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Setting Priorities for One Health research on pesticide risks: a co-designed multi-expert agenda for Europe and beyond

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Abstract

Pesticides pose major concerns for human, animal, and environmental health, yet they remain central to global food production. Addressing pesticide-related risks is inherently interdisciplinary, spanning questions of human and animal health, environmental fate and effects, agricultural practice, risk assessment, regulation, and policy. However, research priorities are often developed within individual disciplines or risk domains. This study co-designed a research agenda for Europe and beyond, focused on the knowledge needed to reduce pesticide-related risks and strengthen the evidence base for agricultural practice, risk assessment, regulation, and policy. It draws on the interdisciplinary expertise and findings from SPRINT (a 5-year Horizon 2020 research project on pesticides and One Health), and a broader, multi-step consultation with pesticide researchers, regulators, policymakers, and other stakeholders. A mixed-methods, co-design approach was used, including a workshop with consortium experts, a policy-mapping exercise, semi-structured interviews, and an online survey for experts and regulators. This process was used to draw systematically on expert insights from across SPRINT and validate and refine research needs through wider stakeholder consultation. The resulting agenda is organised into four interconnected pillars based on the SPRINT multi-scale One Health approach: (1) comprehensive assessment of pesticide effects on human and environmental health; (2) exposure assessment and monitoring; (3) upscaling findings from local to larger spatial scales; and (4) agro-ecological innovation and adoption. Across these pillars, participants prioritised research addressing real-world exposure and use, including in humans, mixture effects, pesticide movement and accumulation in the environment, long-term biomonitoring, assessing high-risk uses, and the viability of lower-pesticide farming systems. Cross-cutting priorities include climate interactions, real-time monitoring, socioeconomics, policy coherence, trust, advice and knowledge, and financial risk. The agenda goes beyond reaffirming established concerns by identifying where additional evidence, integration, and methodological development are

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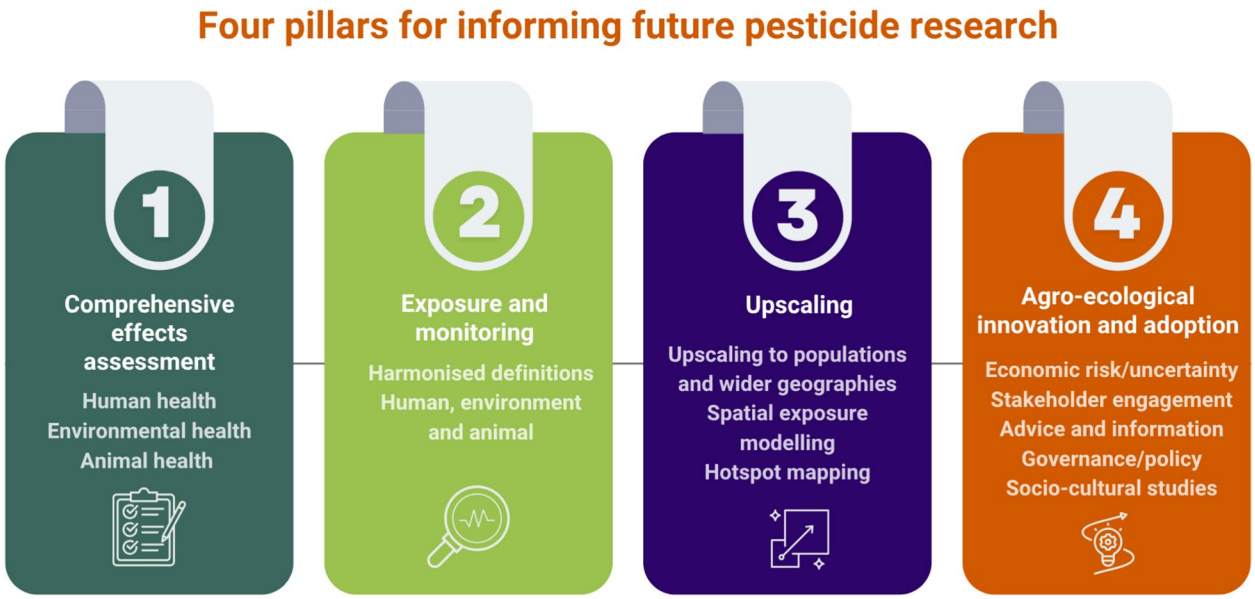
most needed. It provides an integrated guide for aligning future research across disciplines and scales, with clear scientific and policy relevance, supporting improved risk assessment, strengthened monitoring and a transition towards low-pesticide farming, with sensitivity towards economic, cultural, and participatory dimensions.

Graphical Abstract



Introduction and background

Agricultural land occupies around 37% of Earth's land surface, with roughly one-third used for crop production. More than 3 million tonnes of pesticide active substances applied annually in food production [52]. Pesticides remain central to contemporary agriculture but raise concerns about pollution, biodiversity, food security, public health and agricultural transition. Addressing these challenges requires robust evidence on pesticide hazards, exposure, environmental fate, real-world impacts and lower-pesticide alternatives. Knowledge gaps constrain risk assessment, effective pesticide policies, and the development and adoption of lower-pesticide practices.

In the European Union, pesticide risks are governed through pre-market assessment, authorisation and post-market monitoring, informed by scientific knowledge of pesticide hazards, physicochemical properties and exposure contexts, robust assessment and monitoring methods, and behavioural factors shaping pesticide use. Regulation (EC) No 1107/2009 sets requirements for approval of active substances and authorisation of plant protection products, supported by evolving EFSA guidance [21, 22, 24]. Post-market monitoring spans several frameworks, including Regulation (EC) No 396/2005 on pesticide residues in food and feed, the Water Framework Directive (2000/60/EC), the Drinking Water Directive (2020/2184/EU) and the Soil Monitoring and Resilience Directive (2025/2360/EU). The Sustainable Use Directive (2009/128/EC) requires measures to reduce the risks and impacts of pesticide use and promote integrated pest management and alternatives. The Farm to Fork Strategy [15] subsequently set targets to reduce the use and risk of chemical pesticides, and the use of more hazardous pesticides, by 50% by 2030. However, weaknesses in the implementation of the Sustainable Use Directive (EP 2019) [18] and the withdrawal of the proposed Sustainable Use Regulation [25] highlight persistent barriers to pesticide reduction [18, 25].

A substantial evidence base documents pesticide risks across human, animal, and environmental health. Pesticide residues and metabolites can affect biodiversity, soils, water and food safety, particularly where substances are

toxic, mobile, persistent or bioaccumulative [4, 20, 53, 55, 56]. Pesticide exposure has been associated with cancers, neurological disorders, reproductive and developmental effects and antibiotic resistance, with occupational exposure creating particular risks for agricultural land managers [2, 27, 31, 39]. Human exposure occurs through dietary and non-dietary routes, and monitoring studies have identified exposure to mixtures of pesticide residues [46]. Regulatory assessment methods have also advanced, with harmonised models improving the consistency of non-dietary exposure estimates for operators, workers, residents and bystanders [24], and cumulative dietary risk assessment enabling evaluation of combined exposure to pesticides sharing specific toxicological effects.

Despite this evidence base, scientific and methodological gaps constrain pre- and post-market risk assessment and sustainable pest management. Pre-market assessment is limited, for example, by incomplete toxicity testing for some adverse outcomes, including developmental neurotoxicity and endocrine disruption, and by uncertainty around metabolites and mixtures. Post-market evidence is constrained in part by limited understanding of chronic, low-dose, cumulative and non-dietary exposure, as well as gaps in biomonitoring and mixture exposure. Environmental assessment similarly faces gaps in spatial modelling, environmental fate, sensitive-species coverage, mixture toxicity and risk-assessment performance under realistic conditions. Until recently, monitoring efforts and (eco)toxicological studies have largely focused on single substances, or a few compounds, rarely reflecting the complexity of real-world exposure to pesticide formulations, mixtures and degradation products [7, 42]. Although EFSA has developed guidance document on chemical mixture risk assessment [23], integration across environmental matrices, biological endpoints, exposure pathways and spatial scales remains limited, alongside reference values and harmonised methods. This constrains the interpretation of monitoring evidence and its translation into regulatory action [38]. Further research is also needed on lower-pesticide alternatives and the socio-economic and behavioural conditions shaping adoption.

Addressing these gaps does not guarantee that evidence will influence regulation or agricultural practice. Methods, data, ad assessment tools must be incorporated into regulatory frameworks and decision-making processes, particularly where current approaches are inadequate for assessing real-world exposure, mixtures, environmental transport or long-term effects. The Soil Monitoring and Resilience Directive illustrates this challenge: advances in pesticide residue analysis provide a basis for monitoring, but translating these capabilities into comparable measurements across national monitoring systems requires further methodological development and harmonisation [37, 43]. Research must therefore address scientific uncertainties alongside how evidence can best inform regulatory requirements and support pesticide-risk reduction.

Previous research agendas have addressed some of these challenges (e.g. [11, 36, 54]), focusing primarily on scientific knowledge gaps, specific dimensions of pesticide risk assessment [5] or broader agricultural transitions [32]. The fragmentation of IPM research and need for multidisciplinary, system-based approaches have also been highlighted [11]. However, there remains a need for a research agenda connecting real-world pesticide risks, exposure and monitoring evidence with effective policy and regulatory implementation.

This study developed a comprehensive, One Health-based and policy-informed research agenda for reducing pesticide risks across human, animal and environmental health. Drawing on the Horizon 2020-funded SPRINT project and consultations with regulators, scientists, policymakers and other expert stakeholders, it combined an expert workshop, semi-structured interviews, an online survey and validation exercise to identify and prioritise future research needs. Its contribution lies in identifying which knowledge gaps stakeholders consider most important, highlighting emerging and cross-cutting needs, and connecting priorities across exposure and monitoring, risk assessment, agricultural practice, regulation and policy. The resulting agenda specifies priorities for monitoring systems, assessment methods, modelling, economic evidence and governance research to strengthen risk assessment, inform pesticide-risk reduction and support the adoption of lower-pesticide alternatives across diverse agricultural and governance contexts.

Methods

Basis and co-design approach

This study drew on the EU-funded Horizon 2020 project SPRINT (2020–2026), an interdisciplinary Research and Innovation Action which investigated pesticide risks across human, animal and environmental health, alongside the social, economic and policy conditions shaping pesticide use and transition towards lower-pesticide farming systems [12]. SPRINT combined environmental monitoring, biomonitoring, exposure assessment, modelling, toxicological and ecotoxicological testing, and social and policy research [1, 33, 41, 45, 49]. The research agenda drew on the expertise, findings and methodological experience across its work packages to identify research needs within and across these areas.

A co-design approach was used to identify emerging, practice-based and cross-disciplinary research needs that are less visible through literature review alone. SPRINT researchers provided an initial interdisciplinary evidence base, to establish four overarching pillars using a one health framing, which were subsequently scrutinised, refined and prioritised by external experts and stakeholders. This allowed participants to identify additional gaps, challenge the initial framing and assess the practical and policy relevance of proposed priorities. This approach responds to calls for closer collaboration across scientific disciplines [36] and applies the broader One Health research recommendations of Woodruff et al. [57] around agricultural pesticides. The overall co-design process is summarised in Fig. 1.

Developing the research agenda

Research gaps were identified and refined through an internal and external co-design process (September 2024—August 2025), drawing on SPRINT partners and external experts.

An EU policy mapping exercise was conducted through document review, insights from interviews with policymakers [28], SPRINT objectives and researcher input (Sep.–Nov. 2024). Although primarily intended to inform policy recommendations (e.g. Riedel and Bibu 2025), it also informed the research agenda.

Initial research priorities were drafted at an in-person workshop (~50 participants) during the SPRINT plenary meeting (September 2024). Researchers worked in six thematic groups based on work package: (1) pesticide residue distribution and health status, (2) exposure assessment, (3) (eco)toxicological assessment, (4) exposure and risk modelling and mapping, (5) cost–benefit analysis and (6) transition and policy. Each group spent 30 min

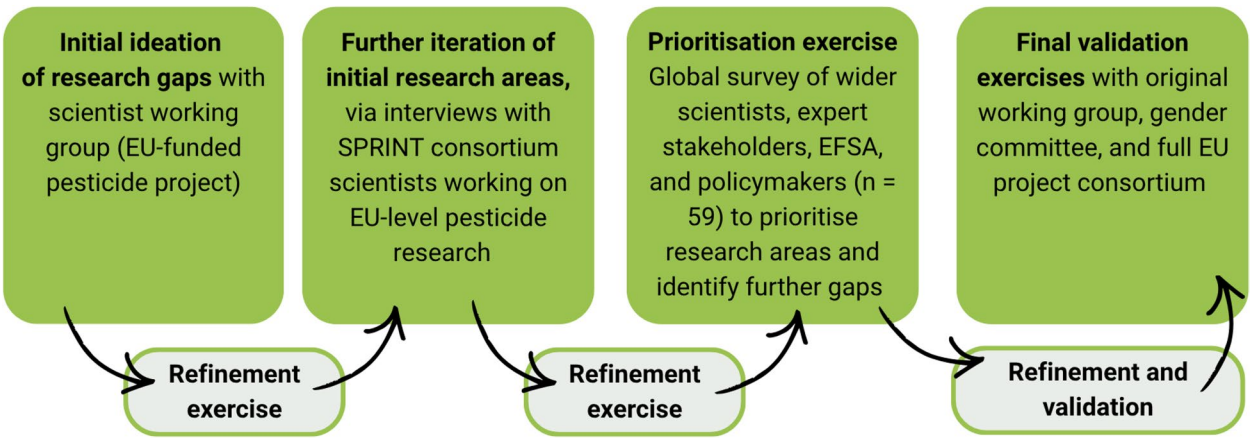


Fig. 1 The ideation process and methods used to co-design a prioritised pesticide research agenda

identifying research gaps and priorities using a collaborative Miro board. The findings informed informed the development of a semi-structured interview protocol, used to further identify gaps with SPRINT researchers.

The interview protocol combined workshop findings, policy mapping and SPRINT results (December 2024). Eight interviews were conducted with SPRINT research teams: Pesticide Monitoring, Ecotoxicology, Human Toxicology, Human Exposure Assessment, Pesticide Behaviour and Fate in the Environment, Upscaled Exposure and Risk Mapping, Life-cycle Analysis, and Transition to Reduced Pesticide Dependence (Jan.–Mar. 2025). A collaborative notetaking template covered pre-market authorisation, monitoring, risk mitigation, and prioritisation/withdrawal, and further research needs. Participants could subsequently revise and synthesise the notes.

Research gaps were consolidated into the first full draft of the research agenda in February 2025, summarising the priorities refined through the interviews. SPRINT's work-package themes were synthesised into four pillars consistent with its interdisciplinary One Health approach and multi-level design (Fig. 2): (1) comprehensive assessment of pesticide effects on human health and the environment; (2) exposure and robust monitoring methodologies; (3) upscaling findings to larger spatial scales; and (4) agro-ecological innovation, economics and stakeholder adoption. Each research priority was reviewed for clarity, readability and appropriate placement within the pillars. Policy recommendations rather than research gaps were excluded. The draft agenda of 48 research priorities reviewed and validated by SPRINT researchers.

Before the formal survey (see below), the draft research agenda was made publicly available for comment by regulatory and scientific stakeholders and publicised through the SPRINT newsletter. At the SPRINT–EFSA workshop (March 2025; 96 EFSA staff members and 18 SPRINT researchers), participants received the agenda

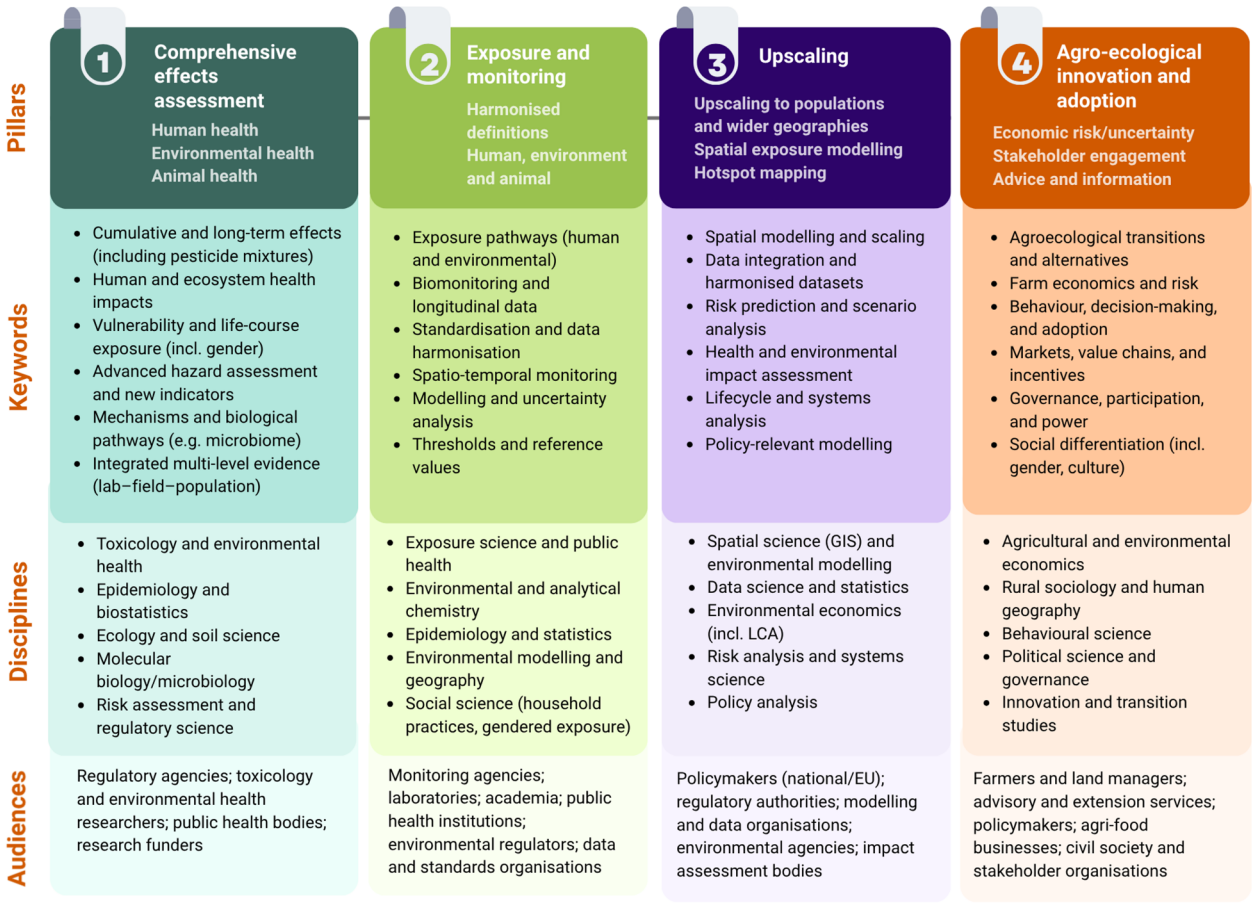


Fig. 2 Schematic diagram presenting the four pillars of pesticide research necessary to inform future policies, regulation, and risk assessment

alongside other SPRINT findings and were invited to assess the relevance, clarity and potential regulatory applicability of the proposed research priorities. Follow-up emails and a Google Forms questionnaire provided further opportunities for EFSA staff to identify gaps or concerns before the formal prioritisation survey. EFSA staff were then then directly invited, with follow-up reminders, to participate in the survey; representative participation was confirmed by EFSA (see below). The draft agenda was also publicised at the SPRINT final event (June 2025), where comments were collected from in-person and online participants. Feedback from both events was recorded in meeting notes and informed subsequent refinements and interpretation.

Expert prioritisation

The draft agenda was further refined and prioritised through an online expert survey (June–August 2025), using the Jisc platform [34]. Participants were recruited from policy, regulation, science, industry, NGOs and agriculture, through direct invitations and a pesticide-focused mailing list of more than 500 contacts. EFSA staff were directly invited, with reminders, and EFSA confirmed participation from relevant divisions. Industry actors were invited to contribute given their roles in pesticide development, research funding and agricultural innovation. Their responses were considered alongside those of other stakeholder groups. No industry-specific weighting was applied. While the geographical focus of the agenda was on Europe, with EU policies in mind, participants from outside Europe and the EU were included to inform pesticide research priorities beyond the EU context and to include a high number of scientific expert contributions. The differing policy and regulatory contexts and heterogeneity in research landscapes are noted for these participants. The invitation made clear that we were seeking expert-input for the exercise, noting that the mailing list likely consisted of interested stakeholders who may work in (un)related fields. The resulting response rate was, therefore, as expected.

Participants selected priority topics within areas relevant to their expertise and also prioritised the four overarching pillars. Participants were asked to 'select up to [x] topics you feel are most important to prioritise for…' within broad research topics within the pillars. Each pillar contained a different number of specific research topics, as identified during the ideation workshop. Participants were therefore asked to select a different number of priority topics depending on the number of options in each research category: a maximum of two priority areas with fewer than five options, and a maximum of three with five or more options. They also prioritised the overarching pillars. During interpretation, it should be recognised that many of the pillars interact and may warrant simultaneous and complementary research across multiple topics.

Qualitative responses captured the reasoning behind prioritisation choices and identified additional research gaps. Analysis combined descriptive statistics, thematic analysis of qualitative data, and crosstab analysis of prioritisations and qualitative data to compare between demographics and sectors, while noting the small numbers of respondents per subgroup.

Final validation exercises

The survey generated 152 additional suggested topics from 30 respondents. Two researchers reviewed these against each other and the original priorities, merging suggestions with substantially overlapping topics and purposes. Distinct aspects of broader themes were retained separately, for example, mixture exposure and occurrence, mixture toxicity and effects, and mixture risk-assessment approaches. No suggestions were excluded on substantive grounds. A total of 61 additional topics were added to the original list of 48 prioritised research gaps. Additional priorities were standardised to a comparable level of detail and expressed as concise research statements, although broader topic areas were retained where further specification would have introduced unwarranted assumptions.

The prioritised agenda was reviewed by SPRINT researchers, the project Advisory Board, the Gender Committee, and selected EFSA and European Commission experts. Reviewers were invited to comment on completeness, relevance, clarity and organisation.

Results

Participant characteristics: prioritisation exercise

59 respondents completed the expert prioritisation survey between June and August 2025. Respondents were highly experienced, with 72% reporting at least 11 years of professional experience, including 25% with more than 31 years of experience. Just 12% (n = 7) had five years or less of pesticide-related experience. The prioritisation exercise therefore primarily reflected the views of experienced stakeholders working in pesticide-related fields.

The survey achieved a relatively balanced gender distribution, with 44% female respondents, 53% male respondents and 3% undisclosed. Participants represented 25 countries from across Europe and beyond. The largest number came from Italy and the Netherlands (n = 7 each), Croatia and Spain (n = 6 each), Germany (n = 5), Switzerland (n = 4), Belgium (n = 3), Czech Republic, Ireland and Portugal (n = 2each). Countries represented by one participant were Argentina, Australia, Brazil, Democratic Republic of Congo, Costa Rica, France, Georgia, Greece, Guyana, the Philippines, Rwanda, South Africa, Tonga, Türkiye and the United Kingdom. The majority of respondent were from EU countries (n = 43). There were also respondents from European non-EU (n = 5) and non-European countries (n = 12).

Respondents came from a range of industries and sectors (Table 1). The target group—scientists and researchers—were highly represented, while farmers, farm workers, consumers, industry actors and communities exposed to pesticide residues were less represented. Industry participation was particularly limited, with only two respondents identifying as industry representatives: one industry representative and one agrochemical manufacturer.

A prioritised pesticide research agenda

Literature screening, expert workshop input and subsequent categorisation informed four key pillars of pesticide-related research (Fig. 2). Topics within each pillar were validated and prioritised through an online survey, which also identified additional gaps (as presented in the full research agenda, Sect. "Full research agenda"). Where relevant, research gaps were separated into 'human' and 'environment' categories to reflect distinct research needs. All suggested topics were taken forward as all participants had strong expertise. The research team scrutinised additional suggestions to ensure they did not entirely duplicate existing gaps via a consolidation exercise.

The following sections introduce each pillar, providing for each pillar a list of research gaps and how these gaps were ranked by participants. A summary of any justifications and remarks is provided for gaps where participants shared why they prioritised particular gaps.

Table 1 Industries/sectors of online survey participants

Industry/sector	Count	Percentage (%)
Scientist/researcher	29	49
Regulatory	8	14
NGO representative	2	3
National Government body representative	6	10
Industry representative	1	2
Private individual	2	3
Food safety authority	1	2
Agrochemical manufacturer	1	2
Farmer organisation	4	7
Land manager	1	2
Other (please specify)	4	7

Pillar 1. Comprehensive assessment of pesticide effects

This pillar represents the need to understand the effects of pesticides–both on human health (4.1.1.) and environmental health (4.1.2). This includes cumulative effects, health impacts, hazard assessment and indicators, mechanisms and biological pathways, and multi-level evidence (see also Fig. 2). Here, we introduce human health research gaps followed by environmental health gaps.

Building a comprehensive assessment of pesticide effects on human health

Table 2 lists the research areas prioritised by online participants in relation to building a comprehensive assessment of pesticide effects on human health. Several participants stated that all topics warranted further investigation, while others framed their choices within wider environmental and societal contexts, linking pesticide risk research to sustainability, biodiversity loss and agroecological transitions.

Table 2 Prioritisation of research topics relating to building a comprehensive assessment of pesticide effects on human health (pillar 1 A)

Priority no	Research topic	Count (%)	Key themes
1	Understanding long-term, low-level exposure and related effect of pesticides on human health outcomes	39 (71%)	• Chronic, low-dose exposure via food, water, and the wider environment • Additive and cumulative exposure and effects, including endocrine disruption and cancer • Need for practical, long-term human biomonitoring • Limits of standard toxicology approaches to study long-term effects and mixtures • Include cross analysis of differentiated data
2	Further develop methods to assess pesticides dose and cumulative and additive exposure thresholds, accounting for data limitations and uncertainties	26 (47%)	• Current approaches could underestimate chronic risks • Mixture effects and do not always reflect variability in exposure patterns • Need for more realistic exposure assessment • Methodological advances needed to handle uncertainty • Differentiation by specific vulnerable groups
3	Advance research on pesticide hazards during vulnerable periods (e.g. pregnancy, early life) and introduce safeguards where health risks remain uncertain	23 (42%)	• Sensitive life stages seen as under-researched, including neurological, hormonal, and immunology • A need to protect these groups within frameworks
4	Link population-based studies to laboratory toxicology work to identify the mechanisms or pesticides of concern	19 (35%)	• Bridging real-world observations with mechanisms to improve causal inference and policy relevance
5	Develop approaches to identify indirect effects of pesticides on human health	19 (35%)	• Indirect and long-term effects remain poorly understood, despite social and economic costs
6	Use hazard assessments to gather toxicologically relevant findings that go beyond existing guidelines	12 (22%)	• Guideline-bound assessments too narrow for chronic, low-dose, or mixture realities • Need evidence around safe limits, aligned with real-world differentiated exposures
7	Reassess the scientific basis for prioritising higher-tier data over lower-tier data in pesticide approval decisions	9 (26%)	• Need for updated, reliable methods • Existing methods seen as partly outdated and unreliable
8	Find ways to translate animal toxicology results to human health	8 (15%)	• Methods for interpreting differentiated animal findings and relevance to human risk assessment • Integrating evidence from epidemiology with toxicity data • Modelling real-world exposure

Survey participants picked up to three priorities. 55 participants took part in this exercise

Building a comprehensive assessment of pesticide effects on the environment

This section focuses on the environmental-health dimension of pesticide risk assessment. The priorities emphasise the need for assessment approaches that better reflect how pesticides behave and interact under real-world ecological conditions (Table 3).

Pillar 2. Developing pesticide exposure and robust monitoring

Pillar two covers research gaps relating to exposure and monitoring. Here, research may focus on exposure pathways, biomonitoring and longitudinal data, standardisation and data harmonisation, spatio-temporal monitoring, modelling, and threshold and reference values. Again, the research gaps have been sub-categorised into: 2 A) Human and animal health and 2 B) Environmental health.

Pillar 2 A: Developing pesticide exposure and robust monitoring in relation to human and animal health.

Pillar 2 A focuses on improving the evidence base for assessing pesticide exposure in humans and animals. The prioritised topics emphasise the need to move beyond fragmented or short-term monitoring approaches towards more practical, standardised and interpretable systems (Table 4).

Pillar 2 B: Developing pesticide exposure monitoring for environmental health.

Pillar 2 B focuses on research gaps relating to environmental exposure and monitoring. Table 5 presents the topics prioritised by survey participants, highlighting both methodological needs and the demand for monitoring that can support more actionable outcomes.

Table 3 Research areas prioritised in relation to building a comprehensive risk assessment for environmental health (pillar 1 B)

Priority no	Option	Count (%)	Key themes
9	Improve understanding of how pesticides move through the environment and accumulate in soils, water, and living organisms, and how this affects biodiversity and ecosystem health in terrestrial and aquatic systems	44 (76%)	• More data on pesticide movement, persistence and accumulation, particularly to support biodiversity protection and regulation
10	Improve the way chemical mixtures are considered in ecotoxicity testing and ecological risk assessment of active substances and pesticides	35 (60%)	• Need to consider real-world exposures to multiple interacting substances
11	Expand OECD testing methods to more accurately reflect real-world ecological conditions in pesticide risk assessments	20 (34%)	• OECD testing methods limited for complex ecological conditions, including full formulations and non-temperate contexts
12	Reassess the scientific basis for prioritising higher-tier data over lower-tier data in pesticide approval decisions	9 (16%)	• Data hierarchies in approval processes linked this to data gaps, outdated methods • Need to assess formulated products as well as active ingredients

Survey participants picked up to two priorities. 58 participants completed this exercise. Priority 12 is identical to priority 7 as this research gap was identified under both environmental and human health contexts

Table 4 Developing pesticide exposure and robust monitoring in relation to human and animal health

Priority no	Research topic	Count (%)	Key themes
13	Establish practical methods for long-term human biomonitoring to support routine monitoring programmes	36 (64%)	• Feasibility, funding, capacity and standardised procedures • Moving biomonitoring from pilot studies to routine programmes
14	Improve understanding of how pesticides behave in the human body to better assess internal exposure and health risks	35 (63%)	• Need for tools and study designs that capture internal dose, kinetics and mixture contributions over time in differentiated ways
15	Develop harmonised definitions and detailed instructions/guidance for monitoring across studies and programmes	24 (43%)	• Inconsistent terminology and procedures as barriers to comparability, data aggregation and policy use
16	Expand assessment of external pesticide exposure to include pathways beyond diet and workplace contact	21 (38%)	• Diet and occupational exposure as too narrow • Need to include wider environmental pathways and product types
17	Continue developing biological guidance values (BGVs*) as reference points for assessing human pesticide exposure	17 (30%)	• BGVs linked to clearer interpretation of biomonitoring data • Terminology differences noted
18	Develop a database on farm animal feed composition to support pesticide risk assessments	15 (27%)	• Lack of a consolidated feed composition resource as a barrier to exposure modelling and tracing residues through animal-derived foods

Survey participants picked up to three priorities. 56 participants completed this exercise

*BGV: biomonitoring guidance value

Table 5 Prioritising topics for developing pesticide exposure and robust monitoring in relation to environmental health

Priority no	Topic	Count	Key themes
19	Investigate how local practices and characteristics influence pesticide monitoring results	30 (51%)	• Monitoring that better reflects real-world conditions • Local practices, environmental factors and landscape-level variation in pesticide behaviour and effects
20	Expand monitoring and tracer studies beyond research fields to better assess diffuse pesticide pollution	28 (47%)	• Extend monitoring beyond controlled research fields to capture diffuse pollution across landscapes • Evidence seen as having limited policy effect unless connected to farming practices, regulatory responses, and follow-up action
21	Establish reference values for pesticide residues and mixtures in more environmental media to guide action	26 (44%)	• Reference values for pesticide residues and mixtures in soils, water and other media as benchmarks for interpreting risk and triggering action • Defining such values, particularly for mixtures, presents practical challenges
22	Develop harmonised definitions and detailed instructions/guidance for consistent monitoring across studies and programmes	24 (41%)	-

As there were just four options, survey participants were able to select up to two priorities. 59 respondents answered this question

Pillar 3: Upscaling findings to larger spatial scales

Pillar three refers to the need to upscale findings to populations and wider geographies. This may include spatial exposure modelling and hotspot mapping, alongside data integration and harmonised datasets (see also Fig. 2). Again, pillar 3 is split into 3 A) human health and 3 B) environmental health.

Pillar 3 A. Upscaling pesticide research to larger scales: human health

Table 6 provides an overview of the topics prioritised by participants in relation to upscaling pesticide-related findings to larger spatial scales for human health assessment.

Pillar 3 B. Upscaling and environmental health

Table 7 presents the topics prioritised by participants in relation to upscaling pesticide-related findings to larger spatial scales for environmental health.

Pillar 4: Agro-ecological innovation and adoption

Pillar four covers several socio-cultural and technological factors that influence a transition to more sustainable use of pesticides. This pillar is split into 3: Pillar 4 A) Pesticides and social cultural, and participatory research; 4 B) Pesticides and policy, governance, and systemic change; and 4C) Agro-ecological innovations, economics, and stakeholder adoption. Together, this pillar includes research about alternatives to synthetic pesticides, farm economics and risk, behaviour and adoption, markets, value chains and incentives, governance, and social differentiation (Fig. 2).

Pillar 4 A. Pesticides and social, cultural, and participatory research

Table 8 presents the topics prioritised by participants in relation to social, cultural and participatory research on pesticides. Not all respondents saw these areas as central to pesticide research, largely noting that this was not their area of expertise, making it harder to judge their relevance. This suggests that, while social, cultural and participatory research was strongly prioritised by many respondents, its contribution may need to be more clearly articulated in relation to pesticide governance and risk assessment. Here, working with social scientists and across disciplines would help to address these gaps.

Pillar 4 B. Pesticides and policy, governance, and systemic change.

Table 9 presents the topics prioritised by participants in relation to pesticide policy, governance and systemic change.

Pillar 4C. Agro-ecological innovations, economics, and stakeholder adoption

Table 10 provides an overview of the topics prioritised by participants in relation to agro-ecological innovations, economics and stakeholder adoption. The priorities emphasise the need for practical and economic evidence on lower -pesticide farming systems, including farm-level costs, performance, yields, profitability and risk.

Participants' justifications reflected a mix of practical, systemic and socio-cultural concerns. Lower-pesticide transitions were seen as requiring clearer evidence for farmers, especially around costs, income and pest-control efficacy, alongside wider consideration of how financial risks could be shared between farmers, markets, policy-makers and consumers. However, a small number of respondents questioned the relevance or framing of some topics, describing them as too generic, insufficiently pesticide-specific or biased in their wording.

Prioritisation of the overarching research pillars

Online survey participants ranked each of the aforementioned pillars for pesticide research (Fig. 3) by extent of attention required, rating most research topics highly, and highlighting the importance of all pillars and underpinning topics as presented in Fig. 2. Comprehensive human and environmental risk assessment emerged as a

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Table 6 Prioritised topics around upscaling pesticide-related findings to larger spatial scales for human health

Priority no	Priority area	Count (%)	Key themes
23	Identify pesticide uses and practices with the highest human exposure potential and health risk and propose safer alternatives	37 (65%)	• Exposure hotspots • Practical mitigation options • First step towards risk reduction where immediate pesticide elimination is unlikely
24	Investigate innovations and agronomic alternatives that reduce health risks associated with pesticide use	30 (53%)	• Need for practical, non-chemical and agronomic alternatives that reduce reliance on hazardous pesticides while supporting viable farming systems
25	Assess the full lifecycle impacts of biopesticides on human health, particularly in the context of integrated pest management (IPM) and organic farming	24 (42%)	• Lifecycle and health impact assessments for evaluating pesticide impacts from production through to degradation and disposal • Biopesticides should be assessed rather than assumed to be risk-free
26	Standardise data collection and formats and ensure public access to support spatio-temporal models of human pesticide exposure and health risk	18 (32%)	• Seen as essential for transparent, comparable, FAIR data and for robust modelling
27	Apply health impact assessments to evaluate how pesticide use and related policies influence specific human health outcomes	16 (28%)	• To translate exposure evidence into policy-relevant understanding of human health outcomes and the effects of pesticide-related policies
28	Further develop spatial modelling methods to estimate human exposure to pesticides across regions and countries, supporting health-related risk assessments	16 (28%)	• Spatial modelling linked to identifying exposure hotspots, pesticide dispersal and targeted mitigation • Reliable modelling depends on standardised, transparent and comparable data
29	Refine lifecycle assessment (LCA) methods to estimate the health-related damage costs of pesticide use across the value chain	8 (14%)	• Estimating wider health-related damage costs, benchmarking impacts, and identifying opportunities to reduce or eliminate hazardous pesticide use

Participants were able to select up to three topics for prioritisation. 57 participants completed this prioritisation

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Table 7 Prioritised topics around upscaling pesticide-related findings to larger spatial scales for environmental health

Priority no	Priority Area	Count (%)	Key themes
30	Identify pesticide uses and practices with the highest environmental impact and ecological risk and propose sustainable alternatives	39 (67%)	• Basis for substitution and innovation • Immediate complete pesticide bans may be unrealistic • Evidence-driven alternatives important for safer and more sustainable practices
31	Explore innovations and agronomic alternatives to reduce environmental harm from pesticide use	32 (55%)	• Access to viable alternatives relevant for supporting risk-management decisions • IPM as a practical strategy, particularly where pesticide reduction requires alternative approaches
32	Investigate the full lifecycle impacts of biopesticides on ecosystems, especially under integrated pest management (IPM) and organic farming systems	25 (43%)	-
33	Harmonise environmental data collection and formats and make datasets publicly available to support spatio-temporal models of environmental exposure and ecological risk	24 (41%)	• Harmonised data as necessary for comparing pesticide-use regimes and drawing reliable conclusions • Data integration and the production of robust regional and wider-scale evidence for policymaking
34	Further develop spatial modelling methods to predict environmental pesticide exposure across regions and countries, accounting for landscape and ecological variation	18 (31%)	• Spatial modelling for understanding how pesticides move through landscapes • Supporting more precise, site-specific management decisions • Upscaling to account for variation between countries, communities and landscapes
35	Refine lifecycle assessment (LCA) methods to estimate environmental damage costs of pesticide use across the entire value chain	11 (19%)	• LCA for identifying opportunities to reduce environmental harms • Capturing system-wide effects and supporting evidence-driven substitution strategies at national and global scales

Participants were able to select up to three topics for prioritisation. 58 participants completed this prioritisation

Table 8 Prioritised topics about social, cultural, and participatory research

Priority no	Research Topic	Count (%)	Key themes
36	Study how different groups present alternatives to chemical pesticides as viable or not, and how this influences policy, regulation, and innovation funding	29 (55%)	• How framings by different actors influence perceived viability, funding, regulation and political momentum • A need to make pesticide-related decision-making more inclusive, representative and trusted
37	Investigate alternative participatory methods for involving stakeholders in decision-making	25 (47%)	• Participatory and socio-cultural research to broaden involvement • Making outcomes fairer, more balanced and more useful
38	Examine how power imbalances affect who gets to participate and influence decisions in policymaking processes	17 (32%)	• Formal and informal hierarchies as shaping whose knowledge is recognised and which perspectives influence policymaking
39	Research how both formal and informal power dynamics shape public consultation processes: who takes part, who has influence, and which voices are heard or overlooked	17 (32%)	• Practical implications of social and cultural dynamics for governance • Power dynamics mean less prominent perspectives and issues risk being overlooked Need to Reduce bias, rebalance policy agendas and support more representative governance Dynamics are complex and context dependent
40	Include gender and other social dimensions in research approaches to better reflect diverse experiences and needs	6 (11%)	• Concerns that male voices may be prioritised in some contexts

Participants could select up to three topics for prioritisation. 53 participants completed this exercise

Table 9 Prioritised topics about policy, governance, and systemic change

Priority no	Research Topic	Count (%)	Key themes
41	Explore how to design systemic transitions that are integrated, practical, and adapted to local contexts	24 (42%)	• Coordinated, multi-level change rather than isolated measures • Need for transitions that are feasible in real-world contexts and sensitive to regional variation • Lower-pesticide systems depend on practical support for farmers, economic viability, social acceptability and coherent policy implementation • Linking effective transitions to alignment between regulation, economics, education and local farming realities, including practical support to reduce barriers for farmers • Economic viability, with cost–benefit evidence important for assessing whether lower-pesticide alternatives can be adopted in practice
42	Investigate the cultural and psychological factors that influence decisions about shifting to lower risk-pesticides or alternative farming systems	18 (32%)	• Cultural and psychological factors linked to farmer and consumer decision-making, social acceptability and adoption of lower risk-pesticides systems • Role of local and indigenous knowledge, particularly in LMIC contexts
43	Assess how EU policies on pesticides and farming are implemented and whether they work well together	15 (26%)	• Policy implementation, coherence and regulatory burden as relevant to farmers' options • Need for regulation to support a range of alternative solutions and informed decision-making

Participants could select one key topic for prioritisation. 57 participants completed this exercise

priority, reflecting its foundational role in understanding pesticide risk and hazards associated with pesticide exposure and informing other research areas.

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Table 10 Prioritised topics about pesticides and policy, governance, and systemic change

Priority no	Research Topic	Count (%)	Key themes
44	Continue research to better understand the real farm-level costs and performance of lower-pesticide farming systems, such as integrated pest management (IPM*), regenerative farming, and pesticide-free approaches	40 (69%)	• Need for further evidence on the farm-level performance of lower-pesticide systems, including costs, yields, practicality and pest-control efficacy • IPM as a relevant approach • Need for systems that prevent pest outbreaks
45	Provide crop-level economic analysis to give farmers clearer information on costs, yields, and income in different farming systems	30 (52%)	• Relevant when assessing whether lower-pesticide approaches are economically feasible and adoptable at scale
46	Explore economic models and ways to share financial risks between farmers, markets, and other actors	16 (28%)	• Financial risk as a key issue in transitions to lower-pesticide farming • Changes in pesticide use need to be assessed in relation to profitability, transition costs and exposure to potential losses • Risk-sharing linked to distributing responsibility across farmers, markets, policy-makers and consumers rather than placing transition risks solely on farmers
47	Investigate how to increase consumer and market demand for disease-resistant crop varieties	12 (21%)	-
48	Study what influences conventional farmers' perceptions of risk when considering a switch to organic farming	11 (19%)	• Better evidence on the practical and economic implications of organic or lower-pesticide systems is needed • Risk linked to wider responsibility, including whether transition risks should be shared across farmers, policymakers, retail and value-chain actors, and consumers

Participants could select up to two topics for prioritisation. 58 participants completed this exercise. '-' under remarks indicates where no specific justifications were provided

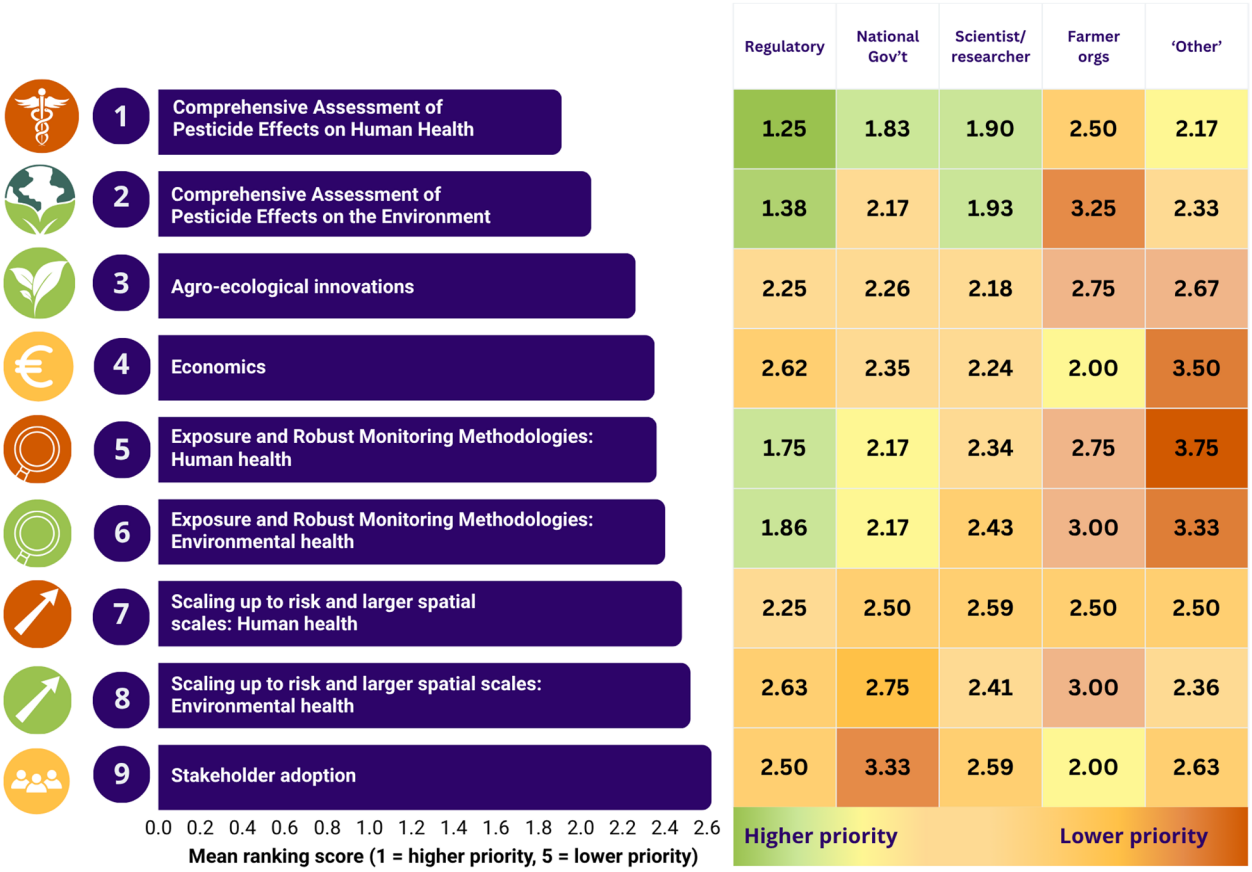

Fig. 3 Ranking exercise of all overarching research topics, including respondent breakdowns (1 = most important, 5 = least important). All 59 survey respondents completed this exercise. 'Other' respondents include agrochemical manufacturers, food safety authorities, industry representatives, NGOs, private indivdiduals, and those who identified as 'other'. These were amalgamated due to relatively small counts

Demographic and sectoral differences

Comparisons between demographic and sectoral groups were exploratory due to small subgroup sizes and should be interpreted with caution. Across the research pillars, sectoral differences were more pronounced than gender or geographical differences. Regulatory respondents placed greater emphasis on research with direct relevance to risk assessment and implementation, including exposure thresholds, biomonitoring, harmonised monitoring guidance, chemical mixtures and spatial modelling. Government respondents focused more on exposure pathways, harmonised environmental data, behavioural and cultural influences, and how alternatives are framed. Scientists and researchers prioritised long-term and low-level health effects, expanded environmental monitoring and whole-system transition research, while farmer organisations placed greater emphasis on harmonised monitoring guidance and pesticide policy implementation and coherence.

Gender differences were modest and inconsistent. Female respondents placed somewhat greater emphasis on long-term human biomonitoring, health impact assessment, monitoring methodologies and stakeholder adoption, while male respondents gave relatively greater priority in some questions to external exposure pathways, farm animal feed data and identifying high-exposure uses and practices. European and global respondents also showed few clear differences, although European participants placed slightly greater emphasis on practical, harmonisation and implementation-focused research, while global participants more often highlighted degradation products and research relevant to agricultural conditions in their regions.

These patterns cannot be interpreted as robust subgroup effects. The overall sample was small, several sectoral categories contained few respondents, and scientists and researchers were overrepresented; no inferential statistical testing was therefore undertaken. Differences in discipline, sector, career stage and geography also cannot readily be separated from apparent demographic effects. The findings should consequently be treated as indicative patterns that warrant investigation in larger and more representative samples.

Full research agenda

The research gaps identified by SPRINT researchers were consolidated with the prioritisation results and additional priorities raised by respondents. Table 11 presents the final research agenda across the four pillars. Minor edits were made at this stage to ensure clarity, drawing on further iteration with the core scientific team.

Priorities presented in the survey were ranked. Additional priorities suggested by participants during the survey were retained to reflect the co-design approach but could not be ranked. Their inclusion does not establish their relative importance or imply lower priority. Instead, they should be interpreted as emerging or complementary areas for further examination.

Under Pillar 1, participants suggested more additional environmental health than human health research gaps (14 versus 4). This may reflect respondents' expertise and the earlier inclusion of human-health gaps in the co-design process, rather than greater environmental research needs.

Discussion

This study co-designed a research agenda to document pesticide risks and develop the evidence, methods, tools and governance conditions needed to address them through policy and practice. The four broad pillars are not, in themselves, novel. They reflect established research concerns and reinforce calls from an earlier IPM-focused agenda for greater interdisciplinary working and practice-relevant research [11]. The contribution of this study instead lies in using co-design to refine, validate and comparatively prioritise research needs across an interdisciplinary One Health framework. Drawing on SPRINT findings and expert judgement alongside wider stakeholder perspectives, the process tested, supplemented and comparatively weighted established research needs, identifying priorities across fields and areas of convergence.

Across disciplines and pillars, the prioritisation exercise highlighted the importance of research on real-world exposure and use of pesticides: long-term and low-dose human exposure, movement and accumulation of pesticides through the environment, practical long-term biomonitoring, identification of high-risk uses and practices, and evidence on the performance and viability of lower-pesticide farming systems. Wider consultation identified cross-cutting needs around climate interactions, real-time monitoring, socioeconomic and demographic differentiation in exposure, policy modelling, trust and knowledge systems, advisory systems and financial risk. These priorities connect hazard and exposure evidence with monitoring, spatial assessment, regulatory interpretation and feasible alternatives, supporting wider calls to connect biophysical evidence, agricultural practices, regulatory processes and the social dimensions of pesticide dependence [36].

Research to enable policy and practice

The priorities identified in this agenda relate to several key decision points in pesticide policy and practice, including pre-market assessment, post-market monitoring, risk mitigation, prioritisation of higher-risk uses, and adoption of lower-risk alternatives. The co-design encouraged researchers to consider fundamental research gaps alongside policy recommendations arising from SPRINT findings [48, 50]. The prioritised research gaps

Table 11 Consolidated research gaps to reduce environmental and health risks from pesticides. Research gaps are ranked according to the prioritisation exercise

Pillar 1: Comprehensive assessment of pesticide effects on health and environment	
Human health	**Environment**
1) Understanding long-term, low-level effect of pesticides on human health outcomes 2) Further develop methods to assess pesticides dose and exposure thresholds, accounting for data limitations and uncertainties 3) Advance research on pesticide hazards during vulnerable periods (e.g. pregnancy, early life) and introduce safeguards where health risks remain uncertain 4) Link population-based studies to laboratory toxicology work to identify the mechanisms or pesticides of concern 5) Develop approaches to identify indirect effects of pesticides on human health 6) Independent well-conducted studies in hazard assessments to gather toxicologically relevant findings that go beyond existing OECD testing methods (the standard regulatory tests used in EU active substance approvals) 7) Reassess the scientific basis for prioritising higher-tier data over lower-tier data in pesticide approval decisions 8) Improve translation of animal and in-vitro toxicology results to human health *Additional Priorities Identified by Survey:* · Mixture Toxicity and Formulation Effects, specifically relating to formulations, additives, and tank mixes · Emerging Biological and Molecular Impact Pathways · Biomonitoring and Environmental-to-Human Exposure Linkages · Comparative and Contextual Risk Assessment	9) Improve understanding of how pesticides move through the environment and accumulate in soils, water, and living organisms, and how this affects biodiversity and ecosystem health in terrestrial and aquatic systems 10) Improve the way chemical mixtures are considered in ecotoxicity testing and ecological risk assessment of active substances and pesticides 11) Expand OECD testing methods (the standard regulatory tests used in EU active substance approvals).to more accurately reflect real-world ecological conditions in pesticide risk assessments 12) Reassess the scientific basis for prioritising higher-tier data over lower-tier data in pesticide approval decisions *Additional Priorities Identified by Survey:* · Assess the combined effects of pesticide mixtures rather than only individual compounds · Investigate impacts of pesticides on ecosystem services and ecological resilience, beyond direct toxicity · Pesticide Impacts Beyond Farming Contexts · Precision Application Technologies and System-Level Impacts · Frameworks for Practical Mixture Risk Assessment · Toxic Degradation Products and Environmental Metabolites · Region-Specific Risk Assessment for Non-Temperate Ecosystems · Soil Microbiota, Soil Health, and Trophic Interactions · Climate Change Interactions · Combined Impacts with Other Environmental Stressors · PFAS in Pesticide Products · Mesocosm and Ecosystem-Scale Studies · Threshold values/benchmarks surrounding pesticide mixtures in soil and the atmosphere · Explore the potential of developing binding benchmarks for all ecosystem matrices
Pillar 2: Exposure to pesticides and robust monitoring methodologies	
Human and animal health	**Environment**

Table 11 (continued)

Pillar 2: Exposure to pesticides and robust monitoring methodologies

13) Establish practical methods for long-term human biomonitoring to support routine monitoring programmes
14) Improve understanding of how pesticides behave in the human body to better assess internal exposure and health risks
15) Develop harmonised definitions and standard operating procedures (SOPs) for consistent monitoring across studies and programmes
16) Expand assessment of external pesticide exposure to include pathways beyond diet and workplace contact
17) Continue developing biological guidance values (BGVs) as reference points for assessing human pesticide exposure
18) Develop a database on farm animal feed composition to support pesticide risk assessments
19) Investigate how local practices and characteristics influence pesticide monitoring results
20) Expand monitoring and tracer studies beyond research fields to better assess diffuse pesticide pollution
21) Establish reference values for pesticide residues and mixtures in more environmental media to guide action
22) Develop harmonised definitions and standard operating procedures (SOPs) for consistent monitoring across studies and programmes

Additional Priorities Identified by Survey:

- Mixture Toxicity Beyond additivity
- Socioeconomic, Occupational and Gendered Variability /Vulnerabilities
- New bioactivation pathways
- Exposure to additives, Co-Formulants, and Novel Substances
- Biomonitoring and Contaminated Pathways
- Genetic Susceptibility and Individual Variability
- Broader Exposure Contexts
- Governance and Global Standards
- Improve and harmonize the use of epidemiological studies in human risk assessment
- Apply human health study areas to animal health, especially in livestock intended for human consumption
- Investigate spatial non dietary exposure to pesticides
- Monitor substances that are also used outside plant protection products (e.g. biocides, industrial chemicals)
- Extend monitoring to both surface and groundwater, with attention to how pesticide levels vary seasonally and during rainfall/runoff events
- Emerging contaminants and their metabolites in environmental tracer studies
- Influence of climate variability and extreme weather events on pesticide transport and degradation
- Integrate advanced sensor technologies and remote sensing for real-time pesticide monitoring
- Evaluate the long-term fate and risks of pesticide transformation products (metabolites and degradation by-products)
- Monitor impacts on non-target organisms (e.g., soil microbiota, pollinators, aquatic invertebrates) as part of exposure tracking
- Address ecological effects of PFAS exposure in relation to pesticide monitoring
- Improved communication of contamination data to decision-makers so findings can better inform action

Pillar 3: Upscaling findings to larger spatial scales

Human health

23) Identify pesticide uses and practices with the highest human exposure potential and health risk and propose safer alternatives
24) Investigate innovations and agronomic alternatives that reduce health risks associated with pesticide use
25) Assess the full lifecycle impacts of biopesticides on human health, particularly in the context of integrated pest management (IPM) and organic farming
26) Apply health impact assessments to evaluate how pesticide use, and related policies, influence specific human health outcomes
27) Further develop spatial modelling methods to estimate human exposure to pesticides across regions and countries, supporting health-related risk assessments
28) Standardise data collection and formats and ensure public access to support spatio-temporal models of human pesticide exposure and health risk
29) Refine lifecycle assessment (LCA) methods to estimate the health-related damage costs of pesticide use across all workers and consumers throughout the value chain

Environment

30) Identify pesticide uses and practices with the highest environmental impact and ecological risk and propose sustainable alternatives
31) Explore innovations and agronomic alternatives to reduce environmental harm from pesticide use
32) Investigate the full lifecycle impacts of biopesticides on ecosystems, especially in IPM and organic farming systems
33) Harmonise environmental data collection and formats and make datasets publicly available to support spatio-temporal models of environmental exposure and ecological risk
34) Further develop spatial modelling methods to predict environmental pesticide exposure across regions and countries, accounting for landscape and ecological variation
35) Refine lifecycle assessment (LCA) methods to estimate environmental damage costs of pesticide use across the entire value chain

Additional Priorities Identified by Survey:

- Socio-economic and demographic differentiation in exposure and risk models
- Social and economic impacts of pesticide use (livelihoods, regional economies)
- Real-time or near real-time monitoring systems to support early warning
- Cumulative and long-term effects of multiple pesticides at scale and differentiated by cohorts of various relevant social background (gender, rural/urban, health condition etc.)
- Climate and land-use change impacts on pesticide use and exposure patterns
- Policy scenario modelling to connect research with governance
- Comparative evaluation of regenerative and no-pesticide farming systems
- Linking Highly Hazardous Pesticide (HHP) phase-out with scaling up biopesticides in IPM

Table 11 (continued)

Pillar 4: Agroecological innovation, economics, and stakeholder adoption of low-pesticide practices
Social, cultural and participatory research
36) Study which different groups present alternatives to chemical pesticides as viable or not, and which strategies they use to succeed in influencing policy, regulation, and innovation funding
37) Investigate further participatory methods for involving stakeholders in decision-making about pesticide use and its alternatives
38) Examine how power imbalances affect who gets to participate and influence decisions in policymaking processes
39) Research how both formal and informal power dynamics shape public consultation processes: who takes part, who has influence, and which voices are heard or overlooked
40) Include gender and other social dimensions in research approaches to better reflect diverse experiences and needs
Additional Priorities Identified by Survey:
· Education and awareness campaigns: how they shape public understanding and attitudes toward pesticide use and alternatives and acknowledge diverse affected groups of users and consumers in their targeting
· Trust in institutions, science, and regulatory bodies: how it influences legitimacy, engagement, and acceptance of decisions
· Integration of diverse knowledge systems: e.g. traditional ecological knowledge, indigenous perspectives, farmer knowledge, and local authority structures (chiefs/tribes)
· Communication strategies: effective ways to convey complex pesticide risks and alternatives to diverse groups (m/f farmers, consumers, youth)
· Consumer behaviour and decision-making: the role of labelling, price, and produce appearance in shaping food choices among diverse groups of consumers
· Cost–benefit calculations to include external health costs to farmers to better understand true implications of pesticides on different farming systems
Policy, governance, and systemic change
41) Explore how to design systemic transitions that are integrated, practical, and adapted to local contexts
42) Investigate the social, cultural and psychological factors that influence decisions about shifting to lower-pesticide or alternative farming systems
43) Assess how EU policies on pesticides and farming are implemented and whether they work well together
Additional priorities identified by survey:
• Cross-Sector and Multi-Level Policy Coherence: Examine how pesticide policies interact with agricultural subsidies, trade rules, health policies, environmental regulation, and market incentives across local, national, and international governance levels
• Long-Term and Post-Implementation Policy Evaluation: Assess whether pesticide policies and governance reforms achieve their intended outcomes over time, including delayed effects, behavioural responses, unintended consequences, and opportunities for adaptive policy development
• Governance of Non-Essential Pesticide Uses: Investigate proportionate regulatory approaches to pesticide applications outside essential food production, including ornamental horticulture, amenity spaces, and golf courses
• Bottom-Up and Locally Led Governance Models: Evaluate farmer-led networks, cooperatives, and community-based pest management approaches as governance mechanisms for developing and implementing locally appropriate pesticide-reduction strategies
Agro-ecological innovations, economics, and stakeholder adoption of low-pesticide practices
44) Continue research to better understand the real farm-level costs and performance of lower-pesticide farming systems, such as integrated pest management (IPM), regenerative farming, and pesticide-free approaches
45) Provide crop-level economic analysis to give farmers clearer information on costs, yields, and income in different farming systems
46) Explore economic models and ways to share financial risks between farmers, markets, and other actors
47) Investigate consumer and market attitudes and demand for disease-resistant crop varieties
48) Study what influences conventional farmers' perceptions of risk when considering a switch to organic farming while differentiating to gender, age, sector and farm size
Additional Priorities Identified by Survey:
· Integration of real-time data and digital technologies: Explore the role of tools such as remote sensing, AI, and digital platforms in improving monitoring, risk assessment, and decision-making for pesticide reduction
· Knowledge transfer and advisory systems: Investigate effective mechanisms for extension services, advisory programmes, and farmer-to-farmer learning networks to support adoption of agro-ecological innovations
· Economic risk and uncertainty: Assess how short-term risks, unproven markets, and yield reductions during transition phases shape adoption of low-pesticide practices and identify ways to mitigate these risks through transitional funding and risk-sharing models
· Influence of agri-business actors: Examine the role of pesticide manufacturers, distributors, and input suppliers in shaping adoption pathways, including their power to enable or block innovation
· Education and training systems: Evaluate how existing agricultural extension services and farmer education systems are (or are not) equipped to promote low-pesticide practices, and how they could be strengthened

Additional non-ranked research gaps raised by respondents are listed separately.

identified here therefore provide a basis for considering how future research could strengthen pesticide policy and practice in the EU and beyond.

Current risk assessment frameworks are fragmented between human and environmental compartments and do not always capture realistic exposure conditions. The priorities point to the need for greater integration across environmental and biological evidence, farming practices, and health outcomes. For pre-market assessment, regulated by Reg. (EC) No 1107/2009, important gaps remain in the assessment of mixtures, metabolites, chronic and dietary exposure under realistic conditions [27, 29].

At the same time, several of the prioritised research gaps identified here correspond to, or directly inform, regulatory frameworks, particularly for pre-market assessment. The current EU framework for pre-market pesticide risk assessment, Regulation (EC) No 1107/2009, provides established procedures for assessing pesticide risks, but important uncertainties remain regarding aspects such as mixtures, metabolites, chronic and low-dose effects, multiple exposure pathways and realistic environmental exposure. Incomplete knowledge of these pathways can limit how well assessments reflect real-world exposure and therefore constrain exposure assessment and risk characterisation. Addressing these gaps could directly inform regulatory data requirements for approval and authorisation, testing methodologies and EFSA guidance. Priorities on environmental fate, transport and exposure under realistic conditions could further strengthen exposure assessment and risk characterisation.

For post-market monitoring, a key challenge is translating occurrence and exposure data into evidence that can support regulatory action. Previous research has highlighted limitations in the availability, accessibility, harmonisation and comparability of pesticide monitoring data [3, 6, 9], across fragmented EU policy areas. In human biomonitoring, gaps in toxicokinetic knowledge, including how pesticides are absorbed, distributed, metabolised and excreted, constrain the development of biological guidance values needed to interpret internal exposure and support human biomonitoring programmes. Environmental monitoring presents related challenges. The recently adopted Soil Monitoring and Resilience Directive (2025/2360/EU) illustrates the need to account for temporal and spatial variability and local conditions, alongside thresholds and methods for interpreting monitoring results to inform management and regulatory action. Interoperable data infrastructures, harmonised monitoring protocols and reference values could strengthen regulatory responses to real-world pesticide exposure [10, 13, 57]. The EU-funded SYBERAC project [51], building on the 2022 PERA Roadmap, illustrates efforts to reduce data fragmentation.

Several EU policy instruments require authorities to identify where pesticide risks are greatest and to target monitoring or risk-reduction measures accordingly, but this depends on evidence on where, how and under what conditions risks occur. Under the Sustainable Use Directive (2009/128/EC), Member States must identify priority active substances, crops, regions and practices, yet the harmonised risk indicators provide only a partial basis for doing so. For example, HRI 2 is based on the number of emergency authorisations, weighted by hazard category, and does not account for how, where or when the authorised products are actually used [18]. National Action Plans (NAPs) also vary substantially between Member States, with shortcomings in measurable targets, indicators and timetables, while the European Court of Auditors (ECA) found that available pesticide-use data were insufficiently detailed and comparable to support effective monitoring of risks [30]. Under the Farm-to-Fork Strategy, progress towards the 50% reduction in the use and risk of chemical pesticides is measured primarily using quantities of active substances placed on the market weighted by hazard, while the target for more hazardous pesticides is based on sales of candidates for substitution [16]. These indicators can track aggregate trends but provide limited information on the crops, practices, locations and exposure conditions, the Commission has acknowledged the need to interpret them alongside other evidence on pesticide use and environmental and health impacts [17].

The priorities under Pillar 3 are particularly relevant here, including the identification high-risk pesticide uses and practices, spatial exposure and risk modelling, harmonised data collection, and real-time monitoring. Such research could support risk detection and prioritisation within SUD NAPs by providing more spatially and use-specific evidence on which substances, crops, practices and regions are associated with higher human or environmental risks. This could strengthen targets and indicators, identification of priority risks, and assessment of whether measures address priority risks and interpretation of EU-level trends. The SPRINT Global Health Risk Assessment Toolbox illustrates this potential by integrating pesticide occurrence, exposure and modelling data

to assess risks of pesticide mixtures across scales [48, 50]. Such tools could complement aggregate indicators by identifying where further monitoring, assessment or intervention is needed.

Effective risk reduction also depends on whether lower-pesticide practices are technically feasible, economically viable and acceptable to farmers and other actors [44, 47]. The withdrawal of the proposed Sustainable Use Regulation in 2024 illustrates the difficulty of translating these ambitions into binding and accepted policy measures (European Parliament 2024). Pillar 4 addresses these implementation conditions through research on the farm-level performance and costs of alternatives, crop-level economics, financial risk and risk-sharing, farmer perceptions, market demand, advisory systems, knowledge transfer and participation. Research credibility also depends on research independence, as conflicts of interest can introduce bias into pesticide studies and risk assessment [40]. NAPs and SUD opportunities to apply this evidence through measures promoting IPM and lower-risk alternatives. Research under Pillar 4 could help explain why technically promising alternatives are adopted in some contexts but not others, and which combinations of advice, training, economic incentives, risk-sharing mechanisms and peer or farmer-to-farmer learning are most effective. These findings could inform context-specific support programmes, Agricultural Knowledge and Innovation Systems (AKIS), including advisory and extension services, and regional or local pesticide-reduction plans tailored to different agronomic, economic and social conditions. The key contribution is therefore to move from identifying lower-risk options to understanding the support conditions needed for their sustained adoption in practice.

Several of the priorities also examine power imbalances shaping pesticide use, risk, and transition. Research about trust, knowledge and advisory systems, participation, market demand, financial risk, and how alternatives are framed could identify which and whose knowledge is accepted as legitimate, who influences decision making, and which forms of expertise and interests carry the most power. This requires attention to power across stakeholder contexts.

The priorities span epidemiology, toxicology, ecotoxicology, exposure science, agronomy, modelling, economics, social science and policy studies, reinforcing calls for closer integration between biophysical and social research [36]. Participants identified adoption, trust, power, risk perception and participation as important conditions shaping lower-pesticide transitions. Changes in practice are influenced by costs, market demand, advice, knowledge systems, social learning and how alternatives are framed by different actors [35]. Similarly, whether evidence informs regulation depends on institutional mandates, monitoring requirements, methodological harmonisation, transparency, political priorities, economic incentives and advisory capacity. These factors shape trade-offs between environmental and health protection, agricultural productivity, farmer income, food security and the availability of alternatives. The research agenda therefore extends beyond generating evidence to understanding how it is assessed, interpreted, communicated and incorporated into regulatory frameworks and agricultural knowledge systems.

The agenda should not be interpreted only through an EU policy lens. Pesticide exposure, regulatory capacity, farming systems and access to lower-risk alternatives vary between regions. Research priorities must therefore be adaptable to different institutional and agricultural contexts, particularly where monitoring capacity, regulatory infrastructure or access to alternatives is limited. Comparable methods remain important, but upscaling should not imply a single model of pesticide transition. Approaches must also remain sensitive to differences in landscapes, farming practices, social conditions and governance systems.

Operationalising the agenda

Operationalising the agenda will require coordinated research funding and programme design. Pesticide research is often dispersed across broader programmes addressing chemicals, soils, biodiversity, food systems, environmental health and sustainable agriculture, potentially fragmenting investment across disconnected projects and policy objectives. This agenda could help funders align calls and research portfolios around a coherent set of pesticide-specific priorities linking risk assessment, monitoring, alternatives and the social and economic

conditions shaping adoption. Prioritisation and sequencing will also be important, since some research needs are immediately policy-relevant, while others depend on shared methods, harmonised monitoring, long-term datasets and interoperable data infrastructures.

Different priorities require different forms of investment. Some are suited to time-limited research projects, while others require sustained support for monitoring networks, reference values, modelling platforms and longitudinal studies. Clear institutional ownership and coordination across research funders, regulatory bodies, monitoring authorities and agricultural knowledge systems will therefore be important, alongside cross-disciplinary collaboration. Methods, models and tools should be piloted and evaluated in real-world regulatory and farming contexts, with regulators, farmers, advisors and other stakeholders involved in assessing feasibility and adapting approaches to different agronomic, regulatory and socioeconomic settings. Common standards and shared infrastructures should retain sufficient flexibility while ensuring comparability across contextual differences.

SPRINT demonstrates the value of connecting research outputs with policy recommendations and regulatory and agricultural decision-making [48, 50]. Future programmes should therefore build pathways to application into research design from the outset, ensuring evidence is interpretable, usable and supported by appropriate methods, reference values, institutional responsibilities and feasible risk-reduction measures.

Limitations

The findings should be interpreted as a structured prioritisation exercise rather than a definitive ranking of all pesticide research needs, due to the over-representation of scientists and under-representation by other sectors. Although the survey was promoted through multiple channels to broaden participation, the resulting agenda cannot be assumed to comprehensively reflect the priorities of industry, innovation actors or other underrepresented groups. Greater involvement from these stakeholders could help identify additional research needs and areas of convergence or divergence with priorities identified by research and policy communities. The low level of industry participation may also indicate a broader challenge around communication and alignment between research and industry when developing shared research agendas, although this cannot be established from the present study alone. Future work should therefore include further deliberation with underrepresented groups while recognising diversity within them.

The research gaps were developed with input from expert stakeholders both within and beyond the SPRINT consortium. Nevertheless, there remains some potential for gatekeeping through the initial framing of research gaps by consortium researchers. The co-design process sought to mitigate this by keeping the agenda open to revision throughout and providing multiple opportunities for external participants to suggest additional priorities, refine existing topics and contribute to their validation.

Conclusions

This paper presents a co-designed research agenda for pesticide risk research spanning human and animal health, environmental health, exposure and monitoring, spatial upscaling, governance, and agroecological transition. Across these areas, participants prioritised research that reflects real-world conditions, including long-term and cumulative exposure, mixture effects, pesticide movement through the environment, and the practical feasibility of lower-pesticide farming systems.

The agenda demonstrates a need for more integrated, actionable and policy relevant research, with collaboration between epidemiology, toxicology, ecotoxicology, biomonitoring, environmental monitoring, modelling, agronomy, social science and economic analysis. Priorities include stronger regulatory decision-making, the development and validation of reference values, identification of high-risk uses and locations, and assessment of the benefits and trade-offs of viable alternatives.

Reducing pesticide-related risks is a technical and transition challenge. Here, progress will demand both the evidence identified in this research agenda and on how resulting evidence is integrated and adopted together with economic risk, market conditions, knowledge and advisory systems, public legitimacy, institutional capacity and stakeholder participation. This agenda provides a basis for greater coordinated research funding, harmonised monitoring, improved risk assessment and context-sensitive transition pathways. It offers a practical direction for researchers, funders, regulators and policymakers seeking to reduce pesticide risks while accounting for differences in farming systems, environmental conditions and governance capacity across Europe and beyond.

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

Declarations

Ethics approval and consent to participate Ethical approval for this study was awarded by Wageningen University & Research and University of Gloucestershire. All participants provided informed consent for the study.

Competing interests The authors declare no competing interests.

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