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Beyond Bioefficacy: A Bibliometric Analysis of the Economics, Adoption, and Commercialization of Botanical Pesticides

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Abstract

Botanical pesticides are increasingly investigated as plant-derived options for reducing dependence on synthetic pesticides, yet their progression from technical efficacy to sustained agricultural implementation remains insufficiently understood. This study integrates bibliometric performance analysis, science mapping, and systematic evidence mapping to examine the development and translational orientation of the field. Records were retrieved from Scopus in October 2026 using botanical pest-control terms combined with economic, adoption, market, and institutional concepts. Following predefined screening procedures, 38 articles were retained and analyzed using Biblioshiny and VOSviewer. Evidence was mapped across economic viability, farmer adoption and use, commercialization and scaling, and regulation and institutional support. The literature developed from a predominantly technical foundation toward increasing attention to economics, integrated pest management, and sustainable agriculture. However, this conceptual broadening was not accompanied by comparable integration of translational evidence. Substantive economic evidence was identified in 27 articles and adoption evidence in 15, whereas commercialization and regulatory or institutional evidence were each substantively addressed in only eight articles. Only five publications integrated all four domains. Evidence was concentrated in technical development, field validation, and economic evaluation but became substantially more limited at stages requiring sustained farmer use, product standardization, regulatory readiness, and viable market systems. The principal gap is therefore not a lack of technically promising botanical pesticides, but limited continuity between technical performance and the conditions required for wider implementation. Addressing this gap requires comparable economic assessment, longitudinal adoption research, proportionate regulation, quality assurance, and evidence on value-chain and enterprise performance.

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1. Introduction

Agricultural pest management remains essential to crop productivity and food security, yet continued dependence on synthetic pesticides has raised persistent concerns regarding resistance, environmental contamination, non-target effects, occupational exposure, and human health [1, 2]. These pressures have strengthened the search for pest-management approaches that can reduce chemical dependency while remaining effective and economically feasible under agricultural conditions. Integrated pest management

(IPM) provides an important framework for this transition because it combines complementary control methods rather than relying on a single intervention. Nevertheless, the implementation of ecologically based pest management has frequently lagged behind its conceptual development, particularly in resource-constrained farming systems, where limited technical support, input access, incentives, and institutional capacity can impede adoption [3, 4]. Broader assessments of IPM adoption similarly show that training, accessibility, collective action, policy support, and alignment with farmer circumstances remain critical to implementation [4, 5].

Botanical pesticides represent one group of alternatives with potential relevance to this transition. They broadly include pest-control substances, extracts, preparations, and formulations derived from plants or their secondary metabolites. Depending on their phytochemical composition, these products can suppress pests through toxic, behavioral, and developmental mechanisms. Botanical pesticides are frequently investigated for their diverse modes of action, potential environmental degradability, locally accessible raw materials, and possible compatibility with IPM and agroecological production systems. However, these properties vary among plant species, active compounds, formulations, exposure pathways, and application conditions. Commercially established examples include pyrethrum- and neem-based insecticides, while essential oils and other plant-derived compounds continue to attract interest as potential crop-protection products [6, 7]. Their relevance may be particularly pronounced where conventional pesticides are costly or hazardous and where farmers retain knowledge of locally available pesticidal plants [8, 9].

Promising biological activity does not, however, establish reliable performance under agricultural conditions [10–12]. The concentration and activity of botanical compounds may vary with plant genotype, chemotype, growing environment, harvest stage, processing method, extraction procedure, formulation, and storage. Rapid degradation may reduce environmental persistence but can also shorten residual efficacy and shelf life. Locally prepared products may require little direct financial expenditure while imposing substantial demands for collecting, processing, preparing, and repeatedly applying plant materials. Technical validation must therefore extend beyond laboratory toxicity to include formulation performance, operational consistency, field efficacy, storage stability, and suitability across production contexts [6, 9, 13]. Botanical pesticide reviews have similarly identified formulation limitations and insufficient product standardization as continuing obstacles to wider agricultural use [7].

Economic performance and farmer adoption introduce additional requirements [14]. Positive efficacy, yield protection, or benefit-cost ratios under experimental conditions may demonstrate potential value, but they do not establish that farmers can access, prepare, purchase, or repeatedly use a botanical pesticide [15]. Farmer decision-making is also shaped by perceived reliability, affordability, labor requirements, compatibility with existing practices, knowledge, extension support, material availability, and uncertainty [16]. Awareness, preference, stated willingness, initial experimentation, reported use, and sustained adoption therefore represent distinct outcomes [16–18]. Evidence from the wider IPM literature shows that insufficient training, limited input access, weak incentives, labor demands, and inadequate institutional support can restrict uptake even when pest-management technologies are agronomically promising [4, 5]. Studies of botanical pesticides have similarly indicated that familiarity or positive evaluation does not necessarily lead to routine and continued use [19, 20].

The transition from a technically functional treatment to a market-ready product presents a related but distinct challenge. Commercial development requires consistent production, scalable processing, product standardization, regulatory approval, distribution, and viable demand [21–23]. These requirements differ across farmer-made preparations, cooperative or community-level processing, and standardized industrial formulations. Regulatory pathways also vary among jurisdictions and can influence registration costs, development time, and incentives for private investment. Appropriate regulation can support product identity, efficacy, safety, and user confidence, but procedures developed for conventional single-active-ingredient pesticides may not always align with chemically complex botanical mixtures or small-scale production models [6, 24]. International differences in registration requirements and evaluation timelines can further hinder product development and cross-border commercialization. These conditions help explain why sustained scientific interest in plant-derived pesticidal compounds has not produced an equivalent expansion in registered products and market penetration [6].

Previous reviews of botanical pesticides can be grouped into three broad categories. The first comprises narrative and systematic syntheses of botanical sources, phytochemistry, modes of action, bioefficacy, environmental properties, formulation constraints, and safety [6, 7, 25, 26]. Recent reviews further indicate that,

despite their diverse biological activities and potential sustainability advantages, botanical pesticides continue to face constraints related to active-material variability, formulation performance, product standardization, regulatory approval, and compliance with commercial product requirements [27, 28].

The second examines specific translational concerns, including commercial opportunities for essential-oil-based products, production and regulatory mechanisms in sub-Saharan Africa, and the movement of botanical insecticides from laboratory studies to farm application [9, 13, 24, 29]. These reviews have identified important constraints related to efficacy variability, formulation stability, product standardization, registration, and market development. However, their principal purpose has been to synthesize technical characteristics, challenges, and prospective opportunities rather than to systematically quantify how economic, behavioral, regulatory, and commercial evidence is distributed and integrated across the literature.

A third group consists of bibliometric reviews addressing botanical pesticides or related research fields. Existing analyses have mapped biopesticide research broadly, formulation-oriented biopesticide research, botanical insecticides targeting Lepidopteran pests, and regionally bounded biopesticide research [30]. These studies have documented publication growth, influential authors and countries, collaboration patterns, technical themes, formulation strategies, and research trends. Their scope, however, is either broader than botanical pesticides, restricted to particular formulations, target-pest groups, crops, or regions, or primarily concerned with scientific production and conceptual structure. Comparable bibliometric work has therefore not established whether increasing scientific attention to botanical pesticides has produced an integrated evidence base connecting economic viability, farmer adoption and continued use, regulatory readiness, and demonstrated commercialization or scaling.

Bibliometric studies in related fields have documented the growing integration of agricultural productivity with environmental sustainability, economic analysis, agroecology, ecosystem services, and institutional governance [31]. For example, Fazli et al. [32] identified a shift in agrochemical research toward environmental management, green-economy perspectives, and stronger integration of economic and ecological concerns. Related studies have mapped the convergence of agricultural economics with environmental sustainability, the movement of IPM toward agroecological and climate-responsive perspectives, and the growing importance of governance and resilient supply chains in agribusiness systems [32–34]. However, these studies address broader domains such as agrochemicals, agricultural economics, IPM, and agribusiness governance rather than the specific translational development of botanical pesticides [3, 35]. Consequently, they do not establish whether the expansion of botanical pesticide research has been accompanied by corresponding advances in economic evaluation, farmer adoption, regulatory readiness, and commercial scaling.

A bibliometric approach is particularly relevant to this question because botanical pesticide research spans multiple disciplines, geographic settings, terminologies, and analytical traditions [36]. Bibliometric analysis can reveal publication growth, influential contributions, geographic leadership, collaboration structures, conceptual relationships, and thematic change [37]. It can therefore show whether the field has remained concentrated on technical efficacy or has progressively incorporated economic, behavioral, regulatory, and commercial concerns. A conventional narrative review cannot as readily demonstrate how these dimensions are positioned within the structure and temporal development of the research field. Nevertheless, bibliometric patterns alone cannot determine whether individual publications contain substantive evidence of profitability, affordability, farmer use, market development, or institutional readiness. High publication frequency or keyword prominence does not necessarily indicate that implementation-oriented evidence is sufficiently developed. What remains missing is an integrated assessment linking the bibliometric evolution of botanical pesticide research with article-level evidence on whether technical advances have been accompanied by economic evaluation, farmer adoption, regulatory readiness, and commercial scaling.

Accordingly, this study combines bibliometric performance analysis, science mapping, and systematic evidence mapping to examine the development and translational orientation of botanical pesticide research. The specific contribution is threefold. First, the study maps how the field has developed conceptually and whether research attention has shifted beyond technical efficacy toward economic, behavioral, regulatory, and commercial concerns. Second, it distinguishes the visibility of these concerns in bibliometric networks from the presence of substantive article-level evidence. Third, it evaluates how economic viability, farmer adoption and use, commercialization and scaling, and regulation and institutional support overlap and where evidence narrows along the pathway from technical development to wider implementation. Unlike previous reviews that

primarily synthesize technical performance, particular translational constraints, or field-level publication patterns, this study integrates field-level bibliometric structures with conservative article-level evidence coding. It therefore identifies not only how botanical pesticide research has evolved, but also whether the literature provides connected evidence for transforming technically promising plant-derived pest-control options into accessible, repeatedly used, appropriately regulated, and commercially sustainable agricultural practices.

2. Methods

2.1. Study Design and Analytical Framework

This study combined bibliometric performance analysis, science mapping, and systematic evidence mapping to examine the development, conceptual structure, and translational evidence base of botanical pesticide research. Bibliometric performance analysis was used to characterize publication growth, citation influence, geographic participation, institutional contributions, and international collaboration, whereas science mapping was used to examine relationships among countries, publications, and research concepts. These complementary approaches are appropriate for identifying the major contributors, intellectual organization, conceptual structure, and temporal development of a research field [38–40].

Systematic evidence mapping was conducted primarily from titles, abstracts, and keywords and was supplemented by targeted full-text verification. Unlike effect-focused systematic reviews, evidence maps categorize and organize a heterogeneous literature to identify evidence concentrations, patterns, and gaps across predefined dimension [41–43]. Four non-mutually exclusive evidence domains were examined: economic viability, farmer adoption and use, commercialization and scaling, and regulation and institutional support.

The evidence was subsequently organized into six analytical stages: technical development and bioefficacy, field validation, economic evaluation, farmer adoption and use, regulation and institutional support, and commercialization and scaling. Articles could contribute to multiple domains and stages. The pathway was therefore used to compare evidence coverage rather than to represent a strictly linear innovation process.

2.2. Data Source and Search Strategy

Bibliographic records were retrieved exclusively from Scopus on 8 October 2026. Scopus was selected because it provides curated bibliographic and citation records together with consistently structured author, affiliation, country, keyword, cited-reference, and citation metadata required for performance analysis and network construction [44, 45]. Both Scopus and Web of Science are established sources for bibliometric research, but their journal coverage, subject representation, and indexing structures differ. Comparative studies indicate that Web of Science applies more selective journal coverage, whereas Scopus covers a broader range of indexed journals, including substantial coverage of journals also indexed in Web of Science [46, 47]. This broader coverage was considered appropriate because botanical pesticide research spans crop protection, agricultural science, environmental sustainability, economics, and regionally oriented agricultural research. Comparative research has also shown that Scopus provides relatively complete affiliation and country information, which was particularly important for the country-, institution-, and collaboration-level analyses conducted in this study [48].

A single database was retained to preserve consistency in document classification, citation indexing, affiliation records, cited-reference data, and network construction. Combining records from Scopus and Web of Science would have required cross-database deduplication and metadata harmonization before the bibliometric analyses. Nevertheless, the use of Scopus alone limits the comprehensiveness of the review because publications indexed exclusively in Web of Science or other bibliographic databases, as well as non-indexed regional literature, may have been excluded. The findings should therefore be interpreted as a structured representation of the Scopus-indexed literature rather than an exhaustive account of all research on the economics, adoption, and commercialization of botanical pesticides.

An initial all-fields search was conducted to assess the breadth of the literature and returned 9,986 records. This exploratory search was not subjected to eligibility screening. The formal search was subsequently restricted to titles, abstracts, and keywords to improve topical specificity and reproducibility. The TITLE-ABS-KEY field searches the principal topical metadata of Scopus records, including titles, abstracts, and keyword fields.

The search query combined terminology describing botanical pesticides and related plant-derived pest-control products with terms representing economic viability, farmer adoption, commercialization, markets, scaling, regulation, policy, and extension. Multiple botanical-pesticide variants were included because the literature uses overlapping terms such as *botanical pesticides*, *botanical insecticides*, *pesticidal plants*, *plant-derived pesticides*, and *plant-based biopesticides*. The translational terms were included to identify publications

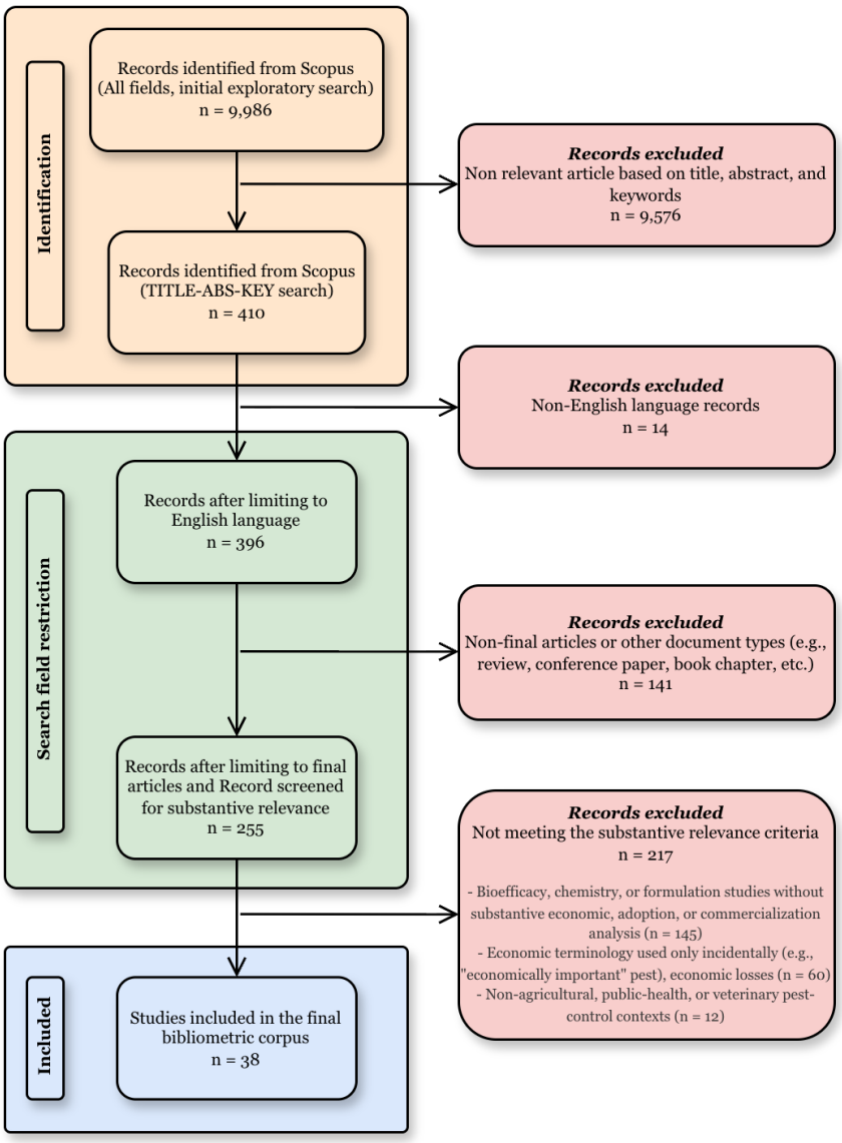


Figure 1. Search refinement, substantive-relevance screening, and study-selection process.
Note: The initial all-fields search was exploratory and was not included in eligibility screening.

in which relevant evidence was reported through economic, behavioral, commercial, or institutional concepts.

The formal Scopus query was: ("botanical pesticide*" OR "botanical insecticide*" OR "plant-based pesticide*" OR "plant based pesticide*" OR "plant-derived pesticide*" OR "plant derived pesticide*" OR "plant-derived insecticide*" OR "plant derived insecticide*" OR "plant-origin pesticide*" OR "plant origin pesticide*" OR "pesticidal plant*" OR "botanical biopesticide*" OR "plant-based biopesticide*" OR "plant based biopesticide*") AND (econom* OR socioeconomic* OR "socio-economic*" OR "economic viability" OR "economic feasibility" OR "economic evaluation" OR "economic performance" OR "economic benefit*" OR "economic impact*" OR "cost effectiveness" OR "cost-effectiveness" OR "cost benefit*" OR "cost-benefit*" OR profitab* OR affordab* OR "farm income" OR "farmer income" OR livelihood* OR "farmer adoption" OR "technology adoption" OR "adoption intention*" OR "adoption decision*" OR "willingness to adopt" OR "willingness to pay" OR commerciali* OR marketability OR "market development" OR "market potential" OR agribusiness OR "value chain*" OR scalability OR "scaling up" OR "regulatory barrier*" OR "market barrier*" OR "adoption barrier*" OR "policy support" OR "extension service*")).

The formal search returned 410 records. Limiting the results to English-language publications reduced the dataset to 396 records. Records were then restricted to documents indexed as articles and assigned final publication status, resulting in 255 records for substantive-relevance screening. No publication-year restriction was applied.

The search strategy was intentionally inclusive because terminology relating to economic relevance, adoption, commercialization, and regulation was not consistently applied across the literature. Accordingly, topical precision was established through substantive screening rather than through extensive exclusion terms in the search query.

2.3. Eligibility Criteria and Study Selection

Articles were eligible when they addressed botanical pesticides or other plant-derived products used in agricultural pest management and provided substantive evidence on at least one of the following dimensions: economic viability, farmer adoption or use, commercialization or scaling, or regulation and institutional support. Eligible agricultural contexts included crop production, plant protection, stored-product pest management, and other operational settings related to agricultural production.

Articles evaluating bioefficacy or field performance were retained only when they also reported a relevant translational dimension, such as costs, benefit-cost ratios, financial returns, farmer behavior, product development, market conditions, or regulatory issues. Publications with review- or strategy-oriented content were eligible when indexed by Scopus as articles and when they provided a detailed synthesis of at least one evidence domain.

Records were excluded if they:

1. focused exclusively on toxicity, mortality, repellency, phytochemistry, extraction, formulation, or bioefficacy without substantive economic, adoption, commercialization, or regulatory analysis;
2. used economic terminology only incidentally, such as *economically important pest*, *economic damage*, or *economic losses*, without evaluating economic outcomes or translational processes;
3. addressed public-health, veterinary, household, or other non-agricultural pest-control contexts;
4. focused solely on non-botanical pest-control agents without separately interpretable evidence on plant-derived products;
5. were not written in English; or
6. were not indexed as final journal articles.

The 255 records were screened using titles, abstracts, and keywords against the predefined substantive-relevance criteria. Records with unclear relevance were reassessed by comparing their stated objectives, methods, and reported outcomes with the eligibility criteria. Screening was conducted against predefined eligibility criteria to maintain a transparent and reproducible connection between the research questions, the retrieved records, and the final analytical corpus. This structured approach is consistent with evidence-mapping methodology, in which broad searches are followed by systematic relevance screening and categorical data extraction [42].

Of the 255 records screened, 217 were excluded. These comprised 145 records focused on bioefficacy, chemistry, or formulation without substantive translational analysis; 60 records in which economic terminology was used only incidentally; and 12 records addressing non-agricultural, public-health, or veterinary contexts. The final bibliometric corpus comprised 38 articles. The search refinement and study-selection process is summarized in Figure 1.

2.4. Data Extraction and Bibliographic Standardization

The final records were exported from Scopus in CSV format. The extracted metadata included authors, publication year, document title, abstract, source title, DOI, author affiliations, corresponding-author information, author keywords, index keywords, citation counts, and cited references. The records were examined for incomplete metadata, bibliographic duplication, and inconsistent terminology before analysis. Data cleaning and standardization are important in bibliometric research because unresolved variations in names, affiliations, and keywords can fragment conceptually identical items and alter network structures [38, 39].

Country names and institutional affiliations were reviewed for spelling and naming variants. Geographic production was examined using three complementary units: country occurrences across author affiliations, corresponding-author countries, and country-level documents in the co-authorship network. These measures were not treated as interchangeable because they represented overall participation, publication leadership, and network involvement, respectively.

Author keywords were standardized using a thesaurus developed from an exploratory co-occurrence analysis with a minimum threshold of one occurrence. The standardization corrected spelling and encoding errors and merged singular-plural forms, synonymous expressions, and equivalent technical terms. Conceptually related but non-equivalent terms were retained separately to avoid collapsing distinct analytical concepts. Such normalization is particularly consequential in co-word analysis because keyword co-occurrences are used to represent the conceptual relationships and thematic organization of a research field [39].

Conceptually related but non-equivalent terms were retained separately. These included *bioefficacy* and *efficacy*; *economics* and *cost-benefit analysis*; *pest control*, *pest management*, and IPM; and *farmer adoption*, *farmer knowledge*, and *farmer perceptions*.

The geographic descriptor *Africa* was excluded from the final author-keyword network because it represented a study location rather than a substantive research concept. The broader term *pesticides* was retained because it provided a conceptually valid connection between botanical products and the wider pesticide literature.

2.5. Bibliometric Performance and Science-Mapping Analyses

Bibliometric performance analysis and thematic mapping were conducted using the bibliometrix package and its Biblioshiny interface, version 5.0, in R version 4.5.2. bibliometrix provides an integrated workflow for importing bibliographic records, calculating performance indicators, constructing bibliographic networks, and examining the conceptual, intellectual, and social structures of a research field [49]. Network and temporal-overlay visualizations were generated using VOSviewer version 1.6.20, software developed for constructing and visually representing bibliometric networks [50].

Performance indicators included annual scientific production, publication growth, citation patterns, influential publications, source contributions, country participation, corresponding-author countries, institutional affiliations, and international collaboration. Performance analysis describes the contributions and influence of research constituents, whereas science mapping examines relationships among those constituents and the structure of the knowledge domain [38]. Citation counts were treated as a snapshot of the Scopus records retrieved on 8 October 2026 rather than as fixed measures of long-term influence.

Country collaboration was additionally evaluated using single-country publications and multiple-country publications. A single-country publication contained authors affiliated exclusively with institutions in one country, whereas a multiple-country publication involved affiliations from more than one country.

2.5.1. Country Co-authorship Analysis

International collaboration was examined in VOSviewer using country co-authorship analysis and full counting. Co-authorship analysis represents the social structure of a research field by identifying collaboration relationships among authors, institutions, or countries, while full counting assigns full weight to each participating unit in a publication [38, 39].

The minimum thresholds were one document and zero citations per country. Twenty-three countries met the thresholds. The final visualization was restricted to the largest connected component, which consisted of 13 countries. The connected network comprised four clusters, 23 links, and a total link strength of 35.

Node size represented the number of documents associated with each country, links represented international co-authorship relationships, and total link strength measured the aggregate strength of each country's collaborative connections. Cluster membership was generated using the VOSviewer clustering procedure. VOSviewer is designed to construct and display bibliometric maps in which node size, relational proximity, links, and clusters facilitate interpretation of the structure of bibliographic networks [50].

2.5.2. Author-Keyword Co-occurrence and Temporal Analysis

The conceptual structure was examined through author-keyword co-occurrence analysis in VOSviewer using full counting. Co-word analysis assumes that terms appearing together within publications reflect conceptual relationships and can therefore be used to identify major topics and the organization of a research domain [39].

An exploratory analysis with a minimum threshold of one occurrence was initially conducted to inventory keyword variants and construct the thesaurus. Following thesaurus-based standardization and removal of the geographic descriptor *Africa*, 113 author keywords were retained. The final analysis used a minimum threshold of two occurrences. This threshold reduced the influence of article-specific keywords while retaining concepts that recurred across the focused 38-article corpus.

Twenty-one keywords met the threshold, and all formed a single connected network. The resulting network comprised five clusters, 52 links, and a total link strength of 69. In the network visualization, node size represented keyword occurrence, link thickness reflected co-occurrence strength, and node color represented cluster membership. A temporal overlay was generated from the same network using the average publication year of documents containing each keyword. Overlay visualization in VOSviewer enables network items to be displayed according to an attribute such as publication year, thereby supporting interpretation of the temporal positioning of concepts within a common network structure [50].

2.5.3. Thematic-Map Analysis

A thematic map was generated in Biblioshiny using standardized author keywords. The thematic-map procedure begins with a keyword co-occurrence network and positions thematic clusters according to their centrality and density, enabling comparison of their relevance to the overall field and their internal development [49, 51].

The analysis included up to 50 terms, applied association normalization, and used the Walktrap clustering algorithm. The minimum cluster frequency was set to one, and two labels were displayed per thematic cluster. Stemming was disabled because spelling variants and synonymous expressions had already been standardized, and predefined synonym and stop-word lists were applied.

Themes were positioned according to Callon centrality and Callon density. Centrality represented the extent of a theme's connections with other themes in the field, whereas density represented the strength of relationships within the theme. The resulting quadrants were interpreted as motor themes, basic themes, niche themes, and emerging or declining themes [51]. Themes with low cluster frequencies were interpreted cautiously because their positions could be sensitive to the focused corpus size and clustering parameters.

2.6. Systematic Evidence Mapping

Systematic evidence mapping was conducted to characterize the presence, distribution, and integration of translational evidence within the 38 articles. Evidence mapping is appropriate for broad and heterogeneous research questions because it organizes the available literature into predefined categories and identifies evidence concentrations and gaps without necessarily estimating pooled intervention effects [41, 42].

Four non-mutually exclusive evidence domains were defined: (1) ECO: economic viability; (2) ADO: farmer adoption and use; (3) COM: commercialization and scaling; and (4) REG: regulation and institutional support.

Economic evidence included explicit empirical analysis or detailed synthesis of treatment and production costs, financial returns, profitability, affordability, marketable yield, yield-related economic benefits, livelihood outcomes, or comparisons with alternative pest-management approaches. Adoption evidence included farmer knowledge, perceptions, preferences, stated willingness, actual or reported use, willingness to pay, adoption determinants, accessibility, training, and extension support. Commercialization evidence included product development, demonstrated or prospective market entry, processing, trade, value chains, private-sector participation, patents, production capacity, distribution, and scaling. Regulatory and institutional evidence included product registration, efficacy and safety documentation, standardization, quality control, formulation stability, policy support, extension systems, institutional coordination, and public-private collaboration.

Coding was based initially on article titles, abstracts, author keywords, and index keywords and was supplemented by targeted full-text verification. Each domain was assigned one of three evidence levels:

- Yes: substantive evidence, defined as explicit empirical analysis or detailed review-based synthesis within the relevant domain;
- Partial: partial or contextual evidence for which article-specific analysis, disaggregated findings, or implementation outcomes were incomplete; or
- No: no substantive evidence within the relevant domain.

The coding was multi-label, allowing each article to contribute to more than one domain. Classification rules were deliberately conservative. Descriptions of botanical pesticides as *economical* or *cost-effective* without supporting analysis were not automatically classified as substantive economic evidence. Recommendations that a technology *should be adopted* were not treated as adoption evidence. The use of a commercially available formulation as an experimental treatment was not interpreted as evidence of commercialization, and brief references to regulatory importance were insufficient for substantive regulatory classification.

Farmer knowledge, preferences, willingness, initial use, reported use, and sustained adoption were treated as distinct outcomes. Similarly, prospective commercial potential was distinguished from demonstrated commercialization involving actual market entry, established value chains, sales, or sustained business performance. This distinction was necessary to avoid interpreting favorable perceptions or prospective opportunities as evidence of continued farmer use or verified commercial performance.

Full texts were selectively examined when abstracts and bibliographic metadata did not provide sufficient information for definitive classification and when publications were central to the adoption, commercialization, regulatory, or multidomain evidence base. Priority was given to articles with ambiguous classifications, coverage of several evidence domains, or translation-oriented analyses that could not be evaluated adequately from abstracts alone. Eleven priority articles

were verified using full texts. Two unavailable publications, Gahukar [52] and Suji & Kumar [53], were retained as abstract-only records and were not used as principal sources for detailed claims that could not be verified from their abstracts.

The evidence map was designed to characterize evidence coverage and integration rather than to estimate pooled intervention effects or rank articles according to methodological quality. Evidence-mapping guidance distinguishes this broad descriptive purpose from effect-focused systematic reviews and indicates that formal critical appraisal is particularly important when evidence is categorized by effect direction or intended to support subsequent effect synthesis [41, 42]. Accordingly, no meta-analysis or formal risk-of-bias assessment was performed.

2.7. Innovation-to-Adoption Pathway Analysis

The systematic evidence map was extended into an innovation-to-adoption pathway to examine how evidence was distributed from technical development to wider agricultural implementation. Consistent with the purpose of evidence mapping, the pathway was used to organize heterogeneous evidence and identify stages in which coverage was concentrated or limited, rather than to test a causal or strictly sequential model of innovation [42].

Six analytical stages were defined: (1) TECH: technical development and bioefficacy; (2) FIELD: field validation; (3) ECO: economic evaluation; (4) ADO: farmer adoption and use; (5) REG: regulation and institutional support; and (6) COM: commercialization and scaling.

TECH included botanical-material characterization, identification of active materials, extraction, formulation, biological efficacy, target-pest suppression, mode of action, and related technical validation. FIELD included evaluations conducted under field, on-farm, crop-production, farmer-managed, participatory, stored-product, or other operational agricultural conditions. Laboratory-only studies were not classified as field validation. Detailed review-based syntheses were classified as substantive field evidence only when they explicitly synthesized evidence from agricultural or operational settings rather than merely recommending that field validation should be conducted.

ECO, ADO, REG, and COM followed the operational definitions established in the systematic evidence mapping. Economic evaluation therefore required explicit analysis or detailed synthesis of costs, returns, profitability, affordability, or related economic outcomes. Adoption covered knowledge, preferences, willingness, actual or reported use, and adoption determinants, while preserving the distinction between intention, initial use, and sustained adoption. Regulation and institutional support covered registration, standards, quality assurance, policy, extension systems, and institutional coordination. Commercialization and scaling covered product development, processing, markets, value chains, private-sector participation, production scale, and verified or prospective commercial activity.

Each stage was classified as substantive, partial or contextual, or absent, following the same decision rules applied in Section 2.6. Articles could contribute to several stages because technical development, field validation, economic analysis, farmer research, and market or regulatory assessment could occur within the same publication. Conversely, an article could address a later stage without substantively examining all preceding stages.

The pathway was therefore treated as a non-linear analytical framework rather than a sequential attrition funnel. Counts at each stage represented the number of articles providing evidence on that stage and were not interpreted as the number of innovations successfully progressing through a development pipeline. A higher article count was also not treated as evidence of greater methodological quality, technical maturity, adoption success, regulatory preparedness, or commercial readiness.

Substantive evidence counts were used as the principal measure of pathway coverage. Articles containing partial or contextual evidence were retained as a separate category to show additional domain relevance without equating incomplete discussion with substantive analysis. This separation allowed the pathway analysis to identify where the literature moved beyond technical and field evaluation and where evidence became more limited at stages requiring farmer behavior, institutional coordination, regulatory processes, and functioning supply and market systems.

2.8. Data Visualization and Reporting

Descriptive tables and figures were used to report publication, citation, geographic, institutional, and thematic patterns. VOSviewer was used for country co-authorship, author-keyword co-occurrence, and temporal-overlay visualizations, while Biblioshiny was used to generate the thematic map [49, 50].

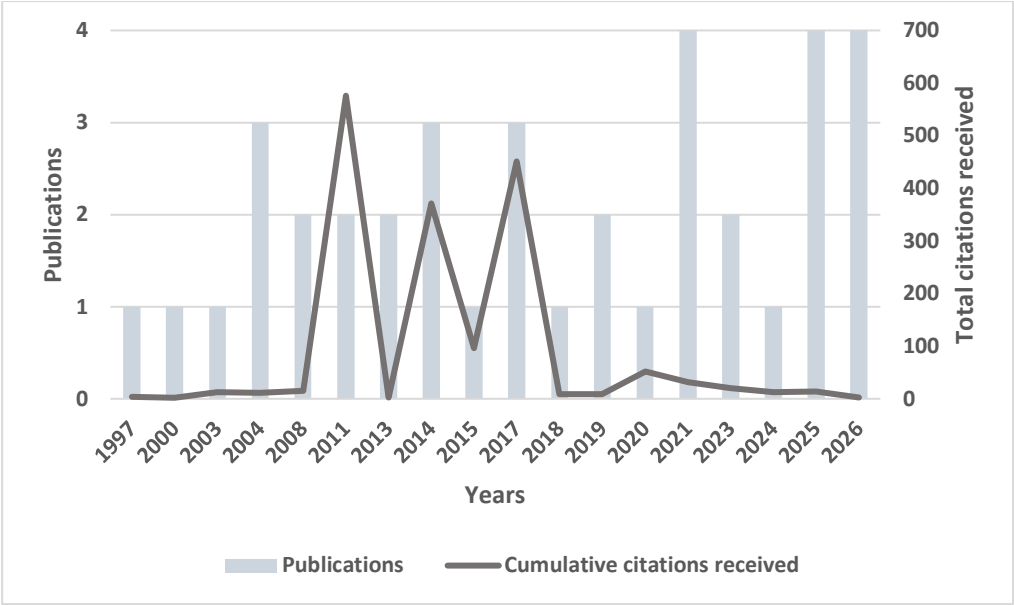


Figure 2. Annual publication output and total citations received by publication year.
Note: Citations are cumulative as of October 2026; the 2026 publication count includes records indexed up to that date.

An UpSet plot was used to display substantive evidence intersections among ECO, ADO, COM, and REG. UpSet represents sets and their intersections through a matrix-based layout and was selected because it communicates the size and composition of multiple overlapping intersections more clearly than a conventional Venn diagram when categories are non-mutually exclusive [54]. Articles containing only partial or contextual evidence were included in domain totals but excluded from substantive intersections.

A horizontal stacked bar chart was used to compare substantive and partial or contextual evidence across the six innovation-to-adoption stages. All percentages were calculated using the final corpus of 38 articles as the denominator. Because domain and stage coding was multi-label, percentages were not expected to sum to 100%.

3. Results

3.1. Growth and Evolution of the Research Field

The 38 articles included in the final corpus were published between 1997 and 2026. As shown in Figure 2, publication activity was initially sporadic, with only one to three articles published in individual years and several years without eligible publications. Research output became more sustained during the recent period, reaching four articles in 2021, 2025, and 2026. Overall, 23 articles, representing 60.5% of the corpus, were published between 2018 and 2026. This distribution indicates increasing scholarly attention to the economic, adoption, and commercialization dimensions of botanical pesticides.

Citation impact was more strongly concentrated than publication output. As illustrated in Figure 2, articles published in 2011 received the highest cumulative number of citations, with 576 citations, followed by articles published in 2017 with 451 citations and those published in 2014 with 371 citations. Together, articles from these three publication years accumulated 1,398 citations, accounting for 82.6% of the 1,693 citations received by the entire corpus. Thus, although publication activity has recently increased, the citation profile of the field remains dominated by a relatively small group of earlier contributions.

Articles published in 2025 and 2026 had accumulated 14 and 3 citations, respectively. These lower citation counts should be interpreted in relation to their shorter citation windows rather than as evidence of limited scholarly influence. Moreover, the 2026 publication count represents only the records indexed up to the data-extraction date. Overall, the temporal pattern indicates a research field with increasing publication activity but a citation structure that remains concentrated in several foundational publication years.

3.2. Influential Publications and Knowledge Foundations

The 38 articles were distributed across multiple publication outlets, reflecting the interdisciplinary character of research on the economic, adoption, and commercialization dimensions of botanical pesticides. *Pestology* published the largest number of articles, with five publications, while *Food Security* and *Industrial Crops and Products* contributed three articles each. Several journals contributed two articles, including

Table 1. Most influential publications on the economics, adoption, and commercialization of botanical pesticides.

Rank	Publication	Source	GC	LC	TC/year	Principal contribution
1	Isman et al. [29], Commercial opportunities for pesticides based on plant essential oils in agriculture, industry and consumer products	*Phytochemistry Reviews*	491	1	30.69	Assessed the commercial potential, product development, and market opportunities of essential-oil-based pesticides.
2	Stevenson et al. [9], Pesticidal plants in Africa: A global vision of new biological control products from local uses	*Industrial Crops and Products*	210	4	21	Connected locally used pesticidal plants with product development, regulatory change, and wider biological-control markets.
3	Isman [13], Bridging the gap: Moving botanical insecticides from the laboratory to the farm	*Industrial Crops and Products*	187	1	18.7	Identified the barriers preventing promising laboratory findings from becoming reliable and accessible farm-level technologies.
4	Sola et al. [24], Botanical pesticide production, trade and regulatory mechanisms in sub-Saharan Africa: Making a case for plant-based pesticidal products	*Food Security*	125	4	9.62	Examined production, trade, registration, and regulatory conditions affecting botanical pesticide development in sub-Saharan Africa.
5	Grzywacz et al. [8], The use of indigenous ecological resources for pest control in Africa	*Food Security*	123	4	9.46	Positioned indigenous pest-control resources within accessible, locally grounded, and economically sustainable agricultural systems.
6	Amoabeng et al. [15], Cost: Benefit analysis of botanical insecticide use in cabbage: Implications for smallholder farmers in developing countries	*Crop Protection*	123	6	9.46	Provided direct cost-benefit evidence on botanical insecticide use and its economic implications for smallholder farmers.
7	Mkenda et al. [55], Extracts from field margin weeds provide economically viable and environmentally benign pest control compared to synthetic pesticides	*PLOS ONE*	96	3	8	Combined field efficacy, economic viability, and effects on beneficial organisms in comparison with synthetic pesticides.
8	Kamanula et al. [19], Farmers' insect pest management practices and pesticidal plant use in the protection of stored maize and beans in Southern Africa	*International Journal of Pest Management*	85	3	5.31	Documented farmer practices, knowledge, and the use of locally available pesticidal plants for stored-product protection.
9	Mkindi et al. [56], Invasive weeds with pesticidal properties as potential new crops	*Industrial Crops and Products*	54	3	5.4	Explored field-tested pesticidal weeds as potential crop-protection products and new income-generating crops.
10	Houngbo et al. [57], Farmers' knowledge and management practices of fall armyworm in Benin, West Africa	*Agriculture*	52	0	7.43	Analyzed farmers' knowledge, perceived crop losses, and pest-management practices, including the use of plant-based control options.

Note: GC = global Scopus citations; LC = citations within the 38-article corpus; TC/year = annualized global citations. Citation data were retrieved in October 2026.

Agriculture, *Indian Journal of Agricultural Sciences*, *International Journal of Pest Management*, *Journal of Biopesticides*, *Journal of Entomological Research*, and *PLOS ONE*. The absence of a single dominant publication outlet indicates that the field remains distributed across crop protection, agricultural science, food security, industrial crops, and sustainability-oriented literature.

The most influential publications reveal the principal contributions that have shaped the development of the field (Table 1). Isman et al. [29] recorded the highest global citation count, with 491 citations and an annualized citation rate of 30.69 citations per year. The study examined commercial opportunities associated with essential-oil-based pesticides and therefore provided an early connection between botanical pesticide research, product development, and market potential. It was followed by Stevenson et al. [9], with 210 global citations, and Isman [13], with 187. These publications expanded the discussion from botanical pesticide efficacy toward the conversion of locally used pesticidal plants into biological-control products and the translation of promising laboratory findings into practical farm-level applications.

Global and local citation patterns nevertheless reflected different forms of scholarly influence. Although Isman et al. [29] dominated the global citation ranking, the publication received only one citation from articles within the final corpus. In contrast, Amoabeng et al. [15] received six local citations, the highest local citation count among the included publications. Its centrality within the corpus reflects the direct relevance of cost-benefit assessment to the specialized literature on botanical pesticide economics. Stevenson et al. [9], Sola et al. [24], and Grzywacz et al. [8] each received four local citations, confirming the importance of locally available pesticidal plants, indigenous ecological resources, production and trade systems, and regulatory mechanisms within the internal knowledge structure of the field. Mkenda et al. [55], Mkindi et al. [56], and Kamanula et al. [19] also occupied influential positions by connecting field performance with economic viability, potential product development, and farmer practices.

These differences indicate that broad global influence has been led primarily by conceptual publications addressing botanical insecticides, commercial opportunities, and laboratory-to-farm translation. Influence within the specialized corpus, however, was more closely associated with cost-benefit evidence, smallholder applicability, indigenous knowledge, farmer practices, and the institutional conditions required for production and regulation. Accordingly, global citation counts and local citations provide complementary perspectives: the former indicate visibility across the broader scholarly literature, whereas the latter reveal the publications most frequently used to develop the focused research domain examined in this study.

Reference co-citation analysis was subsequently conducted to identify the intellectual foundations connecting these contributions. As displayed in Figure 3, 28 cited references met the minimum threshold of two citations, of which 25 formed the largest connected component. Following the standardization of duplicate reference variants, the network comprised three clusters, 166 links, and a total link strength of 243. The three clusters represented interconnected foundations related to scientific validation and translational constraints, ethnobotanical knowledge and smallholder-oriented utilization, and field implementation and agroecological integration.

Cluster 1, comprising ten references, represented scientific validation, efficacy variability, and translational constraints. The cluster incorporated research addressing limitations in the available evidence on botanical insecticides, variation in pesticidal efficacy, phytochemical and chemotypic differences, transitions toward safer pest management, and the production and regulatory conditions required for practical deployment. The reference examining distinct chemotypes of *Tephrosia vogelii* had the highest total link strength within this cluster, demonstrating the centrality of chemical consistency and standardization to the development of reliable botanical pesticide products. The cluster therefore indicates that translation beyond laboratory bioefficacy depends on the reproducibility of active materials, the reliability of efficacy evidence, and the institutional mechanisms supporting product development.

Cluster 2 contained nine references and represented ethnobotanical knowledge and smallholder-oriented utilization. The cluster connected ethnobotanical surveys, participatory evaluation, farmer criteria, phytochemical research, income generation, and the use of locally available plant materials in crop protection. The strong connectivity of research on tri-trophic insecticidal effects further demonstrated the relationship between biological validation and the practical use of pesticidal plants. Nevertheless, the reference specifically addressing the costs and benefits of botanical insecticides had relatively limited network connectivity. This position suggests that formal economic evaluation has entered the knowledge base but remains less integrated than research concerning ethnobotanical resources, biological efficacy, and smallholder-oriented use.

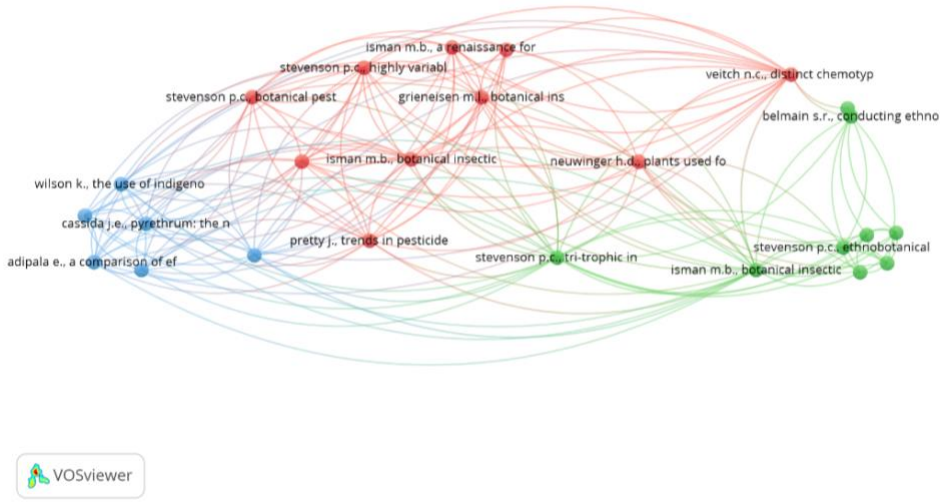


Figure 3. Co-citation network of the intellectual foundations of botanical pesticide economics, adoption, and commercialization research. Note: Node size indicates citations, line thickness indicates co-citation strength, and colors indicate VOSviewer clusters. The network includes 25 references in the largest connected component.

Cluster 3, consisting of six references, represented field implementation and agroecological integration. Its knowledge base linked comparisons between botanical and synthetic insecticides with crop diversification, ecological intensification, field-level pest control, and the utilization of indigenous ecological resources. Research on crop diversification exhibited strong connectivity within this cluster, indicating that botanical pesticide implementation has frequently been situated within broader agroecological pest-management strategies rather than examined as a stand-alone technological intervention.

Across the entire network, the review of botanical insecticides in modern and increasingly regulated agriculture occupied the most central position, receiving six citations within the corpus and attaining 23 links with a total link strength of 36. This centrality reflects the continuing importance of integrating technical efficacy with safety, regulation, and practical agricultural use. Overall, the co-citation structure demonstrates that the intellectual foundation of the field has developed through close relationships among scientific validation, locally grounded knowledge, and field implementation. Formal economic evaluation, market development, and commercialization-oriented evidence, however, remained comparatively peripheral within the network.

3.3. Geographic Distribution and Collaboration Landscape

Geographic participation in the literature was concentrated in Asia, Africa, and the United Kingdom. Based on country occurrences across author affiliations, India recorded the highest frequency, with 26 occurrences, followed by the United Kingdom with 19 and Pakistan with 10. Benin, Malawi, and Tanzania each recorded seven occurrences, while Bangladesh and China each recorded six. These values represent the frequency with which countries appeared across author affiliations rather than the number of unique publications. Nevertheless, the distribution demonstrates the substantial representation of countries where botanical pesticides are particularly relevant to smallholder farming, locally available plant resources, and agricultural pest-management needs.

Publication leadership differed from overall representation in author affiliations, as shown in Table 2. India was the corresponding-author country for five articles, accounting for 13.2% of the final corpus, while Pakistan and the United Kingdom each led three articles. All articles led by India and Pakistan were single-country publications, whereas all three articles led by the United Kingdom involved international co-authorship. Bangladesh and China each led two multiple-country publications, while both articles led by Benin were produced domestically. These patterns demonstrate that high research participation did not necessarily correspond with strong international connectivity. Some countries primarily developed nationally organized research, whereas others participated more extensively in cross-country knowledge production.

Country co-authorship analysis further revealed the difference between geographic participation and international connectivity. At the minimum threshold of one document and zero citations, 23 countries were

Table 2. Leading countries and international collaboration indicators.

Country	Affiliation Occurrences	Corresponding-Author Articles	SCP	MCP	Network Documents	Links	Total Link Strength	Citations
United Kingdom	19	3	0	3	9	9	17	834
India	26	5	5	0	NC	NC	NC	NC
Pakistan	10	3	3	0	5	2	3	24
Tanzania	7	NR	NR	NR	6	6	12	433
Malawi	7	NR	NR	NR	3	4	8	264
China	6	2	0	2	3	5	6	146
Benin	7	2	2	0	NC	NC	NC	NC
Bangladesh	6	2	0	2	NC	NC	NC	NC
Canada	4	1	0	1	3	2	2	888
Kenya	3	NR	NR	NR	2	4	6	140

Note: Affiliation occurrences indicate country frequency across author affiliations. SCP = single-country publications; MCP = multiple-country publications; NR = not reported; NC = not included in the largest connected network component.

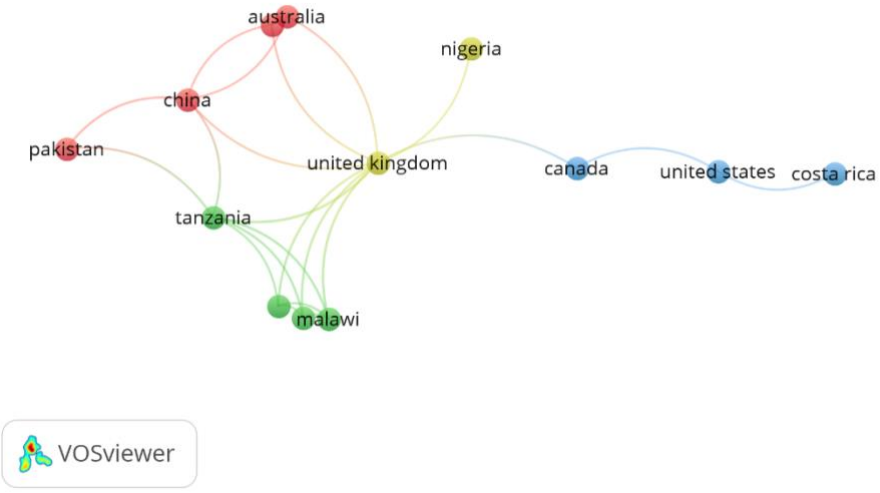


Figure 4. International country co-authorship network in botanical pesticide economics, adoption, and commercialization research. Note: Node size indicates documents, line thickness indicates collaboration strength, and colors indicate VOSviewer clusters. The visualization includes 13 countries in the largest connected component.

identified. As illustrated in Figure 4, 13 countries, representing 56.5% of the identified countries, formed the largest connected component, while the remaining 10 countries were disconnected from the principal collaboration network. The connected component comprised four clusters, 23 links, and a total link strength of 35. Thus, the geographic reach of the literature was broader than its international collaboration structure, with 43.5% of participating countries remaining outside the principal connected component captured by the corpus.

The United Kingdom occupied the most central position in the network, contributing nine documents and establishing nine links with a total link strength of 17. Its central position in Figure 4 indicates a bridging role across several regional collaboration groups. Tanzania was the second most connected country, with six documents, six links, and a total link strength of 12. Malawi followed with four links and a total link strength of eight, while China and Kenya each attained a total link strength of six. These findings identify the United Kingdom as the principal international collaboration hub, while Tanzania served as an important connector within the East and Southern African research network.

The four network clusters demonstrated a geographically differentiated collaboration structure. Cluster 1 connected Australia, China, Ghana, and Pakistan. Cluster 2 comprised Kenya, Malawi, Tanzania, and Zimbabwe, forming a distinct East and Southern African collaboration group. Cluster 3 linked Canada, Costa Rica, and the United States, whereas Cluster 4 consisted of Nigeria and the United Kingdom. Although these clusters displayed regional concentration, several cross-cluster relationships were visible, particularly through the United Kingdom and Tanzania. International knowledge production was therefore organized around a limited

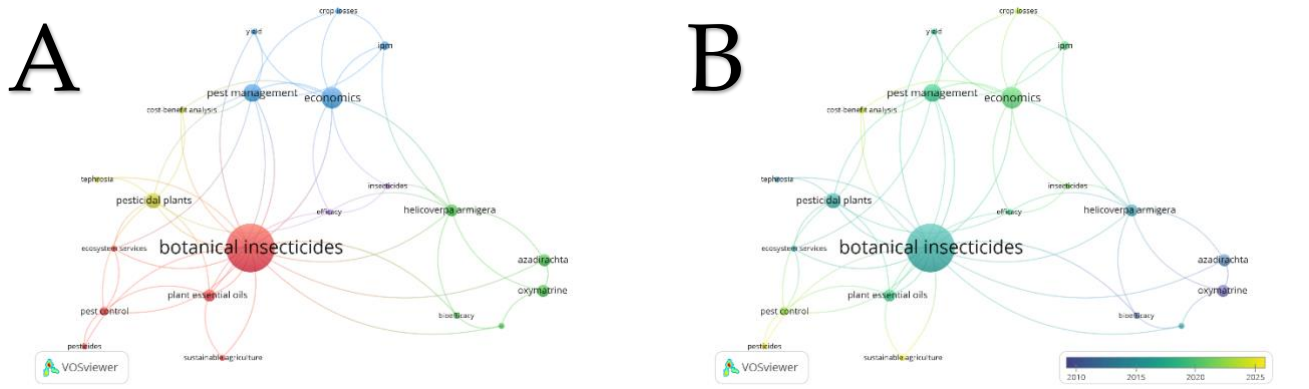


Figure 5. Author-keyword structure and temporal development. (A) Co-occurrence network and keyword clusters. (B) Temporal overlay based on average publication year.
Note: In Panel A, node size indicates keyword occurrence, line thickness indicates co-occurrence strength, and colors indicate clusters. In Panel B, colors indicate the average publication year.

number of bridging countries rather than being distributed evenly among all contributors.

Institutional participation was similarly distributed across several regions. The University of Greenwich was the most frequently represented institution, contributing six articles. Bahauddin Zakariya University, Sher-e-Bangla Agricultural University, Sindh Agriculture University, Universidade Federal de Viçosa, and Université d'Abomey-Calavi each contributed three articles. Most other institutions contributed only one or two articles, indicating that research capacity remained dispersed across numerous organizations rather than consolidated within a small number of specialized research centers.

Overall, the geographic and institutional landscape revealed a clear distinction among research participation, publication leadership, and international connectivity. India demonstrated the strongest corresponding-author leadership but remained outside the principal international co-authorship network because its included publications were produced domestically. In contrast, the United Kingdom combined substantial research participation with the highest network centrality, functioning as the primary bridge across regional collaboration groups. Tanzania also played an important connecting role within the East and Southern African network. These patterns indicate that research on the economic, adoption, and commercialization dimensions of botanical pesticides has achieved relatively broad geographic participation, although international knowledge exchange remains concentrated around a limited number of bridging countries and institutions.

3.4. Conceptual Structure and Thematic Shifts

The conceptual structure of the literature was examined through author-keyword co-occurrence analysis. Following thesaurus-based standardization and the removal of geographic descriptors, 113 author keywords were identified. A minimum threshold of two occurrences retained 21 keywords, all of which formed a single connected network comprising five clusters, 52 links, and a total link strength of 69 (Figure 5A). The network was centered on *botanical insecticides*, *economics*, and *pest management*, indicating that the recurring conceptual structure combined a dominant technical foundation with an increasingly visible economic and production-oriented stream.

Botanical insecticides was the most prominent keyword, occurring 16 times and attaining 15 links and a total link strength of 26. It formed part of a cluster connecting plant essential oils, pest control, ecosystem services, sustainable agriculture, and pesticides. The second major technical cluster linked *Helicoverpa armigera*, azadirachta, oxymatrine, bioefficacy, and red spider mite, reflecting the continued importance of active materials, target organisms, and biological performance. A separate cluster connected pesticidal plants, *Tephrosia*, and cost-benefit analysis, thereby linking locally available plant resources with formal economic evaluation.

The economic dimension was most clearly represented by a cluster comprising economics, pest management, IPM, yield, and crop losses. Economics occurred seven times and attained nine links with a total link strength of 16, while pest management occurred six times and had nine links with a total link strength of 13. Their connectivity indicates that economic considerations were associated with pest-management strategies, productivity outcomes, and avoided crop losses rather than developing as an isolated literature. The complete composition and interpretation of the five clusters are summarized in Table 3.

Table 3. Conceptual clusters identified through author-keyword co-occurrence analysis.

Cluster	Conceptual Interpretation	Principal Keywords	Leading Keyword, Occurrences	Temporal Orientation	Main Implication
1	Botanical pest control and agricultural sustainability	Botanical insecticides, plant essential oils, pest control, ecosystem services, sustainable agriculture, pesticides	Botanical insecticides, 16	Intermediate to recent	Plant-derived pest control was increasingly connected with ecological and sustainability considerations.
2	Bioefficacy, active ingredients, and target pests	*Helicoverpa armigera*, azadirachta, oxymatrine, bioefficacy, red spider mite	*Helicoverpa armigera*, 4	Earlier	The technical foundation remained organized around active materials, target pests, and biological performance.
3	Economic and integrated pest-management outcomes	Economics, pest management, IPM, yield, crop losses	Economics, 7	Intermediate to recent	Economic considerations were connected with pest management, production, and crop-loss outcomes.
4	Pesticidal plants and economic assessment	Pesticidal plants, cost-benefit analysis, *Tephrosia*	Pesticidal plants, 5	Mixed, with recent economic assessment	Formal economic evaluation was emerging within research on locally available pesticidal resources.
5	Comparative efficacy of insecticidal interventions	Efficacy, insecticides	Efficacy, 2	Recent	Comparative performance linked botanical approaches with the wider insecticide literature.

Note: Clusters were generated from standardized author keywords. Temporal orientation reflects the average publication year; low-frequency clusters should be interpreted cautiously.

The temporal overlay suggests a broadening of research attention over time (Figure 5B). Earlier keywords were primarily associated with active ingredients, target organisms, and biological performance, including oxymatrine, bioefficacy, azadirachta, and *Helicoverpa armigera*. Botanical insecticides and pesticidal plants occupied an intermediate temporal position, followed by pest management, plant essential oils, IPM, and economics. More recent terms included pest control, crop losses, cost-benefit analysis, sustainable agriculture, and pesticides. Thus, technical themes remained present, while explicit economic assessment and sustainability-oriented terminology appeared more recently.

The thematic map further distinguished the relevance and internal development of the principal research themes (Figure 6). Seven themes were identified. The largest theme combined botanical insecticides, economics, pest management, cost-benefit analysis, ecosystem services, and yield. It had the highest Callon centrality, at 0.903, and a cluster frequency of 35, but remained in the basic-themes quadrant because of its moderate density. This position indicates that the integration of botanical insecticides with economic and production outcomes was highly relevant to the overall field but remained less internally developed than the principal motor theme.

The *helicoverpa armigera* theme, which included IPM, bioefficacy, and red spider mite, occupied the motor-themes quadrant and had the highest density among the major multikeyword themes. This result confirms that target-pest management and biological performance constituted the most internally developed component of the literature. The pesticidal-plants theme also appeared as a basic theme, linking plant essential oils, pest control, and efficacy. By comparison, *Tephrosia*, crop losses, and sustainable agriculture appeared as low-frequency specialized themes. Their positions should be interpreted as localized thematic concentrations rather than evidence of mature research streams. The azadirachta–oxymatrine theme occupied the emerging-or-declining quadrant; however, its comparatively early average publication years indicate an established technical

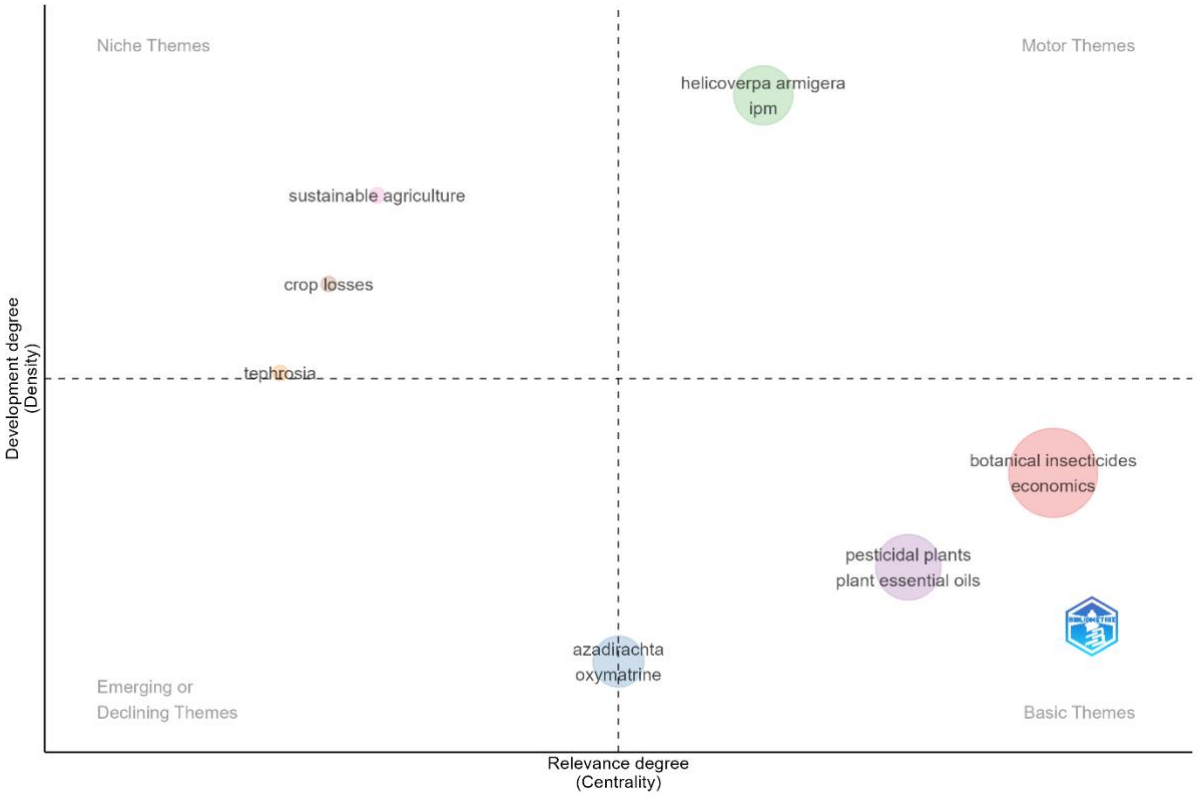


Figure 6. Thematic positioning of author-keyword clusters in botanical pesticide economics, adoption, and commercialization research. Note: Themes are positioned by Callon centrality and density, while bubble size indicates cluster frequency. Quadrants represent motor, basic, niche, and emerging-or-declining themes.

stream with limited recent orientation rather than an emerging research area.

Notably, farmer adoption and commercialization did not occur frequently enough as author keywords to enter the final co-occurrence network or to form independent themes in the thematic map. This absence does not imply that these issues were entirely missing from the literature, but it shows that they had not developed into consistently articulated and recurring conceptual streams. Overall, the conceptual structure indicates that research has broadened beyond technical performance through increasing attention to economics, cost-benefit analysis, crop losses, and sustainability. Nevertheless, adoption and commercialization remained less developed than bioefficacy, pest management, and economic assessment.

3.5. Evidence on Economic Viability, Adoption, Commercialization, and Regulation

Evidence mapping revealed a marked imbalance among the four analytical domains (Table 4). Economic viability was the most frequently represented domain, with 27 articles providing substantive evidence and five providing partial or contextual evidence. In total, 32 articles, representing 84.2% of the corpus, addressed economic considerations at some level. Farmer adoption and use were represented in 18 articles, commercialization and scaling in 13, and regulation or institutional support in 12. However, substantive evidence was considerably narrower, accounting for 15 articles on adoption and only eight articles each on commercialization and regulation. Thus, the literature contained a broad base of economic assessment but progressively smaller bodies of evidence on the behavioral, market, and institutional conditions required for wider implementation.

Economic evidence consisted predominantly of field-level comparisons of treatment costs, yields, avoided crop losses, and financial returns. The reported indicators included benefit-cost ratios, incremental benefit-cost ratios, net or gross returns, treatment and labor costs, marketable yields, profitability, marginal rates of return, and affordability. These evaluations covered vegetables, legumes, cotton, rice, medicinal plants, and smallholder production systems. Across multiple field contexts, selected botanical treatments were associated with favorable economic outcomes relative to untreated controls or alternative management options. However, the findings were context-dependent and were not directly comparable across studies because costing assumptions, labor valuation, price years, comparators, and sensitivity analyses were rarely standardized.

Table 4. Evidence base on the economic viability, adoption, commercialization, and regulation of botanical pesticides.

Evidence Domain	Substantive Evidence, n (%)	Partial/contextual Evidence, n (%)	Main Indicators or Issues	Recurring Evidence	Main Evidence Limitations
Economic viability	27 (71.1%)	5 (13.2%)	Benefit-cost ratio, incremental returns, treatment and labor costs, marketable yield, profitability, marginal returns, and affordability	Selected botanical treatments frequently generated positive returns and could be cost-competitive under specific agronomic conditions.	Costing methods, labor valuation, price assumptions, comparators, and sensitivity analyses were inconsistent.
Farmer adoption and use	15 (39.5%)	3 (7.9%)	Knowledge, perceptions, actual use, willingness to adopt or pay, training, extension, accessibility, and processing requirements	Awareness was often higher than actual use; uptake was associated with efficacy, availability, affordability, labor requirements, and external support.	Few studies distinguished stated willingness, initial trial use, and sustained adoption over time.
Commercialization and scaling	8 (21.1%)	5 (13.2%)	Product development, market niches, processing, trade, supply systems, private-sector participation, patents, and production scale	Commercial potential was strongest where reliable raw materials, processing systems, product niches, and market channels were present.	Prospective opportunities were reported more frequently than verified market entry, sales, or sustained business performance.
Regulation and institutional support	8 (21.1%)	4 (10.5%)	Registration, safety and efficacy documentation, standardization, quality control, formulation stability, policy, and institutional coordination	Registration costs, variable efficacy, weak standards, and fragmented institutions repeatedly constrained translation.	Evidence was concentrated in reviews and regional strategy papers, with limited comparison across jurisdictions.

Note: Domains were non-mutually exclusive, so percentages do not sum to 100%. “Substantive” indicates explicit analysis or detailed synthesis, whereas “partial/contextual” indicates incomplete or non-disaggregated evidence.

Farmer adoption and use were examined through surveys, participatory field trials, program case studies, and detailed review-based syntheses. The recurring factors included farmer knowledge, perceived efficacy, previous experience, raw-material and product availability, processing requirements, affordability, extension contact, training, willingness to pay, and access to botanical products. Several studies revealed substantial differences between awareness and actual use. Farmers could be familiar with pesticidal plants but apply them infrequently because of labor-intensive preparation, inconsistent efficacy, limited raw-material availability, short shelf life, or stronger confidence in synthetic products. Participatory field studies also showed that positive farmer evaluation during an experiment did not necessarily demonstrate continued adoption after the trial. Consequently, stated willingness, farmer preference, initial use, and sustained adoption were treated as distinct forms of evidence.

Commercialization evidence was less common and more heterogeneous. The strongest contributions examined essential-oil products, pyrethrum and neem value chains, product development, processing systems, market niches, trade, supply arrangements, patents, local enterprises, private-sector involvement, and scale-specific production models. Three forms of commercialization evidence were identified: existing commercial products and markets; prospective product or trade opportunities; and the technical and institutional requirements for scaling. Some publications documented established products, companies, retailers, or value chains, whereas others inferred commercial potential from laboratory efficacy, raw-material availability, patent activity, or geographic proximity between sources and potential markets. Prospective commercial opportunity was therefore distinguished from demonstrated market entry, sustained sales, or long-term business performance.

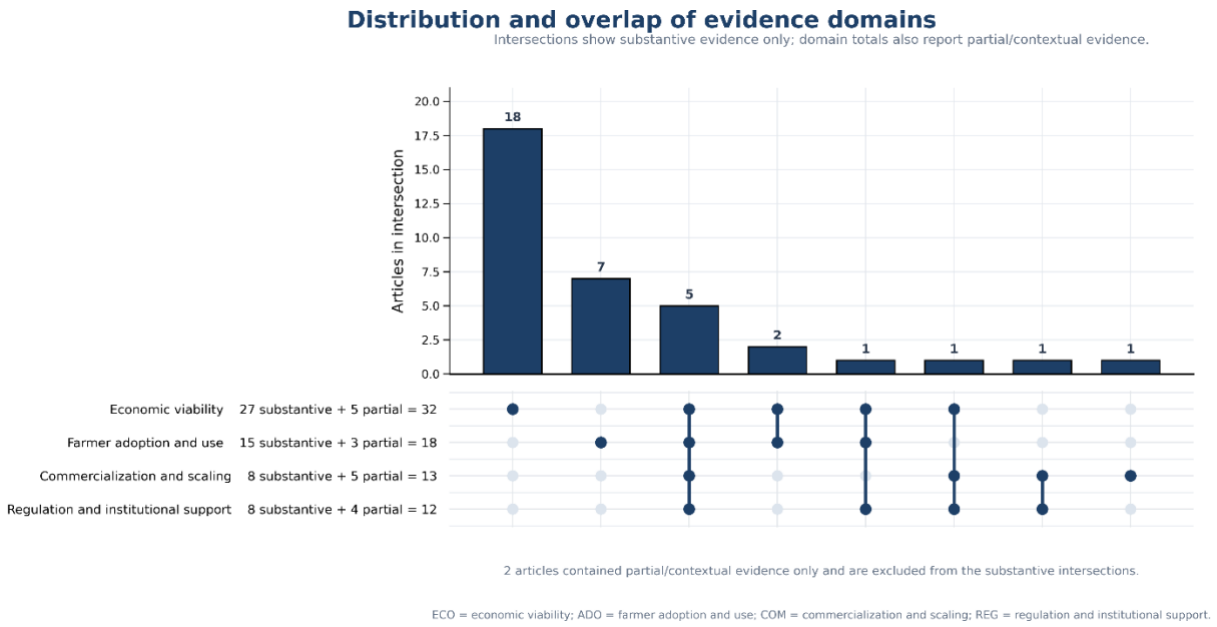


Figure 7. Distribution and overlap of substantive economic, adoption, commercialization, and regulatory evidence.
Note: Bars indicate the number of articles in each substantive intersection, while connected points identify the included domains. ECO = economic viability; ADO = farmer adoption and use; COM = commercialization and scaling; REG = regulation and institutional support.

Regulatory and institutional evidence was concentrated in a relatively small group of review, strategy, and translation-oriented publications. The principal issues were registration costs, efficacy and safety documentation, phytochemical variability, product standardization, formulation stability, quality control, environmental-risk assessment, labeling, regulatory harmonization, and institutional coordination. Regulatory frameworks designed for proprietary synthetic pesticides were frequently described as poorly aligned with chemically complex botanical mixtures and locally produced preparations. Institutional arrangements were also relevant, including extension systems, farmer organizations, research institutes, public-private collaboration, donor governance, and mechanisms for recognizing farmer-generated innovations. Nevertheless, comparative evidence across regulatory jurisdictions remained limited.

The substantive intersection structure further demonstrated the limited integration of evidence domains (Figure 7). Eighteen articles provided substantive economic evidence without simultaneously analyzing farmer adoption, commercialization, or regulation, making ECO-only studies the largest group. Seven articles focused exclusively on farmer adoption and use, while two combined substantive economic and adoption evidence. Only five articles, representing 13.2% of the corpus, provided substantive evidence across all four domains. The remaining multidomain combinations were each represented by one article. Two additional articles contained only partial or contextual evidence and therefore did not enter a substantive intersection.

The five fully integrated publications were predominantly review or translation-oriented contributions rather than conventional field experiments. These studies connected affordability or economic feasibility with farmer use, production scale, product development, market organization, standardization, registration, and institutional support. In contrast, most field experiments stopped after demonstrating biological performance, yield protection, and favorable financial returns. This pattern indicates that evidence integration remained concentrated within a small group of studies specifically concerned with translating botanical pest-control technologies beyond plot-level performance.

Overall, selected botanical treatments were associated with favorable economic outcomes across multiple field contexts, although the indicators, comparators, and costing approaches varied considerably. Economic performance alone did not establish adoption or commercial viability. Farmer use additionally depended on product reliability, labor requirements, knowledge, material availability, access, and extension support. Commercialization required consistent raw materials, scalable processing, product standardization, stable formulations, market channels, private investment, and proportionate regulatory pathways. The concentration of substantive economic evidence alongside much smaller bodies of adoption, commercialization, and regulatory research shows that these dimensions remained insufficiently integrated.

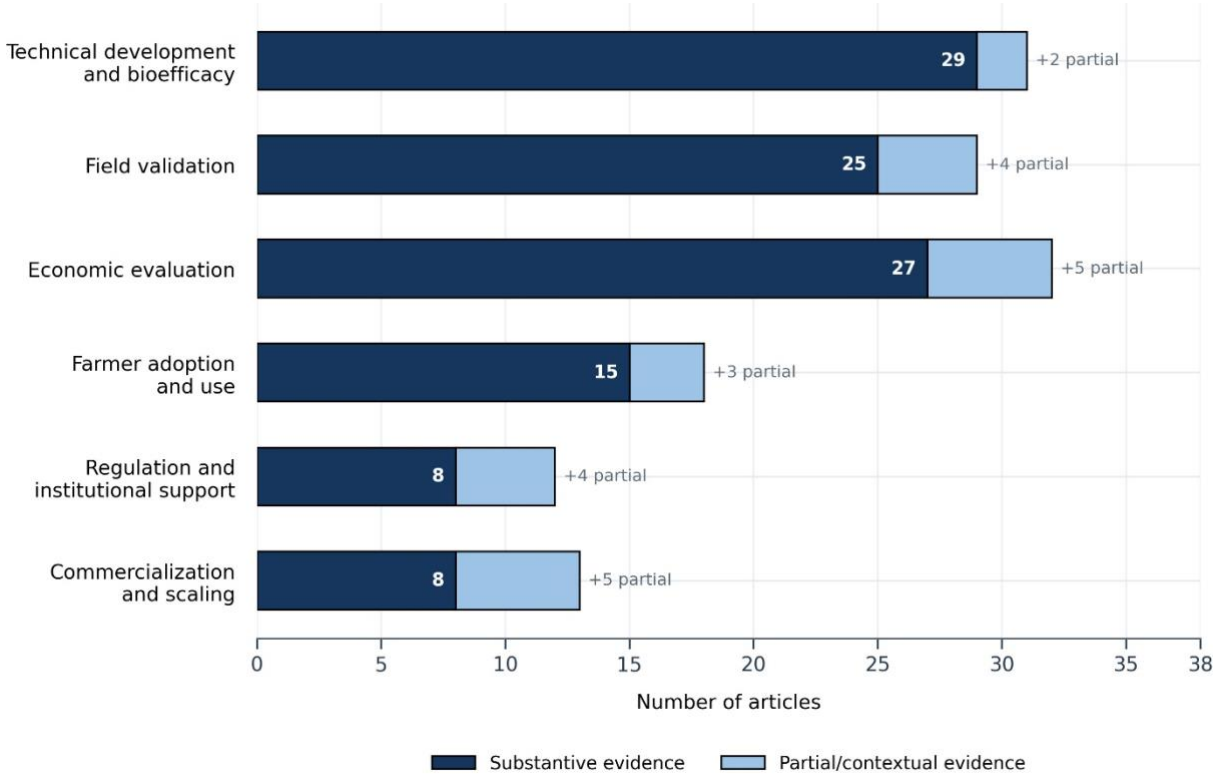


Figure 8. Evidence coverage across the botanical pesticide innovation-to-adoption pathway.
Note: Dark and light bars indicate substantive and partial/contextual evidence, respectively. Articles could contribute to multiple stages.

3.6. The Innovation-to-Adoption Evidence Gap

The distribution of evidence across the innovation-to-adoption pathway revealed a substantial imbalance between the technical and translational dimensions of botanical pesticide research. As shown in Figure 8, substantive evidence was available in 29 articles for technical development and bioefficacy, 25 for field validation, and 27 for economic evaluation. Coverage was considerably lower for farmer adoption and use, with 15 articles, and declined further to eight articles each for regulation or institutional support and commercialization or scaling. Evidence was therefore concentrated in the technical, field, and economic stages, followed by a marked reduction at the stages requiring behavioral, institutional, and market coordination.

Technical development and bioefficacy constituted the most extensively represented stage, with substantive evidence in 29 articles, equivalent to 76.3% of the corpus. This evidence encompassed botanical materials, extraction and formulation, target-pest suppression, biological efficacy, product performance, and detailed technical syntheses. Field validation was also common, with 25 articles providing substantive evidence and four providing partial or contextual evidence. The relatively small difference between technical and field coverage indicates that much of the literature extended beyond laboratory screening to agricultural or operational conditions. Nevertheless, these evaluations remained highly context-specific because they differed in crops, pest species, formulations, application rates, environmental conditions, and comparator treatments.

Economic evaluation was substantively represented in 27 articles, or 71.1% of the corpus. Its coverage slightly exceeded that of field validation because the category included not only field-level financial assessment but also detailed syntheses of affordability, production costs, registration costs, investment requirements, and scale-specific feasibility. In primary field studies, economic evaluation was generally attached to individual treatments and production seasons through benefit-cost ratios, treatment costs, yield effects, avoided crop losses, or financial returns. Thus, economic evidence was extensive but primarily concerned with short-term performance in particular production settings.

The most pronounced narrowing occurred between economic evaluation and farmer adoption. Only 15 articles, representing 39.5% of the corpus, provided substantive evidence on farmer adoption and use. Moreover, the reported outcomes differed in depth, ranging from knowledge, perceptions, preferences, and willingness to adopt to reported or observed use. Relatively few studies examined whether adoption continued after field demonstrations, research projects, or external institutional support had ended.

Consequently, positive field performance and favorable economic results could not be assumed to translate into sustained farmer use.

The evidence base narrowed further at the institutional and market stages. Regulation and institutional support were substantively addressed in eight articles, as were commercialization and scaling. Regulatory evidence was concentrated mainly in review and strategy-oriented publications dealing with registration, standards, safety documentation, quality control, formulation stability, extension systems, and institutional coordination. Commercialization evidence included existing products and value chains, processing requirements, market niches, patents, private-sector participation, and scale-specific production models. However, prospective opportunities were reported more frequently than verified market entry, sustained sales, or long-term enterprise performance.

The pattern in Figure 8 should not be interpreted as sequential attrition through a strictly linear innovation process. Individual publications could contribute to several stages, and economic evaluation could occur alongside field validation or within review-based analyses. Rather, the figure demonstrates differences in evidence coverage. The earlier stages were dominated by outcomes that could be examined through technical experimentation, field performance, and treatment-level economic indicators. The later stages required evidence on farmer behavior, standardized production, institutional capacity, regulatory readiness, investment, and market organization, but these dimensions were examined in substantially fewer publications.

Overall, the innovation-to-adoption gap did not result from a lack of technical investigation or short-term economic evidence. It reflected the limited integration of those findings with sustained farmer use, regulatory readiness, and commercial scaling. The corpus provided extensive evidence that selected botanical treatments had been technically evaluated, tested under field conditions, and assessed economically in specific contexts. Far fewer studies demonstrated how such treatments could be produced consistently, repeatedly accessed and used by farmers, supported through proportionate regulatory systems, and sustained through viable market and supply arrangements. This imbalance constitutes the principal translational gap identified in the reviewed literature.

4. Discussion

This study shows that botanical pesticide research has moved beyond a predominantly bioefficacy-oriented agenda, but the transition from technical promise to sustained use and commercial viability remains fragmented. Technical development, field validation, and economic evaluation were broadly represented, whereas evidence on farmer adoption, regulation, and commercialization was substantially less developed. More importantly, only five of the 38 publications substantively integrated economic viability, farmer adoption, commercialization, and regulatory or institutional support. The principal gap is therefore not simply a shortage of promising botanical materials or field evaluations. It is the limited integration of technical performance with the behavioral, institutional, regulatory, and market conditions required for botanical pesticides to become reliable and sustained components of pest-management systems. This finding builds on earlier concerns that botanical pesticide research has generated considerable scientific interest without a comparable expansion in practical products or use at scale [6, 9, 13].

The conceptual and temporal patterns indicate a broadening of the field rather than a complete departure from its technical foundations. Bioefficacy, active ingredients, botanical insecticides, and target pests remained prominent, but more recent publications increasingly connected these topics with economics, cost-benefit analysis, crop losses, integrated pest management, and sustainable agriculture. This development suggests that botanical pesticides are being repositioned from isolated plant extracts toward components of broader production and sustainability systems. A similar shift from productivity-centered research toward integrated environmental and economic perspectives has been reported in the wider agrochemical literature [32]. The growing association between botanical pesticides, IPM, and sustainable agriculture is also consistent with the broader transition of pest-management research toward agroecology, ecosystem services, and climate-responsive strategies [32]. Nevertheless, the continued centrality of bioefficacy should not be interpreted as evidence of conceptual stagnation. Technical validation remains necessary, particularly because botanical products can vary with plant provenance, growing conditions, extraction procedures, chemotype, formulation, and storage. The problem arises when technical efficacy is treated as the endpoint rather than the beginning of a translational process.

The relatively broad economic evidence base is an important development, but its interpretation requires caution. Field studies have demonstrated that selected botanical treatments can produce favorable benefit-cost ratios, protect marketable yield, or generate returns

comparable to alternative pest-management options under specific conditions [15, 55]. Qualitative assessment has further shown that the apparent low cash cost of locally available pesticidal plants can be offset by collection, preparation, labor, knowledge, and application demands [56]. Participatory assessment further demonstrates that farmers evaluate pesticidal plants through a combination of monetary and non-monetary trade-offs, with limited access to processing tools and knowledge of plant preparation potentially restricting uptake even when farmers perceive broader household benefits [58]. Consequently, favorable treatment-level returns do not establish universal affordability or economic viability. Most economic evaluations were restricted to particular crops, pest complexes, locations, comparators, and production seasons. Differences in the valuation of family labor, treatment preparation, price years, marketable yield, and input accessibility further limited comparison across studies. Few studies tested whether conclusions remained robust under changes in output prices, labor costs, raw-material scarcity, efficacy, or market conditions. This is especially important for smallholders, for whom liquidity constraints and timing of expenses may matter as much as expected net returns. The broader agricultural-economics literature is increasingly integrating economic performance with environmental sustainability and quantitative assessment, but it also remains fragmented across methods and research contexts [33]. Botanical pesticide research would therefore benefit from a common minimum framework reporting treatment and labor costs, price assumptions, yield and quality effects, uncertainty, and sensitivity analysis.

The sharp reduction in evidence at the farmer-adoption stage demonstrates that adoption should not be treated as a single outcome. The studies in the corpus represented different points along a behavioral sequence, including knowledge, perceptions, preferences, willingness, initial experimentation, reported use, and continued application. These outcomes are related but not interchangeable. Farmers may know pesticidal plants without using them, prefer a botanical treatment during a participatory trial without continuing it afterward, or express willingness to adopt without purchasing, preparing, or repeatedly applying the product. Studies from Nigeria and Southern Africa illustrate how efficacy, accessibility, preparation requirements, knowledge, and institutional support can jointly influence the movement from familiarity to use [19, 20]. More recent evidence similarly identifies education, training, extension contact, perceived effectiveness, and access as important determinants of knowledge and willingness to adopt botanical pesticides [59]. These patterns are consistent with evidence from wider IPM research, which identifies insufficient training, weak technical support, limited input access, labor demands, inadequate incentives, and the need for collective action as persistent adoption barriers [4]. Positive efficacy and benefit-cost results are therefore necessary but insufficient. Adoption also depends on whether farmers regard a treatment as reliable, practical, accessible, compatible with existing routines, and sufficiently advantageous under uncertainty. Future evaluations should distinguish intention from behavior and follow farmers beyond demonstrations to examine repeated use, discontinuation, adaptation, and, where a commercial product exists, repeat purchase.

The transition from an effective botanical material to an accessible and market-ready product presents a different set of challenges. Locally prepared extracts, community-scale processing, and standardized commercial formulations should not be treated as equivalent innovation models. Farmer-made preparations may require limited financial investment but can impose substantial labor and knowledge demands and produce variable concentrations. Cooperative or small-enterprise processing may reduce preparation burdens but requires reliable raw-material supply, processing capacity, quality assurance, and distribution arrangements. Industrial products additionally require consistent active-material profiles, formulation stability, shelf life, packaging, labeling, market positioning, and regulatory approval. These production models also differ economically because locally prepared products may offer greater accessibility to resource-constrained farmers but impose substantial preparation and labor requirements, whereas refined commercial formulations can reduce preparation burdens while introducing higher production, distribution, and acquisition costs [60].

Earlier studies identified raw-material availability, standardization, quality control, and registration as central constraints on botanical pesticide commercialization [24, 29], while translation-oriented work has emphasized the gap between laboratory efficacy and products that can be produced and used consistently under field conditions [9, 13]. More recent synthesis likewise concludes that commercialization has progressed more slowly than scientific interest, with neem and pyrethrum remaining dominant and regulatory requirements shaping market development across jurisdictions [6]. This conclusion is reinforced by recent reviews showing that extensive investigation of plant-derived active materials has resulted in relatively few commercially developed products because market entry also requires reproducible active materials,

formulation stability, safety documentation, product standardization, and compliance with regulatory requirements [27, 28]. Regulation should consequently be understood not only as an administrative barrier but also as a mechanism for establishing product identity, efficacy, safety, consistency, and user confidence. Excessively costly requirements may exclude small producers, but weak quality assurance can expose farmers to ineffective products and undermine trust in the wider botanical-pesticide sector. The regulatory challenge is therefore to develop proportionate pathways that recognize the chemical complexity and scale diversity of botanical products without lowering essential standards.

Taken together, the evidence-overlap and pathway analyses reveal that the innovation-to-adoption gap originates from weak connections among otherwise established areas of inquiry. Many field experiments ended after reporting pest suppression, crop protection, yield, and short-term returns, while few followed the same technology into repeated farmer use, standardized production, registration, distribution, or sustained sales. The small number of publications integrating all four translational domains consisted mainly of reviews and translation-oriented analyses rather than longitudinal product-development studies. The evidence base is thus better described as a collection of partially connected segments than as a mature innovation pipeline. Its geographic structure reinforces this interpretation. Countries that led publication output did not necessarily occupy the most connected positions in international networks, while a few countries and institutions acted as collaboration bridges. Similar concentrations of knowledge production and limited integration have been observed in research on agricultural economics, sustainable agrochemicals, IPM, and agribusiness governance [32–34, 61]. International collaboration can support access to analytical methods, formulation technologies, and regulatory expertise, but its value will remain restricted if research priorities, intellectual leadership, and product-development decisions are detached from the farming systems and institutions in which botanical pesticides are expected to operate. Stronger collaboration should therefore combine international scientific capacity with local ownership, farmer participation, and long-term institutional engagement.

Several strengths and limitations shape the interpretation of these findings. By integrating bibliometric mapping with article-level evidence coding, the study moved beyond publication counts to distinguish substantive evidence from contextual references and to separate farmer preference from adoption, commercial potential from demonstrated commercialization, and technical evaluation from market readiness. However, the analysis was based exclusively on a focused Scopus corpus and may not capture publications indexed only in Web of Science or other bibliographic databases, local-language research, technical reports, regulations, company data, or undocumented farmer practices. The relatively small corpus also makes network and thematic positions sensitive to individual publications. Evidence coding relied primarily on titles, abstracts, and keywords, supplemented by targeted rather than universal full-text verification. Moreover, evidence coverage does not measure methodological quality, and the heterogeneity of crops, products, indicators, and comparators precluded pooled effect estimation. Accordingly, the findings should be interpreted as an assessment of the coverage and integration of the Scopus-indexed evidence base rather than as an exhaustive evaluation of all available evidence or the methodological quality of individual studies.

5. Conclusion

Botanical pesticide research has expanded beyond bioefficacy, but its translational development remains uneven. Technical validation, field performance, and economic evaluation have received substantial attention, whereas sustained farmer use, regulatory readiness, and commercial scaling remain less consistently investigated and rarely integrated. The principal gap is therefore not a lack of promising plant-derived pest-control options, but the limited continuity of evidence connecting technical performance with practical implementation.

By combining bibliometric analysis with article-level evidence mapping, this study distinguishes the growth of scientific attention from progress toward adoption and commercialization. The findings indicate that economic viability, farmer adoption, regulation, and market development have largely evolved as separate lines of inquiry. Consequently, favorable efficacy or short-term financial returns alone cannot establish that a botanical pesticide is accessible to farmers, reliable in repeated use, suitable for registration, or sustainable within a viable supply system.

Economically, these findings imply that the viability of botanical pesticides should not be assessed solely through plot-level benefit-cost ratios or short-term yield returns. For farmers, economic feasibility also depends on labor and preparation requirements, affordability, liquidity, product reliability, and continued access to raw materials or formulated products. For producers and

market actors, viability requires consistent raw-material supplies, quality assurance, scalable processing, distribution capacity, sustained demand, and sufficient returns to support continued enterprise activity. Proportionate regulation, extension support, and coordination across the value chain are therefore economically important because they can reduce transaction costs, strengthen product confidence, and improve the conditions for sustained market development.

Closing this gap requires research that follows botanical pesticide innovations beyond experimental validation. Future studies should integrate comparable economic assessment, longitudinal adoption outcomes, product standardization and quality assurance, proportionate regulatory pathways, and evidence on value chains and enterprise performance. Progress will ultimately depend on connecting researchers, farmers, extension services, regulators, producers, and market actors within coordinated development processes. The next stage of botanical pesticide research must therefore establish not only whether plant-derived products can control pests, but under what conditions they can be produced consistently, adopted repeatedly, governed appropriately, and sustained within agricultural systems.

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