretation provided by the respective study. All biodiversity trait responses were recorded by comparing non-burning alternatives against residue burning.

In many studies, multiple traits were measured from a single publication or a single species or a species group in a study. For instance, Asuming-Brempong et al. (2008) reported changes in the composition, richness, dominance and evenness of bacteria and fungi. Definitions of different categories of life history traits recorded from various species are summarized in Supplementary Material S2 (first table). The direction of species responses to residue management practices was categorized as positive, negative, marginally positive, non-significant, or variable. These classifications reflected changes in biodiversity traits, as reported in the publications. For instance, if a particular life history trait of a species or species group was reported to improve or diminish under a non-burning practice compared to burning, it was recorded as positive or negative, respectively, for the non-burning alternatives. Marginally positive responses were recorded when studies explicitly indicated a weakly significant or small increase in trait value, based on the significance level applied (*p*-value ranging from 0.05 to 0.15) and how the significance was interpreted for the observed trait change in the study. Although there were provisions for marginally negative responses, no study has reported that. Variable responses were noted when traits showed multiple opposing trends within the same study. Additional predictors influencing observed responses were also recorded, especially in studies combining laboratory and field experiments.

For the qualitative synthesis, all recorded directions of biodiversity trait responses were systematically organized and categorized based on the type of non-burning practice compared to residue burning. To enhance interpretability across diverse groups of organisms, these responses were further grouped by taxonomic hierarchy, such as at the phylum or order level (particularly within Arthropoda and higher taxa). The frequency of biodiversity traits within each response category was then calculated as a percentage relative to each non-burning practice. These percentages reflect the proportion of traits exhibiting a given directional response, offering a relative, qualitative measure of how different non-burning alternatives affect biodiversity traits across taxa.

2.2.2. SERB

Data extraction followed a similar approach for studies on air pollution impacts on arthropods and birds. Study characteristics (as outlined for primary evidence), biodiversity details (species studied, taxonomic classifications, feeding guilds), species traits (measured traits, trait categories, quantification methods), organismal responses to air pollution (population or community level, and direction of response), and the type of pollutants considered to measure the species response were recorded. If the ambient air or the urban environment was considered, it was grouped under the ambient pollutant category. Feeding guilds of birds were sourced from Birds of the World (2025) and Wilman et al. (2014) unless explicitly stated in the published research.

Studies measuring a group rather than a single species were recorded under multiple species. For example, Bel'skii and Lyakhov (2003) studied the structural transformation of bird communities rather than a single species along a gradient of environmental pollution. Various categories of species' life history traits have been summarized in Supplementary Materials S2 (second table). Unlike the primary impacts of residue burning, where species responses are often assessed through population- and community-level metrics such as changes in abundance, richness, or activity levels, which can be relatively straightforward to interpret as beneficial or detrimental to the species, studies on the secondary effects of air pollution (i.e., SERB) frequently measure a wider range of traits. These include feeding performance, predation or parasitism rates in arthropods, and immunological responses, heavy metal contamination or molecular stress markers in birds.

Given the complexity of these traits, their directional change does not always directly indicate an improvement or decline in species fitness or ecological benefit. Therefore, species responses to air pollution were classified as positive, marginally positive, non-significant, variable, or negative, depending on whether the measured changes in traits were interpreted to enhance, impair, or have negligible effects on the species' fitness, reproduction and survival. This classification was made by assessing how each trait change influenced the overall fitness and survival prospects of the species. In other words, the direction of each trait's response was evaluated based on its implication for species fitness and survival (termed as the effect on the species). A typical example is an increase in heavy metal contamination within a bird species. Because such contamination is known to reduce species fitness, the response was ultimately recorded as negative for the species. By doing this, we ensured that species responses in SERB reflect ecological consequences rather than only physiological or biochemical changes, allowing meaningful comparison across traits. The proportion of all biodiversity traits contributing to each response category was calculated as the percentage of traits for the broader trait category, arthropod order or trophic niche of the birds.

3. Results and discussion

3.1. Residue burning on agrobiodiversity: primary evidence

From the 41 empirical studies, which directly compared residue burning practices with non-burning alternatives, the direction of impacts of burning on agrobiodiversity was examined. Such a comparison provides critical insights into how residue management practices influence ecological dynamics and, ultimately, the production capacity of the farming system. A total of 233 observations or instances of species traits were extracted, which provide valuable information on the population and community structures of affected species. The geographical distribution of studies examining the biodiversity impacts of residue burning reveals notable disparities between the Global South and the North. Of the 41 publications, approximately 34 % (14 studies) were conducted in Asia, 27 % (11) in North America, 12 % (5) each in Africa and South America. The highest number of studies was conducted in the United States (8), followed by three studies each from Australia, Brazil, China, India, Mexico and Pakistan (Fig. 2). Considering the widespread prevalence of residue burning (Krishna and Mkondiwa, 2023), only a small number of agrobiodiversity impact studies have been conducted in India and China, suggesting a potential mismatch between regions most affected by burning and those where biodiversity-related research on burning impacts has been conducted. This geographic skew in the evidence base reflects disparities in research infrastructure, differential research prioritization, access to funding, and institutional capacity, rather than the global distribution of the residue burning practice itself. As such, the ecological consequences of residue burning in low- and middle-income countries may be underrepresented in the peer-reviewed literature. One may keep this limitation of the literature in mind while interpreting the review's findings. Furthermore, this gap points towards the need for more regionally grounded research in data-scarce contexts.[2]

Of the 233 instances of species traits recorded, the majority were documented from the phylum Arthropoda, followed by organisms in the kingdoms Fungi and Bacteria, with a significant focus on soil organisms such as bacteria and fungi, arthropods, and annelids, which are closely linked to agricultural ecosystems and soil health. Nematodes (Nematoda), both free-living and parasitic, along with annelids, were also featured prominently in the reviewed studies. Limited traits were documented for higher trophic-level taxa: one mammal (class Mammalia, order Rodentia) and one frog (class Amphibia, order Anura). Most studies analyzed species within the same class or order, though some explored impacts at broader taxonomic levels.Phylum Arthropoda accounted for 33 % of the measured traits, with Coleoptera (beetles) as the most studied order, followed by mites (Acariformes and Parasitiformes) and spiders (Araneae) within the class Arachnida (Fig. 3a). Half of the orders represented belonged to class Insecta, reflecting its

[2] It is important to distinguish between residue burning in mechanized cereal systems and slash-and-burn agriculture, which is a traditional land-clearing method involving complete biomass removal and often associated with forest conversion. Our review focuses exclusively on the former, which is a growing concern for both air pollution and agrobiodiversity in intensively farmed landscapes.

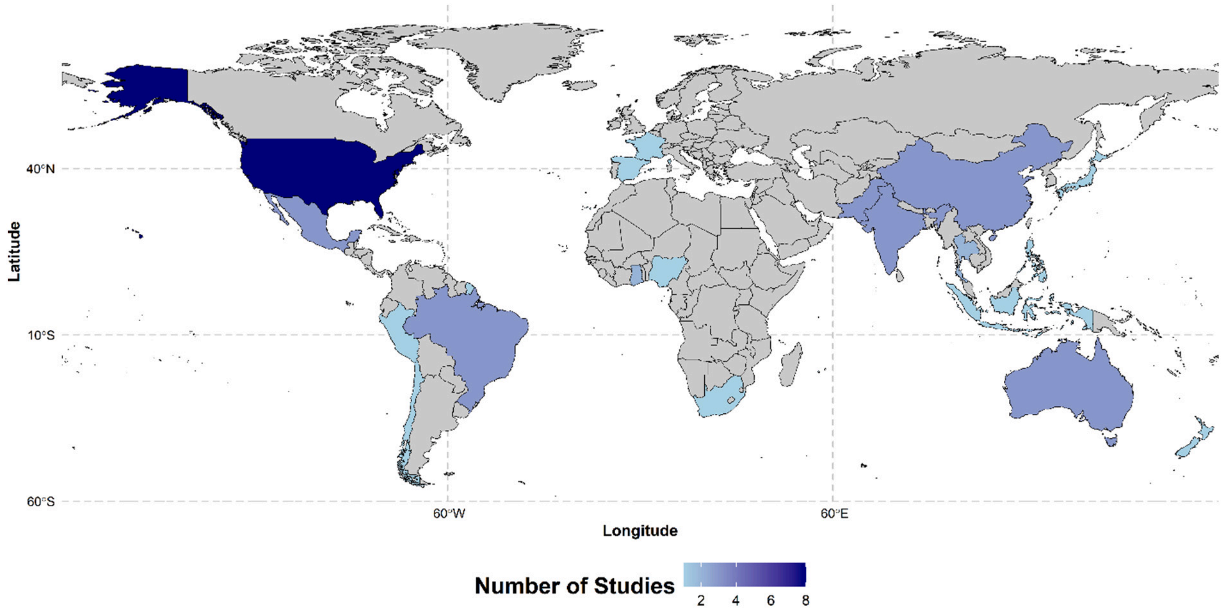

Fig. 2. Regional distribution of published studies on the direct impact of crop residue burning on agrobiodiversity (number of publications = 41). A table showing the number of studies conducted in each country is provided in Supplementary Materials S3 (first table).

diversity as the most species-rich class, including Coleoptera, the most species-rich order. Other insect orders studied included Hymenoptera (including ants), Hemiptera (bugs), Lepidoptera (butterflies and moths), Diptera (flies and parasitoids), and Blattodea (cockroaches). This concentration on Arthropoda reflects a research focus on this phylum, likely due to their abundance, diversity, and ease of sampling in agricultural landscapes. Regarding crops, most publications focused on sugarcane (23 %), followed by rice (13 %), wheat (10 %), and cropping systems like wheat-soybean (10 %), wheat-lupin-wheat (5 %), and wheat-maize (5 %). The highest frequency of species traits was recorded in agroforestry systems (17 %, 37 instances), followed by sugarcane plantations (17 %, 36 instances), maize rotations within agroforestry systems (11 %, 24), and both paddy-fallow system and paddy fields (8 %, 18 instances) (cf. Supplementary Material S4).

Most studies on the impact of residue burning on biodiversity focused on measuring community or population-level traits such as abundance and other metrics of diversity (Fig. 3b). Half the trait responses on species population were abundance (50 %), followed by density (20 %) and relative frequency (16 %). Species richness, biomass, community composition, diversity, microbial concentration, and microbial activity were investigated in very few studies. One study recorded the mortality rate of a frog (Dong et al., 2024). Population and community-level traits, such as abundance and density, are relatively easy to record, while other traits, such as breeding or reproductive-level traits, require greater resources. Possibly for this reason, several important life history traits were left unrecorded.

Species responses under each non-burning crop residue management practice were compared with those under residue burning, with 205 instances of traits recorded for unburned practices (Fig. 3c). Of these, 86 instances (42 %) showed a positive response on the population and community of the species, 67 instances (33 %) a negative response, 42 (20 %) were non-significant, and 5 % showed variable responses. For residue incorporation, 20 traits instances were recorded, with 10 instances (50 %) showing a positive response, one a negative response, and 40 % exhibiting non-significant responses. In the case of residue removal, only nine instances were recorded, with eight showing non-significant responses. The effects of partial retention of crop residues were reported in 13 instances, with two each showing positive and negative responses, three showing marginal significance, and six (46 %) exhibiting no significant response. For full residue retention, 23 trait instances were recorded, with nine instances (39 %) showing a positive response, five (22 %) marginal significance or non-significance, and four (17 %) a negative response. These findings highlight the ecological advantages of alternative management practices relative to residue burning.

Overall, 40 % of species trait instances showed a positive response to non-burning practices compared to residue burning, while 27 % exhibited a negative response. In 25 % of instances, no significant response was observed, suggesting that results are variable across agroecologies and that more research is required to better understand species' responses to residue burning.

Our systematic review demonstrates that non-burning practices significantly benefit soil biodiversity and associated ecological processes vis-à-vis burning (Fig. 3c). Fire-related reduction in the detritus and the resulting damage to soil horizons negatively affect the soil macrofaunal community on the ground (Korobushkin et al., 2017). Non-burning practices promote the abundance (Sul et al., 2013), diversity (Arévalo-Gardini et al., 2020) and biomass (Graham and Haynes, 2006) of soil microorganisms, including bacteria and fungi, leading to enhanced soil quality and nutrient cycling. These practices also support synergistic interactions, such as those between arbuscular mycorrhizal fungi and earthworms, resulting in improved nutrient uptake and plant growth (Cao et al., 2015).

Residue burning practices impair the reproductive cycle of many species, as illustrated by the adverse effects of rice straw ash exposure on a frog species (*Rana dybowskii*), resulting in increased mortality as well as disruptions in skin microbiota which potentially negatively affect the ongoing reproductive success of the natural predator (Dong et al., 2024). Moreover, the overall diversity and frequency of plant pathogenic fungi also increased during residue burning (Arévalo-Gardini et al., 2020). The abundance of plant-parasitic nematodes increased significantly when crop residue was burned compared to when residue burning was avoided in a wheat-soybean cropping system (Brye et al., 2018). Field pests (e.g., rodents) showed an increase in population when residue was burned (Massawe et al., 2007), although further studies are needed to confirm this pattern. Together, these findings demonstrate the ecological benefits of residue management practices that avoid burning and their role in supporting biodiversity and sustainable agroecosystems.

Non-burning practices, like residue incorporation and retention, positively influence soil invertebrates, with increased diversity and

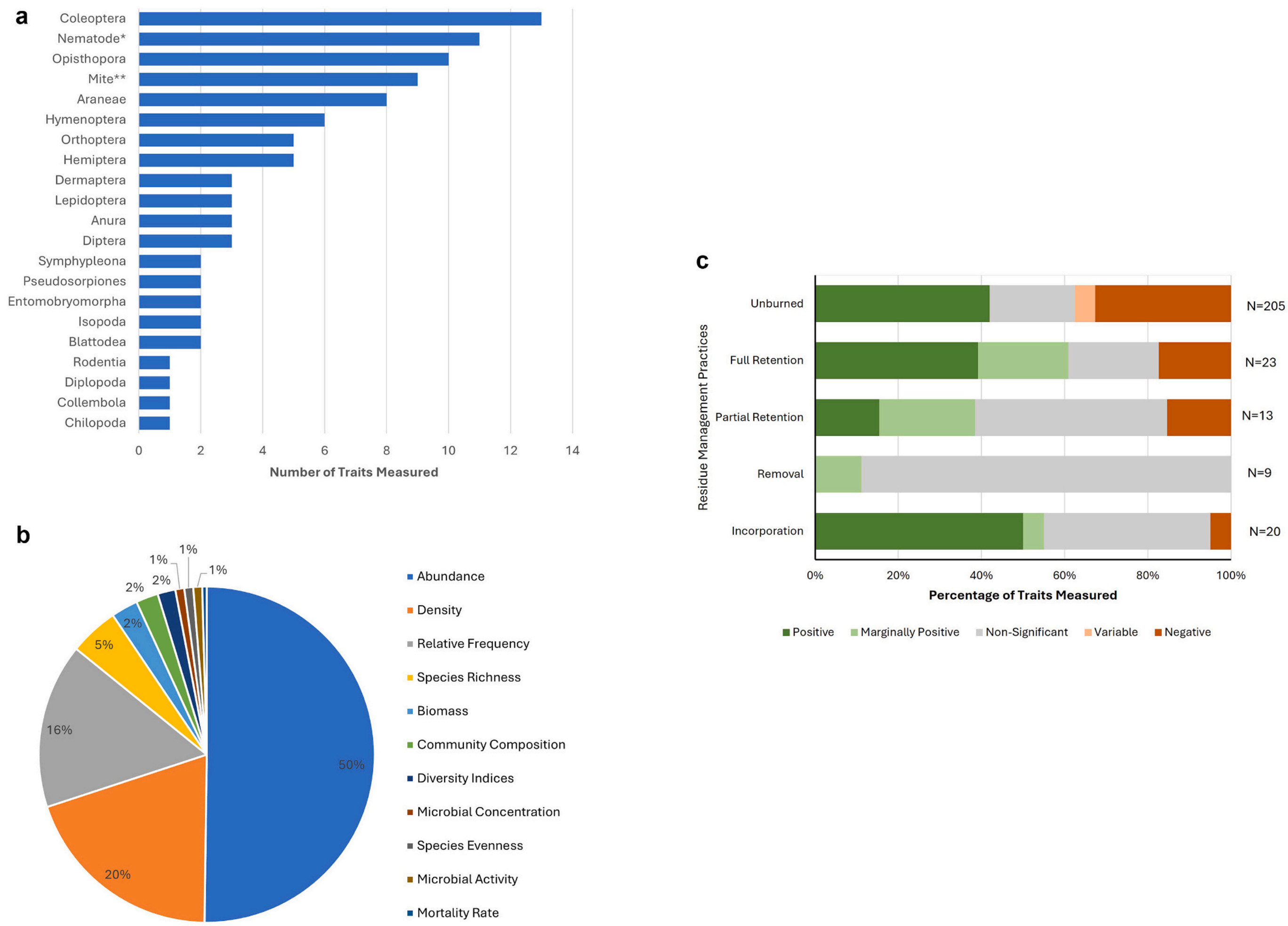

Fig. 3. Various organisms recorded from the publications included in the review for primary evidence, the population and community-level traits of these organisms and the responses of various species to non-burning vs. burning residue management across species traits.
a) Major orders of species recorded from the publications. If the traits are measured for a larger community, where defining taxonomy at the level of order is difficult, they are not represented in the graph. Total frequency of trait responses, $N = 92$.
b) Population and community level traits recorded for various taxa from the publication (Total frequency of trait responses measured, $N = 233$).
c) Responses of various species to non-burning vs. burning practices across species traits.
Notes: Non-burning alternatives include residue incorporation, removal, partial or full retention, and other alternatives; when not specified in a study, non-burning was recorded as general unburned practice. For each non-burning practice, biodiversity trait responses were compared against residue burning, and the direction of the response reflects the change relative to burning. "N" refers to the number of individual biodiversity trait responses recorded across studies. Species responses in terms of their life history traits are aggregated from all non-burning practices by comparison with burning. *Nematodes consist of various orders and the studies have not differentiated them into orders. **Mites consist of two large orders under the class Arachnida (Acariformes and Parasitiformes).

abundance in ants (Sajjad et al., 2012; Subiyakto and Sunarto, 2020; White et al., 2011), abundance of spiders (Sajjad et al., 2012; Srikanth et al., 1997; Subiyakto and Sunarto, 2020), density of predatory mites like *Gamasina* sp. (Edem et al., 2013), and earthworms (Mele and Carter, 1999; Thomason et al., 2017). Free-living nematodes, such as those belonging to the order Dorylaimidae, also showed an increased density in non-burning systems (Rahman et al., 2007). In addition, non-burning practices support natural pest control mechanisms by enhancing the populations of parasitoids (e.g., the braconid fly, a natural enemy of sugarcane stemborer), thus maintaining overall ecosystem balance (Vejar-Cota et al., 2009).

Species responses were largely positive for non-burning practices. Beneficial taxa, including natural predators and decomposers, showed a negative response to residue burning, whereas some pests and parasitic nematodes showed an increased abundance under residue burning. Although most studies focused on arthropods, several key arthropods, including pollinators and decomposers, were highly understudied. Most measured life-history traits were related to population and community level; however, other traits, including reproductive capacity, fitness, or molecular features, were left unexamined. Moreover, how these traits are affected during residue management was not investigated in any of the studies. Furthermore, studies on higher-order species were rare.

Many lower-order taxa, including soil microorganisms and invertebrates, showed positive responses to residue burning in terms of their diversity, abundance and density. These organisms may have higher resilience to sudden increases in temperature and fire than the co-inhabiting species which are sensitive to these changes. Various taxa of soil mesofauna, including Collembola and some mites, have been observed to move vertically down through gaps in the soil to escape the immediate effects of residue and topsoil burning (Furukori et al., 2022). Additional research is required to explore these responses in detail and better understand how a range of species are affected by different residue management practices.

3.2. Residue burning on agrobiodiversity: SERB

Biomass burning, including agricultural residue burning, releases large amounts of aerosols, particulate matter and GHGs resulting in ambient air pollution and climate change either on a regional or global scale (Yin et al., 2019). The open-field burning of crop residues releases a complex mixture of air pollutants, significantly degrading air quality (Chanana et al., 2023). For example, in India, approximately 24 % of the 488 million tonnes of crop residues generated in 2017 were burned, releasing 824 Gg of $PM_{2.5}$, 58 Gg of elemental carbon (EC), 239 Gg of organic carbon (OC), and 211 Tg of CO_2-equivalent GHGs, including CH_4 and N_2O (Ravindra et al., 2019). In addition, hazardous compounds, like polycyclic aromatic hydrocarbons (PAHs) that include the carcinogen benzo(*a*)pyrene, are emitted during combustion, posing long-term health risks even at low exposure levels (Moubarz et al., 2023). Epidemiological evidence shows a threefold increase in acute respiratory infection risk in Indian districts with intensive residue burning, with children being particularly vulnerable (Chakrabarti et al., 2020). In addition, smoke from burning activities often extends beyond local fields, contributing to transboundary air pollution across regions such as Southeast Asia and Europe (Mehmood et al., 2022; Yin et al., 2019). In Northern India alone, residue burning has been estimated to cause 44–98 thousand premature deaths annually due to PM-related exposure between 2003 and 2019 (Lan et al., 2022). While these human health and atmospheric impacts are well documented (Deshpande et al., 2023; Ravindra et al., 2019), direct assessments of how this pollution affects agrobiodiversity remain limited. Since residue burning releases various air pollutants, many of which have been studied in air pollution studies through field observations or controlled experiments, insights from these broader air pollution studies provide a valuable, though indirect, foundation for hypothesizing the SERB on agroecosystems.

3.2.1. Effects of air pollution on arthropods

3.2.1.1. Locations and type of studies. In this section, we summarize the reported impacts of air pollution on arthropods, highlighting how residue burning affects biodiversity through harmful gas emissions. While there could be other impact pathways as a result of residue burning, they have not yet been subjected to detailed investigation. Of the 134 studies used in this analysis, there is a strong geographical bias towards the Global North: 63 (47 %) studies were conducted in European countries, followed by 42 (31 %) in North America, and 6 (4 %) in Australia (Supplementary Materials S3, second table). Only 19 (14 %) were conducted in Asia, and a few each in South America and Africa. All low- and middle-income countries where agronomically-derived air pollution is a severe challenge are understudied: for example, only two studies have been published on research in India, while in many other countries (e.g., Vietnam, Indonesia) with known annual air-pollution peaks, no research has been published (cf. Supplementary Material S5).

In many studies, species were exposed to one or several air pollutants in a controlled environment to understand their response by measuring specific life history traits. Only a few studies investigated species' responses to ambient air pollution containing mixtures of pollutants; of these, the majority of species trait responses (34 % instances) were measured against ozone exposure, either alone or in combination with other pollutants. This was followed by responses to heavy metals (14 %), NO_x (14 %), SO_x (13 %), and particulate matter ($PM_{2.5}$ and PM_{10}; 7 % each).

3.2.1.2. Arthropods studied for their responses. Among arthropods, the highest frequency of life history traits was measured for the order Lepidoptera (moths and butterflies), followed by Coleoptera (beetles and weevils), Hymenoptera (bees, wasps, ants and parasitoid braconid insects), and Hemiptera (true bugs). In terms of family, the highest instances of traits were measured for the family Aphididae (70 instances) of the order Hemiptera. Aphididae are primarily aphids, or sap-sucking insects. The most measured trait for aphids is their feeding performance, attributed to their herbivorous trait. The second highest instances of traits measured was in the family Apidae (bee species; 45 trait instances) belonging to the order Hymenoptera, followed by Chrysomelidae (44 trait instances) consisting of leaf beetles (order Coleoptera), Erebidae (18 trait instances) which is among the most prominent families of moths in terms of species richness, and Lasiocampidae (18 trait instances) which is also a moth family in the order Lepidoptera.

3.2.1.3. Species traits and their effect on air pollution. The reported life history traits of arthropods principally included population and community level traits (34 % of instances), such as abundance, diversity, and species richness (Fig. 4a&b). Growth and development traits accounted for 24 % of reported instances, while traits of physiology and stress maintenance comprised 16 % of reported instances. Traits representing behavioural changes (15 % of instances) and reproductive features (8 %) were also investigated. Additionally, some studies examined molecular mechanisms, morphological changes, heavy metal contamination, and pest potential capacity of species resulting from pollution.

For half (50 %) of the life history traits assessed, most air pollutants were reported as having a negative effect on arthropod species, followed by approximately one-quarter of instances of a positive (24 %) or non-significant (23 %) effect being observed. The negative impact on multiple traits, including mortality, reproductive fitness, and stress tolerance, suggests that increased exposure to air pollution reduces the reproductive fitness and survival capacity of affected species. Species richness and oviposition preference declined in all examined species under polluted conditions.

Behavioural traits were also negatively affected by air pollution, reducing overall species fitness. For example, diminished olfactory response and delayed learning and memory in pollinators under high pollution levels suggest that these air conditions impair foraging success, thereby restricting resource accessibility and survival. A meta-analysis of pollinator species by Ryalls et al. (2024) found that even moderate pollution levels significantly impaired pollinator performance. Elsewhere, the pollutants, ozone and NO_x, reduced the abundance and foraging behaviour of pollinators, including moths, butterflies, honeybees, beetles, parasitic wasps, and flies in temperate agroecologies (Ryalls et al., 2022). These pollutants negatively affected flower visitation frequency, flight activity, and feeding preferences, even at slight increases in the concentration of pollutants. Similarly, in India, honeybees (*Apis dorsata*) exhibited reduced floral visitation with increasing air pollution (Thimmegowda et al., 2020). Furthermore, exposure to pollutants compromised species' key physiological functions, particularly the respiratory capacity of several species, further threatening their survival and ecological roles.

Air pollution significantly disrupts arthropod populations, affecting pollinators, natural predators, and herbivores, which in turn alters key ecosystem services. Studies have shown that air pollutants impair floral scent trails, reducing the ability of honeybees (*Apis mellifera*) to detect floral resources (McFrederick et al., 2008), and affect their learning and memory related to recognizing volatile organic compounds (Leonard et al., 2019a, 2019b). Similar effects have been observed in Buff-tailed bumblebees (*Bombus terrestris*), further highlighting the detrimental impact of pollution on pollinators (Vanderplanck et al., 2021). Additionally, Sweat bees (*Lasioglossum zephyrus*) exhibited reduced flight activity and food availability due to air pollution (Ginevan et al., 1980).

Beyond pollinators, natural predators are also negatively impacted. Exposure to pollutants such as ozone and heavy metals has led to declines in predatory species, including Linyphiid spiders, Wolf spiders (*Alopecosa aculeata*), and carabid beetles, weakening natural pest control mechanisms (Ryalls et al., 2022). Exposure to heavy metal pollution

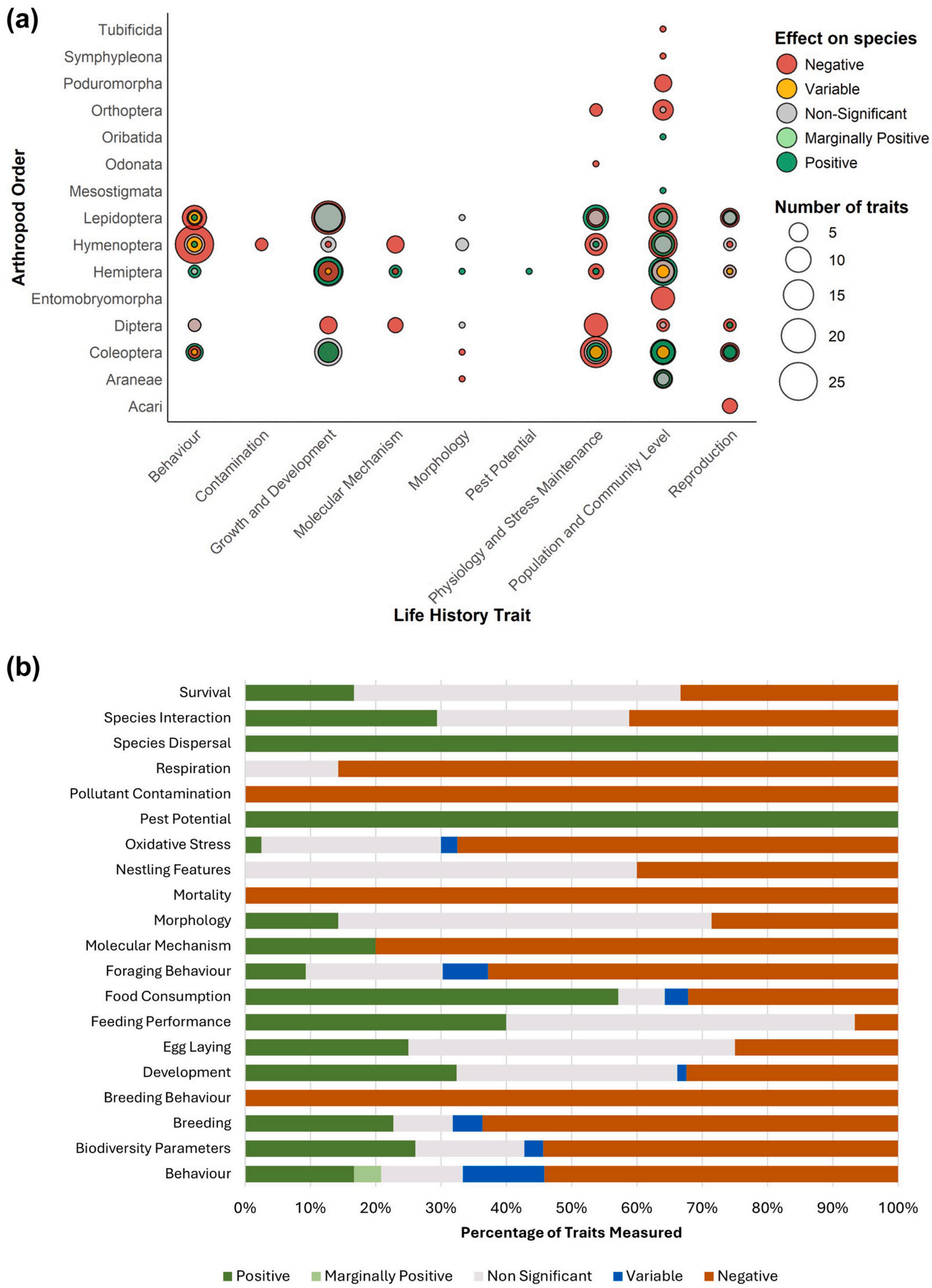

Fig. 4. (a): Major categories of species traits measured in response to air pollution and the effect on different arthropod orders. The different colors represent the various effects of the species as positive, marginally positive, non-significant, variable, and negative, as recorded in the respective studies. The circle size represents the responses recorded for each species trait category for the arthropod order. If life history traits are measured for a larger group of species, where defining arthropod order will be difficult, they were not represented in the graph. Total number of trait responses, $N = 446$.
(b): Species traits measured in response to air pollution and the effect on arthropods. The effect of air pollution (represented as positive, marginally positive, non-significant, variable and negative) is represented as percentages for various life history traits of the arthropods. The number of instances of each life history trait was considered in the analysis, and the percentage share of each effect on species traits is represented in different colors. Total number of trait responses, N, is 465.

has reduced the intra-specific aggressiveness between colonies of Wood ants (*Formica aquilonia*) in Finland (Sorvari and Eeva, 2010). The efficiency of parasitoids, such as *Asobara tabida*, was also reduced under ozone exposure, limiting their ability to control herbivore populations (Gate et al., 1995).

Other research has shown that beneficial invertebrates (e.g., honeybees, spiders, ants, beetles), crucial for ecosystem services such as pollination and pest control, are significantly negatively impacted by common air pollutants, including ozone, NO_x, SO_x, particulate matter, and heavy metals (Table 1). The observed decline of these species raises concerns about food security and agricultural productivity, as beneficial species suffer adverse effects while pest populations increase (Ryalls et al., 2024). Pollination services, including those provided by these species, have been estimated to contribute 5–8 % (equivalent to US$ 235–577 billion in 2015) to the total global value of food production (Murphy et al., 2022).

Conversely, some agricultural pests, including Gypsy moths (*Lymantria dispar*), Tobacco Hornworms (*Manduca sexta*) and Cabbage butterflies (*Pieris brassicae*), displayed increased feeding performance and survival under pollution exposure, suggesting an adaptive advantage (Endress et al., 1991; Jackson et al., 2000; Jøndrup et al., 2002). Aphids (*Aphididae*), in particular, thrived under elevated pollution levels, leading to increased populations and subsequent rises in their predators, such as coccinellid beetles (Hughes et al., 1983; Koponen and Niemelä, 1995).

These studies have shown that air pollution disrupts key ecosystem services by impairing pollination efficiency and natural pest control, leading to reduced crop productivity and increased pest pressure, thereby threatening farm resilience and long-term sustainability. However, a considerable number of studies show that many traits have a non-significant effect on species, which is a possible indication that long-term studies are required to understand the nature of the effect of pollutants on the species with respect to these traits.

3.2.2. Effects of air pollution on birds

3.2.2.1. Locations and types of studies. Of the 75 studies that recorded the effect of air pollution on birds, most were conducted in Finland (16 studies), followed by Russia (11), Spain (10) and Belgium (5) (Supplementary Materials S3, third table). These studies mostly assessed the response of two species of birds, *Parus major* (Great Tit) and *Ficedula hypoleuca* (Pied Flycatcher) to air pollution (Belskii et al., 2005; Belskii and Belskaya, 2013a, 2013b; Belskii and Grebennikov, 2014). Long-term monitoring of these two bird species in both Russia and Finland has resulted in numerous publications on these species from this region, and a more limited understanding of the effects of air pollution on other birds worldwide (cf. Supplementary Material S5).

A range of air pollutants, either in isolation or as a mixture, were used to measure species' responses to various traits. The impact of heavy metals (in 36 % of species traits instances), either in isolation or in combination with other pollutants, was investigated most frequently. Studies also focused on SO_x (35 %), NO_x (10 %), ambient air with a mixture of pollutants (10 %), particulate matter ($PM_{2.5}$ and PM_{10}) (4 %). A few studies have also considered the effects of ozone (2%) and CO_2 on species traits.

3.2.2.2. Avian species studied. From the reviewed studies, 66 bird species were used to examine responses to air pollution across various locations. *P. major* had the highest instances of measured traits (90), followed by *F. hypoleuca* (80), *Emberiza cia* (13) and, *Passer domesticus and Periparus ater* with 10 instances each. Urban exploiters like *Columba livia* were used in six studies to understand their response to air pollution, while synanthropic species like *P. domesticus* were included in nine studies (cf. Supplementary Material S6).

3.2.2.3. Species traits and their response to air pollution. Various life history traits of birds were studied for their response to air pollution, categorized by their roles in the growth, survival, maintenance, and reproduction of the species (Fig. 5a&b). Reproductive traits were the most studied (101 instances), followed by population and community level traits (86 instances), physiology and stress maintenance (85), and heavy metal contamination (51).

Bird species exhibited varied life history trait responses to air pollution, influenced by proximity to pollution sources and intensity. Most species showed negative effects (60 % of instances), compromising their breeding capacity and physiological functioning, while only 4 % displayed positive effects. Interestingly, 34 % of instances had non-significant effects. All trait categories experienced more negative than

Table 1
Key responses of major taxa to residue burning, their ecological roles, and potential impacts.

Taxa	Ecosystem functions	Type of evidence	Documented effects	Sources
Soil Arthropoda	Multiple functions (Nutrient cycling, pest control, pollination and decomposition)	Primary evidence	The diversity and richness of many arthropods declined. Ecosystem services, including pest control, decomposition, nutrient cycling, pollination were disrupted.	Arévalo-Gardini et al. (2020); Subiyakto and Sunarto (2020)
Plant Pathogenic Fungi	Pathogens to plants	Primary evidence	Overall diversity and frequency of the soil fungi that are pathogenic to plants, both spatially and temporally, increased when residue is burned.	Arévalo-Gardini et al. (2020)
Soil microorganisms	Soil decomposition, soil structure and nutrient cycling	Primary evidence	Overall diversity, abundance and composition of soil microbes decreased when residue is burned. Prokaryotes, actinomycetes and fungi increased in non-burning events.	Asuming-Brempong et al. (2008); Harris et al. (1995)
Mastomys natalensis (Rodent)	Rodent pest	Primary evidence	Rodents are non-beneficial for the crop system, and they cannot be controlled by residue burning. Their abundance increased after burning.	Massawe et al. (2007)
Spiders	Natural predator	Primary evidence	Abundance and diversity decreased when the residue was burned.	Sajjad et al. (2012); Subiyakto and Sunarto (2020)
Earthworm	Soil fertility	Primary evidence	Overall density of earthworms decreased.	Mele and Carter (1999); Thomason et al. (2017)
Plant parasitic nematode	Plant parasites	Primary evidence	Abundance and density of eggs, juveniles and adults of parasitic nematodes and their cysts increased when the residue is burned.	Brye et al. (2018); Escalante et al. (2021)
Honey bee, Bumble bee, Sweat bee and Solitary bee	Pollination	SERB	Abundance, learning and memory, foraging, response to floral scent and other pollination-related behaviour are negatively affected by air pollution.	Ginevan et al. (1980); Ryalls et al. (2022); Thimmegowda et al. (2020)
Gypsy moth caterpillar, Willow leaf beetle, Forest Tent caterpillar, Cabbage butterfly and Aphids	Plant pest	SERB	Growth rate and feeding performance of plant herbivores increased as a result of exposure to air pollutants.	Bolsinger and Flückiger (1987); Couture et al. (2012); Wu et al. (1997); Endress et al. (1991); Khaling et al. (2015)
Blackbird, Spotted Flycatcher, Great Tit, Pied Flycatcher	Natural predator	SERB	Density, abundance, foraging and growth are negatively impacted when air pollution increases.	Alaya-Ltifi et al. (2012); Barton et al. (2023); Eeva et al. (2005, 2020); Sanderfoot and Holloway (2017)

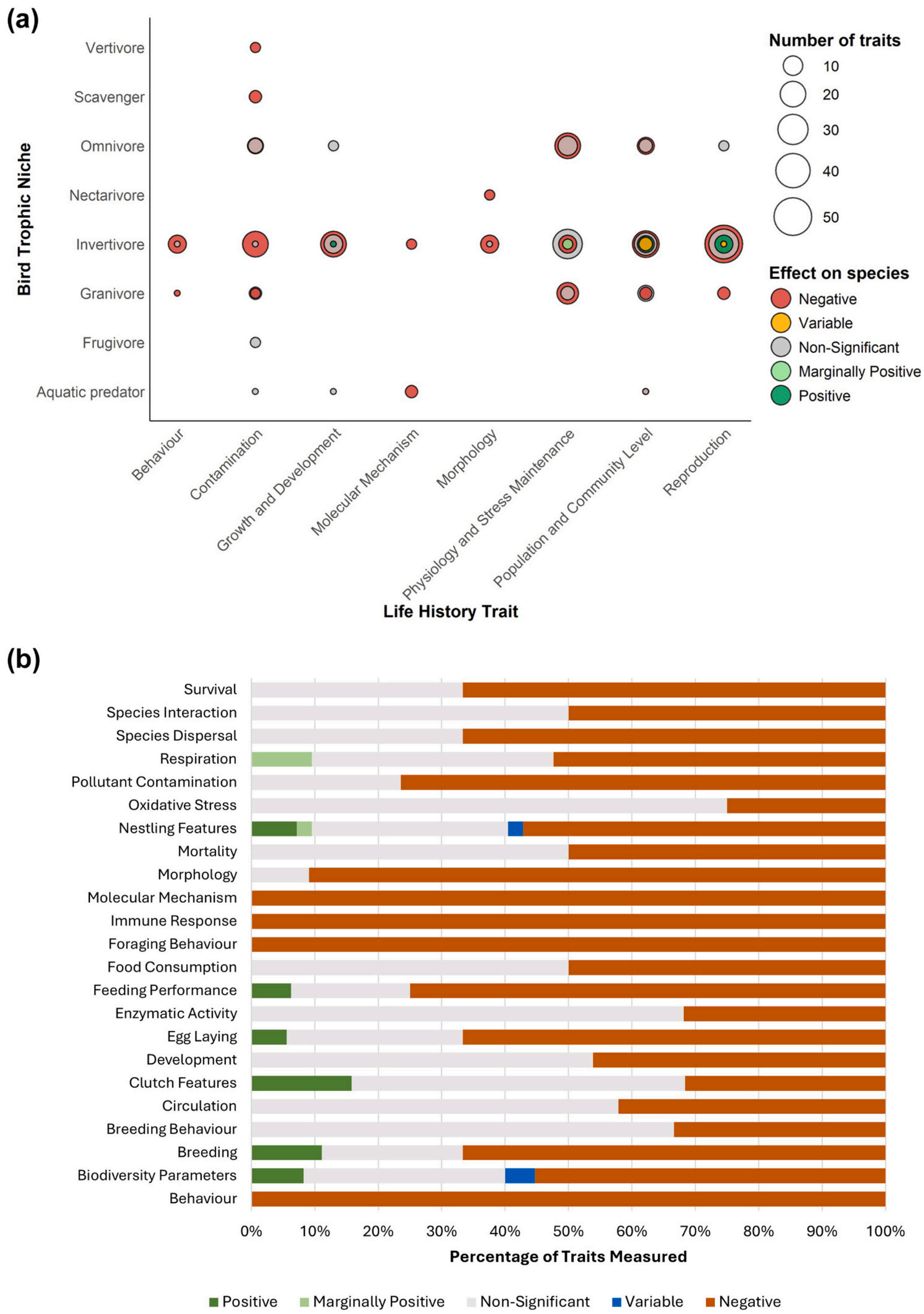

Fig. 5. (a): Major categories of traits used to measure the effect of air pollution on birds belonging to different trophic niches. The different colors indicate the various effects of the species represented as positive, marginally positive, non-significant, variable, and negative, as recorded in the respective studies. The circle size represents the number of responses recorded for each species trait category in the context of air pollution for the respective birds categorized based on their trophic niche. If species traits are measured for a community or group of species, where defining trophic niche will be difficult, they were not represented in the graph. Total number of trait responses, N, is 353.
(b): Species traits measured to record the effect of air pollution on birds. The effect of air pollution (represented as positive, marginally positive, non-significant, variable and negative) is represented as percentages for various life history traits of the birds. The number of instances of each life history trait was considered in the analysis, and the percentage share of each effect on species traits is represented in different colors. The total number of trait instances, N, is 384.

positive effects. For example, among 11 growth and development traits, 62 % showed negative impacts, 35 % were non-significant, and only one showed a positive effect. Similarly, 82 % of behavioural traits measured had negative impacts with no positive effects.

Birds, particularly invertivorous species (those feeding on invertebrates, predominantly arthropods), play a crucial role in agricultural systems by providing pest control services (Table 1). However, air pollution significantly affects their foraging ability and breeding success due to reduced prey accessibility. In polluted environments, the abundance of key prey species, such as caterpillars and snails, decline which adversely impact the diet quality and quantity of the birds. For example, *P. major* experienced reduced snail abundance in acidified soils contaminated with NO_x and SO_x, leading to thinner eggshells and increased egg desertion by the breeding females (Graveland et al., 1994). Similarly, *F. hypoleuca* in Russia faced reduced snail availability in their diet as a result of air pollution (Belskii and Grebennikov, 2014).

Reduced availability of prey species is likely to adversely affect specialist predators (birds feeding on particular prey), while generalist species, including invertivorous and omnivorous taxa, may expand their dietary breadth by exploiting available prey, including beneficial species, thereby exerting additional predation pressure on beneficial arthropods and impacting avian species dependent on these arthropods.

Caterpillar abundance, a critical food source for *P. major*, decreased along gradients of SO_x and heavy metal pollution (Eeva et al., 1998, 2008). This decline forced birds to adopt increased vigilance and resulted in heightened stress levels. The reduction in prey availability and increased vigilant behaviour led to increased stress in three tit species, Crested Tit (*Parus cristatus*), Long-tailed Tit (*Aegithalos caudatus*) and *P. ater*, as a result of SO_x and NO_x pollution in Spain, indicating these insectivorous birds face greater impact in foraging and accessing quality food in their diet such as caterpillars (Brotons et al., 1998). The reduced feeding of birds on caterpillars, combined with the increased abundance of caterpillars in polluted areas, poses a significant threat to agricultural systems, as these pests can inflict substantial crop damage. Thus, the decline of insectivorous birds due to air pollution has negative consequences for pest control and agricultural productivity.

3.2.3. Limitations of the SERB approach

The effects of air pollution on arthropods and birds described here are not directly linked to crop residue burning. We included them as studies explicitly examining biodiversity impacts of residue burning–derived pollution were few. Understanding how residue burning affects organisms at various trophic levels thus remains an important research objective for the future. Nevertheless, broader literature on air pollution impacts in well-studied taxa offers valuable insights into potential species responses. As framed under our SERB framework, it is important to note that findings from ambient pollution studies or isolated pollutant exposures may not fully capture the unique pollution mixtures, concentration spikes, and temporal patterns typical of biomass burning events. Residue burning releases a complex array of pollutants, including greenhouse gases (CO, CO_2, NO_x, SO_x), particulate matter ($PM_{2.5}$, PM_{10}), volatile organic compounds (VOCs), and PAHs, all of which degrade air quality and affect ecosystems (Chanana et al., 2023; Ravindra et al., 2019). The combined effects of these pollutants may differ substantially from those observed under controlled or ambient pollution conditions, and their concentrations can vary by region and crop type. Therefore, the effects presented here should be interpreted as secondary and not definitive causal relationships.

3.3. Translating biodiversity impacts of residue burning into policy action

Crop-residue burning erodes on-farm biodiversity, undermines pollination and natural pest control, and jeopardizes long-term productivity. Our synthesis reveals that these externalities remain largely absent from current policy instruments, most of which focus narrowly on air-quality regulation. Integrating biodiversity metrics into agricultural incentive schemes would create stronger, multi-benefit signals for farmers and project developers.

3.3.1. Expand eligibility for carbon-market finance

Although several countries have imposed legal bans, offered machinery subsidies, and introduced price incentives for alternative crops, residue burning persists and is now spreading into new regions (e.g., Central India; Deshpande et al., 2023), signaling that complementary market-based approaches are urgently needed. Statutory bans on residue burning currently disqualify "non-burn" practices from earning carbon credits, because compliance is viewed as compulsory rather than additional (Cariappa et al., 2024). Robust, field-based evidence that links residue burning to biodiversity loss provides a rationale for revisiting these additionality rules. Crediting both (i) the direct GHG emissions reductions from avoiding residue burning and (ii) the further abatement or sequestration achieved through alternative residue uses, such as incorporation, mulching, biochar production, or bio-energy, would markedly increase the volume of eligible credits. When these credits are paired with verified biodiversity co-benefits, farmers could capture higher market prices, simultaneously boosting income, lowering agriculture's climate footprint, and conserving on-farm biodiversity.

3.3.2. Bundle carbon and biodiversity co-benefits

Carbon credit projects carrying independent biodiversity certification – e.g., Climate, Community, and Biodiversity (CCB) Standards, Sustainable Development Verified Impact Standard (SD VISta), or Social Carbon) – command price premiums of around 37 % in voluntary markets (Forest Trends' Ecosystem Marketplace, 2024). Pilot projects in the US urban-forestry sector already demonstrate higher returns when biodiversity improvements like air quality, water retention, and habitat preservation are verified (City Forest Credits, 2023). Similar bundled credits in residue-burning hotspots could mobilize greater finance for sustainable residue management. A detailed explanation of the scope and challenges of integrating residue management into carbon markets is provided in Supplementary Material S7.

In addition to the monetary incentives, public awareness creation on the long-term benefits of biodiversity-friendly approaches – using flagship species critically affected by residue burning – can cause positive behavioural shifts.

3.3.3. Align national instruments

To translate these opportunities into actionable policies, national governments must align carbon market regulations, biodiversity strategies, and agricultural development plans. This includes adjusting crediting rules to reflect ground realities, piloting bundled carbon–biodiversity projects in residue-burning hotspots, and expanding Payment for Ecosystem Services (PES) schemes that reward pollinator conservation and natural pest control. Farmer-centered policies that provide upfront payments, reduce technological and knowledge barriers, and integrate local perspectives will be essential to achieving widespread and lasting adoption of sustainable residue management practices.

By embedding ecological co-benefits into carbon pricing and subsidy frameworks, governments can convert the biodiversity losses documented here into actionable levers that simultaneously meet climate, agricultural, and conservation goals.

4. Conclusion

The present review generates the first systematic synthesis of evidence on the agroecological impacts of crop residue burning, focusing specifically on its effects on agrobiodiversity and associated ecosystem functions. While existing literature has primarily examined the implications of crop residue burning for air pollution, soil quality, and public health, our review identifies a critical and underexplored dimension – the disruption of biological communities that support sustainable agriculture.

A comprehensive list of studies reviewed in this paper, including those examining the impacts of crop residue burning and air pollution on biodiversity, is provided in the Supplementary Material S8. The findings of these studies demonstrate that residue burning negatively affects a wide range of organisms, including birds, arthropods, and soil biota, both directly (e.g., mortality and habitat loss) and indirectly (e.g., by affecting food availability, soil microclimate, and ecological interactions). For instance, crop residue burning has been shown to reduce soil organic carbon levels, decline soil health, and contribute to unsustainability. It also disrupts the soil biota's community structure, including bacteria and fungi, with many beneficial soil microorganisms being highly sensitive to residue burning. Moreover, burning decreases the abundance and diversity of natural predators such as ants, spiders and ladybird beetles, as well as several other soil arthropods and earthworms. In contrast, residue burning increases the frequency of incidence and severity of several pests and parasitic nematodes. These effects, though context-specific, converge on a common outcome: the erosion of ecosystem services vital for agricultural resilience, including pollination, pest regulation, and nutrient cycling.

By categorizing these impacts and identifying patterns across geographies, taxa, and farming systems, the present review fills a significant knowledge gap in the literature / key evidence blind spots, particularly the limited number of studies from high residue burning regions like India and China. Greater attention is also needed to study the underrepresented groups, like pollinators and higher trophic-level species, that play a critical role in maintaining agroecosystem stability. Focusing research in these areas will deepen scientific understanding and provide a stronger foundation for evidence-based actions in agricultural landscapes affected by residue burning. Understanding the ecological impacts of residue burning can inform the design and scaling of technology interventions, ensuring that government-supported residue management solutions (such as conservation agriculture, regenerative agriculture, mechanized residue incorporation, and biochar production) are tailored to enhance ecosystem services. Public awareness campaigns and farmer capacity-building initiatives should highlight the economic and ecological benefits of biodiversity-friendly practices to farmers. Furthermore, the review offers a novel perspective by linking biodiversity loss from residue burning with the limitations of current incentive schemes. It argues for expanding the scope of carbon market mechanisms to recognize biodiversity co-benefits, which could raise the value of emission reductions and support the transition towards residue management practices that are both climate-smart and biodiversity-friendly. Aligning residue management policies with global environmental commitments, including the United Nations' Sustainable Development Goals, will further support climate adaptation and improve long-term agricultural sustainability.

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CRediT authorship contribution statement

Ashiq Parambil-Peedika: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Alison Laing:** Writing – review & editing, Validation. **Mahesh Kumar Gathala:** Writing – review & editing, Validation. **Adeeth A.G. Cariappa:** Writing – review & editing. **Vijesh V. Krishna:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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