Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Mapping the Sustainability Transition in Liquid and Water-Soluble Fertilizer Research: A Scopus-Based Bibliometric Analysis (2021-2026)

Shuhratjon Yu. Nomozov

shuhratjon.nomozov@mail.ru

Academy of Sciences of the Republic of Uzbekistan

Atanazar R. Seytnazarov

Academy of Sciences of the Republic of Uzbekistan

Umarbek K. Alimov

Academy of Sciences of the Republic of Uzbekistan

Shafaat S. Namazov

Academy of Sciences of the Republic of Uzbekistan

Lazizjon L. Abdullayev

Fergana State Technical University

Systematic Review

Keywords: liquid fertilizer, water-soluble fertilizer, fertigation, bibliometric analysis, sustainability, circular economy, nutrient-use efficiency, sustainable agriculture, science mapping

Posted Date: September 2nd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10555773/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Abstract

Conventional mineral fertilization remains one of agriculture's principal sources of resource inefficiency and environmental burden, motivating a global shift toward more sustainable nutrient management. Liquid and water-soluble fertilizers are attracting growing interest in this context, given their fertigation compatibility, nutrient-use-efficiency gains, and suitability for circular, waste-derived nutrient sources. Yet, this field had not previously been mapped bibliometrically. We analyzed 201 Scopus-indexed documents (196 articles, 5 reviews) published between January 2021 and June 2026, using a PRISMA-2020-adapted approach with bibliometrix and VOSviewer. Annual output rose from 33 documents in 2021 to 47 in 2025. Author productivity departed from Lotka's Law, with 87.7% of the 966 authors contributing only one document, while the field's 130 journals followed a classical Bradford scattering pattern. China and India led national output, with Tamil Nadu Agricultural University the most productive institution; international collaboration remained modest at 15.4%. Keyword co-occurrence and thematic-evolution analyses traced a clear shift toward sustainability and circular-economy themes, with liquid fertilizer as the most generative conceptual node linking precision delivery and waste-derived nutrient sourcing. Collectively, these patterns reveal an institutionally fragmented yet conceptually convergent field, already oriented toward sustainable nutrient management but lacking the collaborative structure to advance it. A software-specific limitation was resolved via independent verification (23 documents, 26 links). This mapping offers the first evidence base for steering the field's transition toward sustainable, resource-efficient fertilization and for aligning future research with global food-security and environmental-sustainability goals, including the Sustainable Development Goals (SDGs) 2, 12, and 15.

1 Introduction

Modern crop production remains fundamentally dependent on mineral fertilizers. Yet, this dependence is now among agriculture’s most consequential sources of resource inefficiency and environmental burden, precisely the kind of production-system problem that sustainability research seeks to resolve. Global inorganic fertilizer use grew from roughly 142 million tonnes in 2002 to about 190 million tonnes in 2023, with nitrogen alone reaching a record 112 million tonnes [1, 2]. The resulting productivity gains, traceable to the Haber-Bosch process now estimated to sustain 40–60% of global agricultural output [3, 4], carry measurable costs [5]. Long-term nitrogen fertilization has been shown to lower soil pH by an average of 15% and suppress key soil enzyme activities by 10–22% [6], while nitrogen fertilizers contribute an estimated 80–90% of anthropogenic ammonia and 60–70% of anthropogenic nitrous oxide emissions [7]; nutrients escaping the root zone further accumulate as salinity and leach into waterways [8]. Because closing yield gaps depends more on targeted nutrient and water management than on expanding cultivated area [9, 10], raising nutrient-use efficiency has become central to reconciling food security with environmental protection [8, 11], and, in sustainability terms, to decoupling agricultural output from resource waste and emissions. These challenges position nutrient-use efficiency and fertilization sustainability at the intersection of multiple Sustainable Development Goals, most directly SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 15 (Life on Land), underscoring the need for evidence-based transitions toward more sustainable fertilization systems.

Against this backdrop, liquid and water-soluble fertilizers have gained traction as a more precise, resource-efficient alternative to granular products. Because nutrients are already dissolved, they can be metered directly into drip or sprinkler lines (a practice known as fertigation), so that timing and dosage track a crop's actual uptake curve rather than a single bulk application. Field evidence supports the efficiency case: micro-sprinkling fertigation in winter wheat improved both grain yield and nitrogen-use efficiency by better synchronizing root, water, and nitrogen distribution [12], and a two-year greenhouse tomato trial showed that matching nutrient-solution frequency to substrate-moisture thresholds raised both fruit quality and combined water-fertilizer use efficiency [13]. At larger scale, a multi-site meta-analysis of Chinese cropping systems found that drip fertigation raised yield by 12%, water productivity by 26%, and nitrogen-use efficiency by 34% relative to conventional practice [14], a profile reaffirmed by recent reviews of drip fertigation with water-soluble fertilizers [15]; pairing liquid fertilizers with urease and nitrification inhibitors can further reduce nitrogen losses and raise maize yield in temperate Mollisols [16, 17]. Such delivery-focused strategies consistently raise apparent recovery efficiency and partial factor productivity across staple crops [18], reinforcing the 4R Nutrient Stewardship principle that how and when nutrients are delivered can matter as much as how much is applied [19].

A parallel strand concerns the source of the nutrients themselves. Rather than relying solely on synthesized salts, a growing body of work explores liquid fertilizers derived from agricultural residues, sewage sludge, and other waste streams, framing nutrient recovery as part of a circular-economy transition in agriculture [20, 21]; liquid biofertilizers in particular offer a practical route for converting such waste streams into a field-ready, nutrient-rich product [22, 23]. This is not a marginal niche: global crop-residue generation exceeds five billion tonnes annually, and recycled-nutrient fertilizers are increasingly discussed as a mechanism for closing regional nutrient loops while reducing dependence on virgin mineral inputs [21]. The convergence of precision fertigation on one side and waste-derived liquid fertilizers on the other describes a field expanding along two fronts at once, both squarely within the sustainability and circular-economy agenda, yet rarely examined as a single, coherent body of literature. This convergence of precision fertigation and waste-derived liquid fertilizers is directly relevant to SDG 12 targets on sustainable resource management and SDG 2 goals for sustainable food production, framing liquid and water-soluble fertilizers not merely as agronomic tools but as instruments of a broader sustainability transition.

This fragmentation is where bibliometric analysis becomes useful. By quantifying publication output, collaboration patterns, and conceptual structure across large document sets, bibliometric methods reveal a research field's shape rather than only its individual results [24]. Within cleaner-production research specifically, science mapping has charted the circular-economy literature and its emergent themes [25] and traced two decades of waste-management research within the circular-economy transition [26]. Comparable studies have mapped adjacent agricultural topics: slow- and controlled-release fertilizers across 1,676 papers from 1990–2023 [27], soil-chemicalization research combining VOSviewer network exports with population-adjusted productivity metrics [28], DSSAT crop modeling within an irrigation-and-fertilizer-management context [29], and variable-rate agrochemical application [30]. The approach has been extended across agricultural-chemistry sub-fields including mineral-fertilizer

development trends [31], biochar-based and seaweed- and lichen-based biofertilizers [32, 33], microbial bioconversion of waste biomass [34], nano-agricultural applications [35], and fertilizer-related carbon emissions [36, 37]; yet none of these prior studies examined liquid or water-soluble fertilizers as its object. A confirmatory search combining bibliometric-specific terminology with our core topic terms, conducted in June 2026, returned only a single tangential result concerned with compost-tea preparation [38], providing direct empirical confirmation of this gap. Given how rapidly this subfield is publishing and how directly it intersects both precision-irrigation infrastructure and circular-economy policy, that omission leaves researchers, editors, and funding bodies without a reliable map of the field.

This study addresses that gap through a bibliometric analysis of 201 Scopus-indexed articles and reviews on liquid and water-soluble fertilizers published between 2021 and 2026. Using bibliometrix/Biblioshiny in R alongside VOSviewer, we ask: (i) how has research output and impact evolved, and how mature is the field? (ii) How are research capacity and collaboration distributed across authors, institutions, and countries, and how integrated or fragmented is that structure? (iii) What is the field's conceptual structure, and to what extent is it converging on sustainability themes such as nutrient-use efficiency, loss reduction, and circular, waste-derived nutrients? By quantitatively mapping the intellectual, thematic, and collaborative structure of this literature, this study provides the first evidence base for steering the field's transition toward sustainable, resource-efficient nutrient management and for informing research prioritization and policy dialogue oriented toward the Sustainable Development Goals, particularly in regions such as Central Asia, where precision fertilization infrastructure and circular-economy approaches to nutrient management remain underdeveloped.

2 Materials and Methods

2.1 Data Source and Search Strategy

To map the sustainability transition in liquid and water-soluble fertilizer research, bibliometric data were retrieved from the Scopus database (Elsevier) on 15 June 2026. Scopus was selected as the sole data source for three methodological reasons. First, in the applied agricultural, environmental, and chemical sciences framing this field, Scopus offers broader journal and conference coverage than the Web of Science Core Collection, reducing the risk of omitting relevant venues [39–41]. Second, a single source preserves internal consistency across author, affiliation, source, and citation metadata; merging databases introduces de-duplication and field-harmonization artifacts that can distort indicators, particularly in small corpora. Third, single-database Scopus retrieval is an established standard in science mapping, ensuring comparability with the prior domain mappings against which our findings are benchmarked. We treat this as an explicit scope condition and address its coverage implications in Section 4.5. The search query was applied to title, abstract, and author-keyword fields:

TITLE-ABS-KEY ("liquid fertilizer" OR "liquid NPK fertilizer" OR "fluid fertilizer" OR "solution fertilizer" OR "suspension fertilizer" OR "liquid complex fertilizer" OR "water-soluble fertilizer") AND TITLE-ABS-KEY ("production technology" OR "manufacturing" OR "formulation" OR "synthesis" OR "agronomic efficiency" OR

"fertigation" OR "nutrient uptake" OR "crop yield" OR "physicochemical propert") AND PUBYEAR > 2020 AND LANGUAGE (English)*

The query comprised two conceptual blocks joined by the Boolean AND operator: the first captured common synonyms and terminological variants for liquid and water-soluble fertilizers, while the second restricted results to documents addressing production technology or agronomic efficiency, using the wildcard operator (*) to capture morphological variants. Because all inclusion criteria were embedded directly within this search string, the exported dataset (n = 234) already reflected these criteria at the point of retrieval, with no additional filtering applied post-export beyond the document-type screening described in Section 2.2. The dataset was exported in four parallel formats (CSV, BibTeX, RIS, and plain text; export date 15 June 2026); all four exports contained the same 234 records, confirming that no data were lost or altered during export rather than serving as an independent check on the search itself.

2.2 Study Selection

Document selection followed PRISMA 2020 guidelines [42], adapted here for a bibliometric science-mapping study aimed at identifying knowledge gaps and informing research prioritization toward sustainable nutrient management, rather than a systematic review of intervention effects. Of the 234 identified records, no duplicates were detected. At the eligibility stage, 33 records were excluded based on document type: conference papers and conference reviews (n = 24), books and book chapters (n = 7), and letters/data papers (n = 2). The final analytic dataset comprised 201 documents (196 articles, 5 reviews). The complete selection process is illustrated in Fig. 1.

2.3 Data Cleaning and Quality Control

The Scopus CSV export was converted into an analysis-ready bibliometric data frame in R (v.4.5.1) using the convert2df() function of the bibliometrix package (v.5.4.1) [43]. A field-level missing-data assessment (Table 1) was conducted on the 234-record dataset before document-type filtering. Core fields were fully complete, whereas Keywords Plus was missing for 54.7% of records; all keyword-based analyses therefore relied exclusively on Author Keywords (DE).

Table 1
Field-level completeness of Scopus metadata for the initially retrieved dataset (n = 234).

Code	Field	Missing (n)	Missing (%)	Status
AU	Author	0	0.00	Excellent
DT	Document Type	0	0.00	Excellent
SO	Source (Journal)	0	0.00	Excellent
LA	Language	0	0.00	Excellent
PY	Publication Year	0	0.00	Excellent
TI	Title	0	0.00	Excellent
TC	Total Citations	0	0.00	Excellent
AB	Abstract	0	0.00	Excellent
C1	Affiliation	0	0.00	Excellent
DI	DOI	9	3.85	Good
DE	Author Keywords	18	7.69	Good
RP	Corresponding Author	15	7.46	Good
ID	Keywords Plus	110	54.73	Critical

Author Keywords underwent thesaurus-based synonym normalization, consolidating spelling and morphological variants (e.g., "fertilizer/fertilizers/fertiliser" and "water-soluble fertilizer/water soluble fertilizers") into single canonical terms before all downstream keyword analyses. An identical thesaurus, reformatted for VOSviewer's specification, was applied consistently across all VOSviewer-based network analyses.

Author country of affiliation was extracted using bibliometrix's metaTagExtraction() function. Automated extraction failed to resolve country for 33 of 201 records, largely owing to non-standard affiliation formatting; a supplementary rule-based extraction using the countrycode package's ISO reference list reduced unresolved records to 3 of 201 (1.5%). Country names were subsequently standardized (e.g., "USA" → "United States", "Russian Federation" → "Russia"). Because standardized author names can obscure or conflate distinct individuals, the fifteen most productive authors (Fig. S3) were manually cross-checked against affiliation and, where available, ORCID records to confirm that no erroneous merging or splitting of author identities had occurred within this subset.

2.4 Bibliometric Analysis Tools

Descriptive indicators (Fig.s 2–7 and S1-S7) were computed in R (v.4.5.1) [44] using bibliometrix (v.5.4.1) [43] and Biblioshiny, with figures re-rendered in ggplot2 for stylistic consistency. Network analyses (Fig.s

8–10 and S8-S10) were performed in VOSviewer (v.1.6.20) [45], using full counting and association-strength normalization [46] throughout, with manually tuned attraction/repulsion parameters reported per analysis; network layouts were generated using a force-directed graph-drawing algorithm [47] and partitioned into clusters via a modularity-based community-detection technique [48].

2.5 Bibliometric Indicators

Table 2 consolidates the software, functions, and parameters applied across the thirteen indicator groups, including Bradford's Law [49], Lotka's Law [50], the thematic-evolution framework of Cobo et al. [51], and Ward's method of hierarchical clustering underlying keyword-cluster assignment in the thematic map [52].

Table 2
Consolidated analytical parameters applied across the bibliometric indicators.

Indicator	Software / Function	Key Parameters
Annual production & citation dynamics	R / bibliometrix biblioAnalysis()	AGR; TCperYear normalized by document age
Bradford's Law (journals)	R / bibliometrix bradford()	Zone 1/2/3 partitioning
Lotka's Law (authors)	R / bibliometrix lotka()	Kolmogorov–Smirnov goodness-of-fit
Most productive institutions	R (custom script)	First-listed affiliation (AU_UN)
Country production & collaboration	R / rnaturalearth, biblioNetwork()	Full counting (AU_CO)
Three-field plot	Biblioshiny	AU_CO – DE – SO, Sankey diagram
Trend topics / thematic map	R / fieldByYear(), thematicMap()	Min. frequency = 3
Thematic evolution	R / thematicEvolution()	Two sub-periods: 2021–2023, 2024–2026
Keyword co-occurrence network	VOSviewer 1.6.20	Full counting; min. occurrence = 3; association strength
Author / country collaboration network	VOSviewer 1.6.20	Co-authorship; min. 2 documents/unit
Bibliographic coupling	VOSviewer 1.6.20	Documents; min. 10 citations/document
Co-citation network	VOSviewer 1.6.20	Cited authors; min. 10 citations/author
Citation network	VOSviewer 1.6.20; bibliometrix 5.4.1	Documents & sources; 0 links via VOSviewer (software limitation); 23 docs/26 links via bibliometrix cross-check (Fig. 10)

During the preparation of this work the authors used Claude (Anthropic) to assist with translation of the manuscript from Uzbek into English and with academic language editing. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

3 Results

3.1 General Bibliometric Performance

The final dataset comprised 201 documents (196 research articles, 5 reviews) published across 130 distinct sources between 2021 and the first half of 2026, drawing on 966 unique authors and 9,730 cited references. Each document carried a mean of 5.78 co-authors, and only three documents (1.5%) were single-authored, underscoring the strongly collaborative character of the field. Annual output rose from 33 documents in 2021 to a peak of 47 in 2025, following an uneven but broadly upward trajectory (28 in 2022, 30 in 2023, 36 in 2024; Fig. 2). Because only the first half of 2026 (27 documents) was captured at the time of export, the computed annual growth rate (-3.93%) reflects this partial-year artefact rather than a genuine contraction of the field.

The mean number of citations per document was 6.51, with a mean annual citation rate (TCperYear) of 1.38. When disaggregated by publication year (Fig. S1), citation intensity peaked for the 2022 cohort (mean TCperYear = 3.59) before declining steadily through 2023 (2.28) and 2024 (1.10), reaching zero for the 2025–2026 cohort (74 documents, 37% of the corpus).

The ten most-cited documents in the corpus (Table 3) collectively accounted for 484 citations. Bhardwaj et al. (2022, Frontiers in Plant Science) was the single most-cited work (113 citations), followed by Sun et al. (2022, Agricultural Water Management; 83 citations), a result consistent with the broader evidence base on water- and nitrogen-use-efficiency gains from fertigation reviewed above [12, 18].

Table 3
Ten most globally cited documents in the dataset.

Rank	Reference	Journal	TC	TC/Year
1	Bhardwaj et al. (2022)	Frontiers in Plant Science	113	22.60
2	Sun et al. (2022)	Agricultural Water Management	83	16.60
3	Simoni et al. (2021)	J. Water Process Engineering	49	8.17
3	Upadhyay et al. (2023)	Front. Sustainable Food Systems	49	12.25
5	Alneyadi et al. (2024)	J. Agriculture and Food Research	42	14.00
6	Lobanov et al. (2021)	Frontiers in Plant Science	41	6.83
6	Niu et al. (2021)	PLOS ONE	41	6.83
8	Khan et al. (2022)	Frontiers in Marine Science	38	7.60
9	Jamison et al. (2021)	Agronomy 33	5.50	
10	Izydorczyk et al. (2022)	Journal of Hazardous Materials	31	6.20

3.2 Authors, Institutions, Countries, and Sources

Source analysis (Fig. S2) identified Plant Science Today (11 documents), Frontiers in Plant Science (8), and Agronomy (7) as the three most productive journals, followed by Agriculture (Switzerland), Science of the Total Environment, and Sustainability (Switzerland) (5 each). Bradford's Law partitioning (Fig. 3) divided the field's 130 journals into a 14-journal core (Zone 1), a 50-journal Zone 2, and a 66-journal Zone 3 comprising mostly single-article outlets, a scattering pattern typical of an actively diversifying applied research area, and one broadly similar to that reported for other recent bibliometric mappings of precision-agriculture sub-fields [30].

At the author level (Fig. S3), the most productive author contributed 10 documents. Author productivity departed markedly from the theoretical Lotka distribution (Fig. 4): the fitted exponent (Beta = 2.95) was substantially steeper than the classical value of 2.0, and although the goodness-of-fit was high (R^2 = 0.933), a Kolmogorov-Smirnov test confirmed a statistically significant deviation (p = 0.037). Of 966 authors, 847 (87.7%) contributed exactly one document.

Institutional productivity, based on first-listed affiliations (Fig. S4), was led by Tamil Nadu Agricultural University (India, 14 documents), followed by Sichuan University (6) and a cluster of institutions with 3–4 documents each.

Country-level analysis using full counting of all co-authors' countries (Fig. 5) identified China (161 author-country instances) and India (156) as the dominant contributors, followed at a considerable distance by the United States (35), Brazil (25), and Poland (23); 50 distinct countries were represented overall. Using the alternative, corresponding-author-based counting convention, China and India accounted for 55 and

49 articles respectively (27.4% and 24.4% of the corpus), with an international co-authorship rate of 15.4%. The geographic distribution is shown as a choropleth map (Fig. 5) and, in network form, as a country collaboration graph (Fig. S5).

3.3 Conceptual Structure of the Research Field

The three-field plot (Fig. S6), linking author countries, author keywords, and source journals, confirms India's and China's centrality to the keyword landscape, with "fertigation", "yield", and "water-soluble fertilizer" as the principal conduits connecting country-level output to publication venues.

Trend-topic analysis (Fig. S7) traced a temporal succession of dominant vocabulary: early documents (2021) clustered around "growth", "drip fertigation", and waste-processing terms; 2022–2024 was dominated by "fertigation", "water-soluble fertilizer", "liquid fertilizer", and "yield"; and 2025–2026 saw "biomass", "soil amendment", and "rhizosphere" consolidate alongside "sustainable agriculture" and "crop productivity".

The strategic thematic map (Fig. 6) situated "sustainable agriculture" alone in the Motor Theme quadrant (high centrality, high density), marking it as a well-developed and central direction. "Water-soluble fertilizer", "liquid fertilizer", and "fertigation" occupied the Basic Theme quadrant (high centrality, lower density), consistent with their role as foundational but still actively evolving concepts. "Fertilization", "citrus greening", "phosphorus", and "biomass" formed Niche Themes, while "chitosan" and "biofortification" appeared in the Emerging/Declining quadrant.

Thematic evolution analysis across two equal sub-periods (2021–2023 vs. 2024–2026; Fig. 7) showed strong conceptual continuity for "fertigation" (48.1% lineage strength retained within the same theme) and "water-soluble fertilizer" (47.9%), while "liquid fertilizer" diversified substantially, branching into "hydroponics" (26.7%), "fertilizer" (21.9%), and "calcium nitrate" (16.6%) in addition to retaining a strong self-connection (70.6%),the single largest lineage in the entire evolution diagram. This suggests that liquid fertilizer functions as the field's most generative conceptual node, seeding several downstream research directions.

Keyword co-occurrence network analysis in VOSviewer (full counting, association strength normalization, minimum occurrence = 3; Fig. 8) resolved 30 keywords into six clusters and 81 links (total link strength = 116). The largest cluster centered on "fertigation", "water-soluble fertilizer", "nutrient uptake", and "drip irrigation"; a second cluster combined "liquid fertilizer" with "organic liquid fertilizer" and "resource recovery"; a third combined "fertilizer", "circular economy", "phosphorus", and "biomass"; and smaller clusters captured "sustainable agriculture"/"drip fertigation", "organic fertilizer"/"hydroponics", and a waste-valorization group ("sewage sludge", "microbial community"). This structure corroborates the thematic map (Fig. 6) in identifying sustainability and circular-economy concepts as increasingly integrated with, rather than peripheral to, the field's technical fertigation core.

3.4 Collaboration and Citation-Based Networks

The author collaboration network (co-authorship, minimum 2 documents/author; Fig. 9) resolved 83 qualifying authors into 25 distinct clusters connected by 181 links (total link strength = 350). Rather than a single dominant collaboration core, the field comprises numerous small, densely interconnected research teams with comparatively few cross-team links.

The country collaboration network (Fig. S8) reinforced the choropleth findings (Fig. S5): China and India anchor the largest, most densely connected cluster, a second cluster links the United States, United Kingdom, Germany, and Canada, and several countries remain unconnected to any partner within the dataset.

Bibliographic coupling at the document level (minimum 10 citations per document; Fig. S9) identified 39 qualifying documents forming 23 clusters connected by only 19 links (total link strength = 37). Most documents shared no substantial common reference base with any other in the corpus, although a small core cluster of four highly interconnected publications was identified. This sparse coupling reflects heterogeneous reference bases across studies, consistent with the field's interdisciplinary span (Section 3.3). In contrast, co-citation analysis at the cited-author level (Fig. S10) produced a far denser structure: 28 cited authors in four clusters connected by 214 links (total link strength = 829), indicating that a comparatively small group of authors is repeatedly co-cited across the broader literature on which this corpus is based, thereby forming a recognizable intellectual core.

Finally, direct citation analysis in VOSviewer, applied at document and source levels without a citation threshold, returned no links within the corpus (0 among 201 documents; 0 among 47 qualifying sources). Because this null result was unexpected and contradicted the co-citation structure reported above, we cross-validated it using the localCitations() and histNetwork() functions of the bibliometrix package, which identify intra-corpus citations through normalized author–year–source matching rather than the DOI-based matching VOSviewer appears to require. This method identified 23 documents (11.4% of the corpus) cited at least once within the dataset, accounting for 26 intra-corpus links (Fig. 10). We therefore attribute the null result to a software-specific limitation in parsing this DOI-free Scopus export rather than to a genuine absence of internal citation structure. Even by this corrected count, intra-corpus citation remains sparse relative to corpus size, consistent with the citation lag documented in Section 3.1 (Fig. S1), given that 37% of the corpus was published in 2025–2026.

4. Discussion

4.1 Principal Findings and Field Maturity

This bibliometric analysis showed that scientific activity on liquid and water-soluble fertilizers grew consistently, albeit unevenly, between 2021 and 2026, confirming that the field is in an active phase of development (Section 3.1). At the same time, the findings reveal a discrepancy between the field's institutional and conceptual maturity. Institutionally, the field has not yet stabilized (Sections 3.2, 3.4). This should be read with caution: deviation from the classical Lotka exponent is common in young, fast-

growing fields generally, so the pattern is at least as consistent with the field's youth as with a specific lack of institutional consolidation. Conceptually, however, the field already shows meaningful consolidation: the thematic map and keyword co-occurrence network (Section 3.3) converge on a compact set of core concepts (fertigation, water-soluble fertilizer, and liquid fertilizer) around which more specialized themes organize themselves coherently. A comparable dual pattern (institutional immaturity alongside conceptual coherence) has been reported for other young, rapidly expanding sub-fields within agricultural chemistry, including mineral and slow/controlled-release fertilizers [27] and soil chemicalization research [28]; given that this comparison rests on only two prior studies, we treat it as suggestive rather than a firmly established generalization. One plausible driver of this pattern is that conceptual consolidation in applied agronomic fields can be shaped by external forces (shared funding priorities, regulatory frameworks for nutrient management, and circular-economy policy agendas in major producing countries) that impose a common vocabulary on researchers well before they form stable, cross-institutional collaborations.

Read through the lens of sustainability, this externally driven convergence is significant: it suggests the field is already aligning its vocabulary with resource-efficiency and circular-economy goals even before its research community has organizationally consolidated, reflecting a conceptual readiness that the right funding and integration mechanisms could translate into coordinated progress toward the SDGs.

4.2 Geographic and Institutional Concentration: Implications

The dominance of China and India, and the concentration of institutional output within a small number of leading centers (Section 3.2), together with the tendency of author and country collaboration to cluster within rather than across national and institutional boundaries (Section 3.4), points to a need for broader international integration if the field is to mature beyond its current constellation of largely independent national research programs. From a sustainability perspective, this geographic concentration carries particular implications: if the field's transition toward sustainable nutrient management is to have global reach, it will require deliberate efforts to build research capacity and international collaboration in regions (including Sub-Saharan Africa, Central Asia, and Latin America) where precision fertilization infrastructure is most needed but scientific representation remains limited.

4.3 Conceptual Evolution: From Fertigation Technique to Sustainability Integration

The thematic evolution analysis (Section 3.3, Fig. 7) revealed an important shift in the field's conceptual development: whereas narrow, technically oriented concepts (fertigation, drip irrigation) dominated the first sub-period (2021–2023), the second sub-period (2024–2026) saw "sustainable agriculture" consolidate as an independent, high-centrality node (Fig. 6) and new terms ("rhizosphere", "soil amendment", "biomass") emerge in the trend-topic analysis (Fig. S7). This integration of fertigation from a narrow technical concern into a broader sustainability discourse is consistent with the circular-economy and bio-based fertilizer literature discussed above [20, 21], and parallels the waste-to-nutrient-

recovery landscape mapped by Babcock-Jackson et al. [53], whose review likewise identified waste valorization and green ammonia synthesis as rapidly growing sub-themes [54]. Liquid fertilizer followed a related but distinct trajectory: rather than being absorbed into this broader sustainability discourse, it retained the strongest self-connection in the entire thematic evolution diagram (Section 3.3) while simultaneously branching outward, showing that its conceptual centrality has grown, not eroded, even as the field diversifies around it. The keyword co-occurrence network (Section 3.3) reinforces this picture: the circular-economy cluster is directly linked to, rather than isolated from, the core fertigation cluster, suggesting that waste-based and precision-agronomic strands of this literature are becoming increasingly integrated rather than developing as separate sub-fields.

In sustainability terms, this integration is the study's central substantive signal: the field’s most generative concept (liquid fertilizer) is actively bridging precision-agronomic efficiency and waste-derived, circular nutrient sourcing: the two mechanisms through which the sector can most plausibly reduce its resource and emission intensity, directly contributing to SDG 12 (Responsible Consumption and Production) and SDG 2 (Zero Hunger).

4.4 Implications for Steering the Field's Sustainability Transition

The mapping yields a coherent, actionable picture: conceptually, the field is converging on cleaner-production themes, yet institutionally it remains fragmented (Sections 3.2–3.4). This mismatch, rather than any single ranking, is the study's most consequential finding, and it points to three priorities for accelerating the transition the field is already moving toward, summarized by stakeholder in Table 4.

First, research capacity on the sustainability frontier is dispersed. Because the circular-economy cluster is linked to, but not yet embedded within, the core fertigation cluster (Section 3.3, Fig. 8), targeted funding and multilateral programs connecting the isolated groups working on nutrient recovery, loss reduction, and resource-efficient fertigation would advance the field more than additional dispersed single-group output; the prevalence of single-document authors (87.7%; Section 3.2) reinforces that this productive base is thin.

Second, liquid fertilizer's role as the field's most generative conceptual node (Section 3.3) makes it the natural entry point for a synthesis that couples precision fertigation with waste-derived nutrient recovery, the coupling most likely to reduce dependence on virgin mineral inputs and associated emissions.

Third, the consolidation of “sustainable agriculture” as an independent motor theme in 2024–2026 (Section 3.3) indicates that the evidence base is mature enough to inform policy: liquid and water-soluble fertilizer technologies can be written explicitly into sustainable-intensification and nutrient-management instruments.

Table 4
Principal findings and corresponding sustainability-oriented actions.

Finding	Primary stakeholder	Suggested action (sustainability lens)
Conceptual convergence on sustainability and circular-economy themes, but institutional fragmentation (Sections 3.3–3.4)	Funding agencies	Fund cross-institutional consortia focused on the resource-efficiency and circular-nutrient frontier rather than dispersed single-group work
Collaboration fragmented into 25 clusters; 15.4% international co-authorship (Sections 3.2, 3.4)	International programs	Integrate isolated groups working on nutrient recovery, loss reduction, and efficient fertigation into multilateral networks
Liquid fertilizer is the most generative node, bridging precision delivery and circular sourcing (Section 3.3)	Researchers	Use liquid fertilizer as the entry point for work coupling precision fertigation with waste-derived nutrient recovery
“Sustainable agriculture” consolidated as an independent motor theme (Section 3.3)	Policymakers	Embed liquid and water-soluble fertilizer technologies in sustainable-intensification and nutrient-management policy
Sparse but genuine intra-corpus citation linkage (23 of 201 documents; Section 3.4)	Journal editors	Encourage synthesis work that explicitly bridges the precision-agronomic and circular-nutrient strands

4.5 Study Limitations

Several boundary conditions frame these results. First, the corpus comprises 201 documents. This is not a sample but a near-complete census of the field as delimited by our protocol: liquid and water-soluble fertilizer research is a young, precisely bounded subfield, and its modest volume is a characteristic of the field itself rather than an artefact of restrictive filtering, since a focused Boolean strategy deliberately prioritized precision over raw volume. Second, reliance on Scopus alone entails a known coverage bias: documents indexed only in Web of Science, regional databases, or the grey literature fall outside the frame, so our indicators should be read as characterizing the Scopus-indexed core of the field [39]; a dual-database extension incorporating Web of Science is a natural direction for future work as the field matures. Third, only English-language publications were included, potentially excluding relevant non-English studies. Fourth, institutional productivity (Fig. S4) used first-listed affiliations only; a full-counting approach would likely credit internationally collaborative institutions more highly and offers a useful cross-validation for future work. Fifth, because the query required co-occurrence with a second block of agronomic and technical terms (Section 2.1), documents discussing liquid or water-soluble fertilizers in purely compositional, regulatory, or market terms were excluded; the corpus should thus be read as a technically oriented subset of the field, and the bio-based and organic sub-branch identified in Section 3.3 as a lower-bound estimate of its true activity. Finally, the 7.5% missingness in the corresponding-author field (Table 1) means that country-level collaboration indicators should be interpreted with some caution.

5 Conclusions

To our knowledge, this is the first bibliometric mapping dedicated to liquid and water-soluble fertilizer research. The field is in a consistent but not yet consolidated growth phase: its institutional structure, author productivity, collaboration patterns, and geographic distribution (Sections 3.1–3.2, 3.4), remains fragmented, carrying direct implications for its capacity to contribute to global sustainability goals, particularly SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production).

Conceptually, however, the field is converging: it is evolving from narrow fertigation concerns toward sustainability and circular-economy integration, with liquid fertilizer as the most generative node seeding, rather than being absorbed by, these newer directions (Section 3.3), and an internal citation structure that, once a software-specific parsing limitation was resolved, proved sparse but genuine, consistent with the pronounced citation lag of a young, rapidly publishing field (Section 3.4). The central message is the mismatch between this conceptual convergence and the field's institutional fragmentation: research on liquid and water-soluble fertilizers is already oriented toward sustainable, resource-efficient nutrient management, but it lacks the integrated structure needed to advance that agenda efficiently.

Accordingly, the priority is not more dispersed output but coordinated effort on the sustainability frontier: coupling precision fertigation with waste-derived nutrient recovery, integrating the groups now working separately on these strands, and quantifying the resource-efficiency outcomes the field aspires to. Methodologically, future work should extend the mapping to multiple databases, apply a bio-based terminology-specific search, and use full-counting institutional analysis. These constraints (Section 4.5) bound the precision of country, institution, and sub-branch-level findings but do not alter the field-level patterns. By providing the first evidence base for this field, the study equips researchers, funding agencies, and policymakers to steer its emerging transition toward sustainable, resource-efficient nutrient management and to align that transition with the Sustainable Development Goals, particularly in regions where the need for precision fertilization and circular-economy approaches is greatest.

Declarations

Competing interests

The authors declare no competing interests.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Supplementary information

Supplementary data to this article can be found online. File S1: Scopus search query, export parameters, and PRISMA screening log; File S2: Full exported bibliographic dataset (CSV); File S3: Consolidated R scripts (bibliometrix/Biblioshiny) and VOSviewer parameter/thesaurus files used for all bibliometric analyses, including the localCitations() and histNetwork() verification underlying Fig. 10; File S4: Supplementary figures S1–S10, referenced throughout Section 3 (annual citation intensity, source productivity, author productivity, institutional productivity, country collaboration map, three-field plot, trend topics, country collaboration network, bibliographic coupling network, and co-citation network).

Funding

This research received no external funding.

Author Contribution

Author contributionsShuhratjon Yu. Nomozov: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization, Project administration. Atanazar R. Seytnazarov: Validation, Resources, Writing – review and editing, Supervision. Umarbek K. Alimov: Validation, Writing – review and editing. Shafaat S. Namazov: Resources, Writing - review and editing. Lazizjon L. Abdullayev: Formal analysis, Writing - original draft, Visualization.

Data Availability

The data presented in this study, including the search query, exported bibliographic records, and R code used for analysis, are available as Supplementary Materials.

References

1. Ludemann CI, Wanner N, Chivenge P, Dobermann A, Einarsson R, Grassini P et al. A global FAOSTAT reference database of cropland nutrient budgets and nutrient use efficiency (1961–2020): nitrogen, phosphorus and potassium. Earth Syst Sci Data [Internet]. 2024 [cited 2026 July 24];16:525–41. https://doi.org/10.5194/essd-16-525-2024
2. FAO, Inorganic fertilizers, Rome. Italy: FAO; 2025 [cited 2026 July 24]. https://doi.org/10.4060/cd5938en
3. Erisman JW, Sutton MA, Galloway J, Klimont Z, Winiwarter W. How a century of ammonia synthesis changed the world. Nat Geosci [Internet]. 2008;1:636–9. https://doi.org/10.1038/ngeo325. [cited 2026 July 24];.

4. Stewart WM, Dibb DW, Johnston AE, Smyth TJ. The Contribution of Commercial Fertilizer Nutrients to Food Production. Agron J [Internet]. 2005;97:1–6. https://doi.org/10.2134/agronj2005.0001. [cited 2026 July 24];.
5. Singh B, Singh AK, Singh J, Rani P. Impact of Chemical Fertilizers on Soil Health and Environmental Quality. Orient J Chem 2026 [Internet]. 2026 [cited 2026 July 24];2:762. https://doi.org/10.13005/ojc/420237
6. Zhang L, Zhao Z, Jiang B, Baoyin B, Cui Z, Wang H et al. Effects of Long-Term Application of Nitrogen Fertilizer on Soil Acidification and Biological Properties in China: A Meta-Analysis. Microorganisms [Internet]. 2024 [cited 2026 July 24];12:1683. https://doi.org/10.3390/microorganisms12081683
7. Pan S-Y, He K-H, Lin K-T, Fan C, Chang C-T. Addressing nitrogenous gases from croplands toward low-emission agriculture. npj Clim Atmos Sci [Internet]. 2022;5:43. https://doi.org/10.1038/s41612-022-00265-3. [cited 2026 July 24];.
8. Kopittke PM, Menzies NW, Wang P, McKenna BA, Lombi E. Soil and the intensification of agriculture for global food security. Environ Int [Internet]. 2019;132:105078. https://doi.org/10.1016/j.envint.2019.105078. [cited 2026 July 24];.
9. Mueller ND, Gerber JS, Johnston M, Ray DK, Ramankutty N, Foley JA. Closing yield gaps through nutrient and water management. Nat [Internet]. 2012;490:254–7. https://doi.org/10.1038/nature11420. [cited 2026 July 24];.
10. Vollset SE, Goren E, Yuan C-W, Cao J, Smith AE, Hsiao T et al. Fertility, mortality, migration, and population scenarios for 195 countries and territories from 2017 to 2100: a forecasting analysis for the Global Burden of Disease Study. The Lancet [Internet]. 2020 [cited 2026 July 24];396:1285–306. https://doi.org/10.1016/S0140-6736(20)30677-2
11. Zhang X, Davidson EA, Mauzerall DL, Searchinger TD, Dumas P, Shen Y. Managing nitrogen for sustainable development. Nat [Internet]. 2015;528:51–9. https://doi.org/10.1038/nature15743. [cited 2026 July 24];.
12. Zheng M, Zhao Y, Zhang L, Hao L, Zhang Z, Lv L et al. Micro-Sprinkling Fertigation Enhances Wheat Grain Yield and Nitrogen Use Efficiency by Reducing N Redundancy and Increasing Root–Water–Nitrogen Spatiotemporal Coordination. Plants [Internet]. 2025 [cited 2026 July 24];14:2713. https://doi.org/10.3390/plants14172713
13. Liu S, Qiang X, Liu H, Han Q, Yi P, Ning H, et al. Effects of Nutrient Solution Application Rates on Yield, Quality, and Water–Fertilizer Use Efficiency on Greenhouse Tomatoes Using Grown-in Coir. Plants [Internet]. 2024;13:893. https://doi.org/10.3390/plants13060893. [cited 2026 July 24];.
14. Li H, Mei X, Wang J, Huang F, Hao W, Li B. Drip fertigation significantly increased crop yield, water productivity and nitrogen use efficiency with respect to traditional irrigation and fertilization practices: A meta-analysis in China. Agricultural Water Manage [Internet]. 2021 [cited 2026 July 24];244:106534. https://doi.org/10.1016/j.agwat.2020.106534

15. Kaviyazhagan S, Gurusamy A, Subramanian E, Prabhaharan J, Amutha R, Sivasankari B, et al. Drip fertigation of water-soluble fertilizers: A tool to enhance nutrient and water use efficiency- A comprehensive review. Plant Sci Today [Internet]. 2025. https://doi.org/10.14719/pst.10298. [cited 2026 July 24];12.
16. Ren W, Li X, Liu T, Chen N, Xin M, Qi Q et al. Impact of controlled-release fertilizer on nitrogen use efficiency, greenhouse gas emissions, and environmental sustainability in sunflower cropping systems. Eur J Agron [Internet]. 2026 [cited 2026 July 24];174:127963. https://doi.org/10.1016/j.eja.2025.127963
17. Li X, Zhang X, Wang S, Hou W, Yan L. The Combined Use of Liquid Fertilizer and Urease/Nitrification Inhibitors on Maize Yield, Nitrogen Loss and Utilization in the Mollisol Region. Plants [Internet]. 2023 [cited 2026 July 24];12:1486. https://doi.org/10.3390/plants12071486
18. Govindasamy P, Muthusamy SK, Bagavathiannan M, Mowrer J, Jagannadham PTK, Maity A et al. Nitrogen use efficiency—a key to enhance crop productivity under a changing climate. Front Plant Sci [Internet]. 2023 [cited 2026 July 24];14:1121073. https://doi.org/10.3389/fpls.2023.1121073
19. Fixen PE. A brief account of the genesis of 4R nutrient stewardship. Agron J [Internet]. 2020;112:4511–8. https://doi.org/10.1002/agj2.20315. [cited 2026 July 24];.
20. Aborisade MA, Long H, Rong H, Kumar A, Cui B, Oladeji OA et al. Bio-Based Fertilizers from Waste: Nutrient Recovery, Soil Health, and Circular Economy Impacts. Toxics [Internet]. 2026 [cited 2026 July 24];14:90. https://doi.org/10.3390/toxics14010090
21. Cordeiro CM, Sindhøj E. Situating the discourse of recycled nutrient fertilizers in circular economy principles for sustainable agriculture. Front Sustain [Internet]. 2024;5:1465752. https://doi.org/10.3389/frsus.2024.1465752. [cited 2026 July 24];.
22. Allouzi MMA, Allouzi SMA, Keng ZX, Supramaniam CV, Singh A, Chong S. Liquid biofertilizers as a sustainable solution for agriculture. Heliyon [Internet]. 2022;8:e12609. https://doi.org/10.1016/j.heliyon.2022.e12609. [cited 2026 July 24];.
23. Chojnacka K, Moustakas K, Witek-Krowiak A. Bio-based fertilizers: A practical approach towards circular economy. Bioresource Technol [Internet]. 2020;295:122223. https://doi.org/10.1016/j.biortech.2019.122223. [cited 2026 July 24];.
24. Donthu N, Kumar S, Mukherjee D, Pandey N, Lim WM. How to conduct a bibliometric analysis: An overview and guidelines. J Bus Res [Internet]. 2021;133:285–96. https://doi.org/10.1016/j.jbusres.2021.04.070. [cited 2026 July 24];.
25. Goyal S, Chauhan S, Mishra P. Circular economy research: A bibliometric analysis (2000–2019) and future research insights. J Clean Prod [Internet]. 2021;287:125011. https://doi.org/10.1016/j.jclepro.2020.125011. [cited 2026 July 24];.
26. Ranjbari M, Saidani M, Shams Esfandabadi Z, Peng W, Lam SS, Aghbashlo M et al. Two decades of research on waste management in the circular economy: Insights from bibliometric, text mining, and content analyses. J Clean Prod [Internet]. 2021 [cited 2026 July 24];314:128009. https://doi.org/10.1016/j.jclepro.2021.128009

27. Li X, Li Z. Global Trends and Current Advances in Slow/Controlled-Release Fertilizers: A Bibliometric Analysis from 1990 to 2023. Agriculture [Internet]. 2024 [cited 2026 July 24];14:1502. https://doi.org/10.3390/agriculture14091502
28. Bungau GS, Radu A-F, Radu A, Tit DM, Negru PA. Bibliometric Mapping of Soil Chemicalization and Fertilizer Research: Environmental and Computational Insights. Algorithms [Internet]. 2025 [cited 2026 July 24];18:660. https://doi.org/10.3390/a18100660
29. Gao S, He P, Fu Y, Li Y, Wang H, Wang Q et al. Mapping the Evolution of DSSAT Model Research: Trends, Transitions, and Future Frontiers. Agronomy [Internet]. 2026 [cited 2026 July 24];16:141. https://doi.org/10.3390/agronomy16020141
30. Vargas BC, Ribeiro Furtado Júnior M, Coelho ALDF, Privitera S, Lupica S, Trusso Sfrazzetto A et al. Bibliometric and Scientometric Analysis of the Application of Agricultural Pesticides at Variable Rates. Agriculture [Internet]. 2026 [cited 2026 July 24];16:557. https://doi.org/10.3390/agriculture16050557
31. Gao Z, Zhao L, Geng H, Li M, Chen D, Zhang Y. Bibliometric and literature review of the development of mineral fertilizers. Environ Sci Pollut Res [Internet]. 2023;31:27–42. https://doi.org/10.1007/s11356-023-31209-w. [cited 2026 July 24];.
32. Wang J, Wang B, Bian R, He W, Liu Y, Shen G et al. Bibliometric analysis of biochar-based organic fertilizers in the past 15 years: Focus on ammonia volatilization and greenhouse gas emissions during composting. Environ Res [Internet]. 2024 [cited 2026 July 24];243:117853. https://doi.org/10.1016/j.envres.2023.117853
33. Ouala O, Essadki Y, Oudra B, El Khalloufi F, Martins R. Bibliometric Analysis Towards Industrial-Scale Use of Marine Algae and Lichens as Soil Amendments and Plant Biofertilizers for Sustainable Agriculture. Phycology [Internet]. 2025 [cited 2026 July 24];5:29. https://doi.org/10.3390/phycology5030029
34. Kiruba NJM, Saeid A. An Insight into Microbial Inoculants for Bioconversion of Waste Biomass into Sustainable Bio-Organic Fertilizers: A Bibliometric Analysis and Systematic Literature Review. IJMS [Internet]. 2022 [cited 2026 July 24];23:13049. https://doi.org/10.3390/ijms232113049
35. Luo X, Li J, Guo S, Yu H, Zeng X, Zhou Z, et al. Analysis of research status and trends on nano-agricultural application: a bibliometric study. Front Plant Sci [Internet]. 2025;16:1530629. https://doi.org/10.3389/fpls.2025.1530629. [cited 2026 July 24];.
36. Yang L, Wang Z, Cui Y, Song Y, Zhou L, Wu W et al. Research progress on fertilizer carbon emissions: a bibliometric analysis (2008–2024). Front Environ Sci [Internet]. 2025 [cited 2026 July 24];13:1592151. https://doi.org/10.3389/fenvs.2025.1592151
37. Pang Y, Zhang M, Zhong H, Cevin T, Sun C, Zhang S et al. Current Progress and Future Trends in Carbon Sources and Sinks in Farmland Ecosystems: A Bibliometric Analysis (2002–2023). Biology [Internet]. 2025 [cited 2026 July 24];14:365. https://doi.org/10.3390/biology14040365
38. Yin J, Wang J, Zhao L, Cui Z, Yao S, Li G et al. Compost tea: Preparation, utilization mechanisms, and agricultural applications potential – A comprehensive review. Environmental Technology &

Innovation [Internet]. 2025 [cited 2026 July 24];38:104137. https://doi.org/10.1016/j.eti.2025.104137

39. Baas J, Schotten M, Plume A, Côté G, Karimi R. Scopus as a curated, high-quality bibliometric data source for academic research in quantitative science studies. Quant Sci Stud [Internet]. 2020 [cited 2026 July 24];1:377–86. https://doi.org/10.1162/qss_a_00019
40. Burnham JF. Scopus database: a review. Biomed Digit Libr [Internet]. 2006 [cited 2026 July 24];3:1. https://doi.org/10.1186/1742-5581-3-1.
41. Mongeon P, Paul-Hus A. The journal coverage of Web of Science and Scopus: a comparative analysis. Scientometrics [Internet]. 2016 [cited 2026 July 24];106:213–28. https://doi.org/10.1007/s11192-015-1765-5
42. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ [Internet]. 2021. https://doi.org/10.1136/bmj.n71. [cited 2026 July 24];n71.
43. Aria M, Cuccurullo C, bibliometrix. An R-tool for comprehensive science mapping analysis. J Informetrics [Internet]. 2017 [cited 2026 July 24];11:959–75. https://doi.org/10.1016/j.joi.2017.08.007
44. R Core Team. R: A Language and Environment for Statistical Computing [Internet]. Vienna, Austria: R Foundation for Statistical Computing; 2024. https://www.R-project.org/.
45. Van Eck NJ, Waltman L. Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics [Internet]. 2010 [cited 2026 July 24];84:523–38. https://doi.org/10.1007/s11192-009-0146-3
46. Eck NJV, Waltman L. How to normalize cooccurrence data? An analysis of some well-known similarity measures. J Am Soc Inf Sci [Internet]. 2009;60:1635–51. https://doi.org/10.1002/asi.21075. [cited 2026 July 24];.
47. Fruchterman TMJ, Reingold EM. Graph drawing by force-directed placement. Softw Pract Exp [Internet]. 1991;21:1129–64. https://doi.org/10.1002/spe.4380211102. [cited 2026 July 24];.
48. Blondel VD, Guillaume J-L, Lambiotte R, Lefebvre E. Fast unfolding of communities in large networks. J Stat Mech [Internet]. 2008. https://doi.org/10.1088/1742-5468/2008/10/P10008. [cited 2026 July 24];2008:P10008.
49. Bradford SC. Sources of Information on Specific Subjects. Engineering. 1934;137:85–6.
50. Lotka AJ. The Frequency Distribution of Scientific Productivity. J Wash Acad Sci. 1926;16:317–23.
51. Cobo MJ, López-Herrera AG, Herrera-Viedma E, Herrera F. An approach for detecting, quantifying, and visualizing the evolution of a research field: A practical application to the Fuzzy Sets Theory field. J Informetrics [Internet]. 2011;5:146–66. https://doi.org/10.1016/j.joi.2010.10.002. [cited 2026 July 24];.
52. Ward JH. Hierarchical Grouping to Optimize an Objective Function. Journal of the American Statistical Association [Internet]. 1963 [cited 2026 July 24];58:236–44. https://doi.org/10.1080/01621459.1963.10500845

53. Babcock-Jackson L, Konovalova T, Krogman JP, Bird R, Díaz LL. Sustainable Fertilizers: Publication Landscape on Wastes as Nutrient Sources, Wastewater Treatment Processes for Nutrient Recovery, Biorefineries, and Green Ammonia Synthesis. J Agric Food Chem [Internet]. 2023;71:8265–96. https://doi.org/10.1021/acs.jafc.3c00454. [cited 2026 July 24];.
54. Kodama TK, Nagano MS, Miyata HH, Ometto AR, Beal C. A comprehensive analysis of sustainable fertilizer-related publications within the context of circular economy: Insights from the field of business management. Clean Prod Lett [Internet]. 2024;7:100077. https://doi.org/10.1016/j.clpl.2024.100077. [cited 2026 July 24];.

Figures

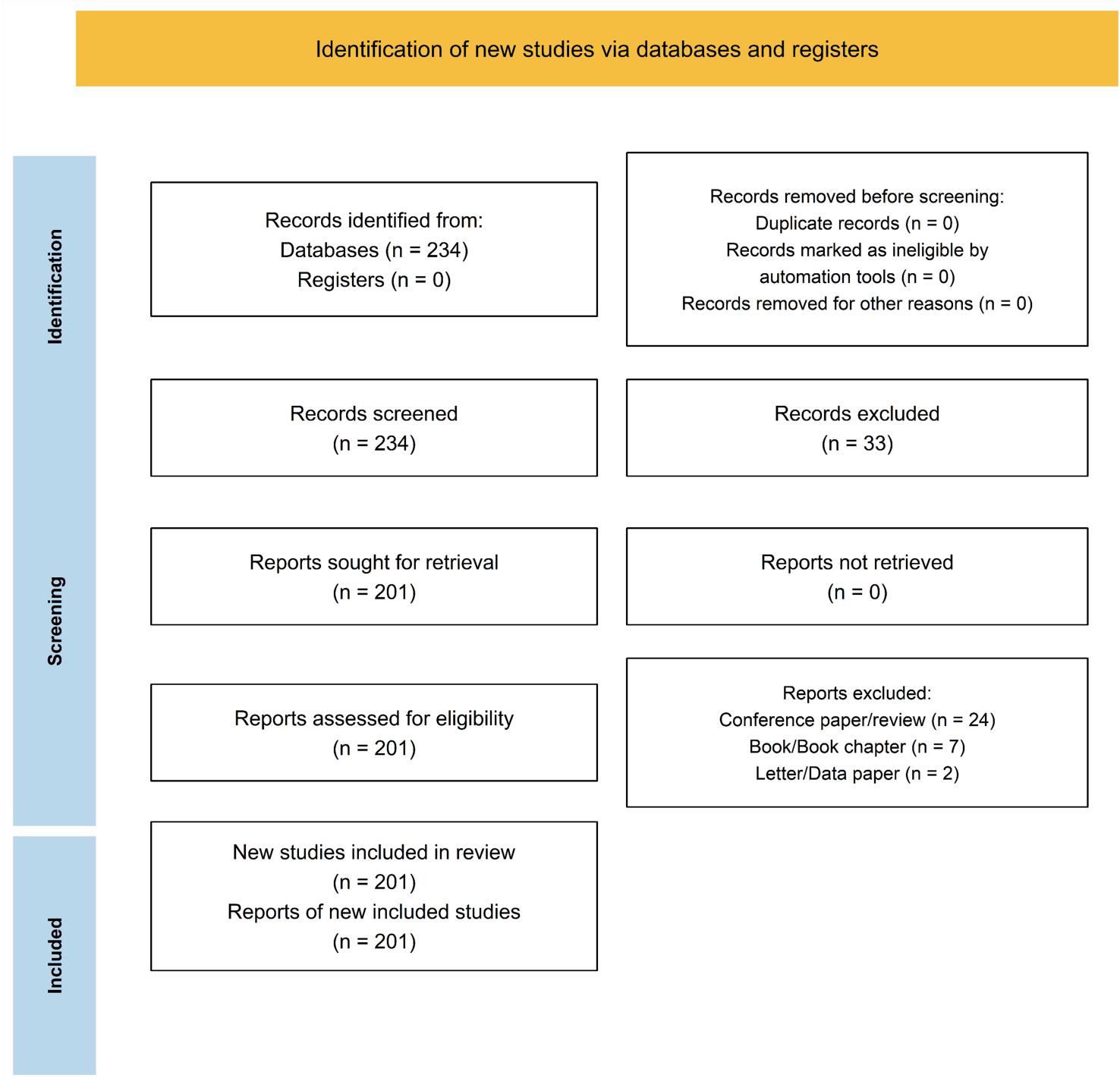


Figure 1

PRISMA 2020 flow diagram illustrating the study selection process for the bibliometric analysis of liquid and water-soluble fertilizer research.

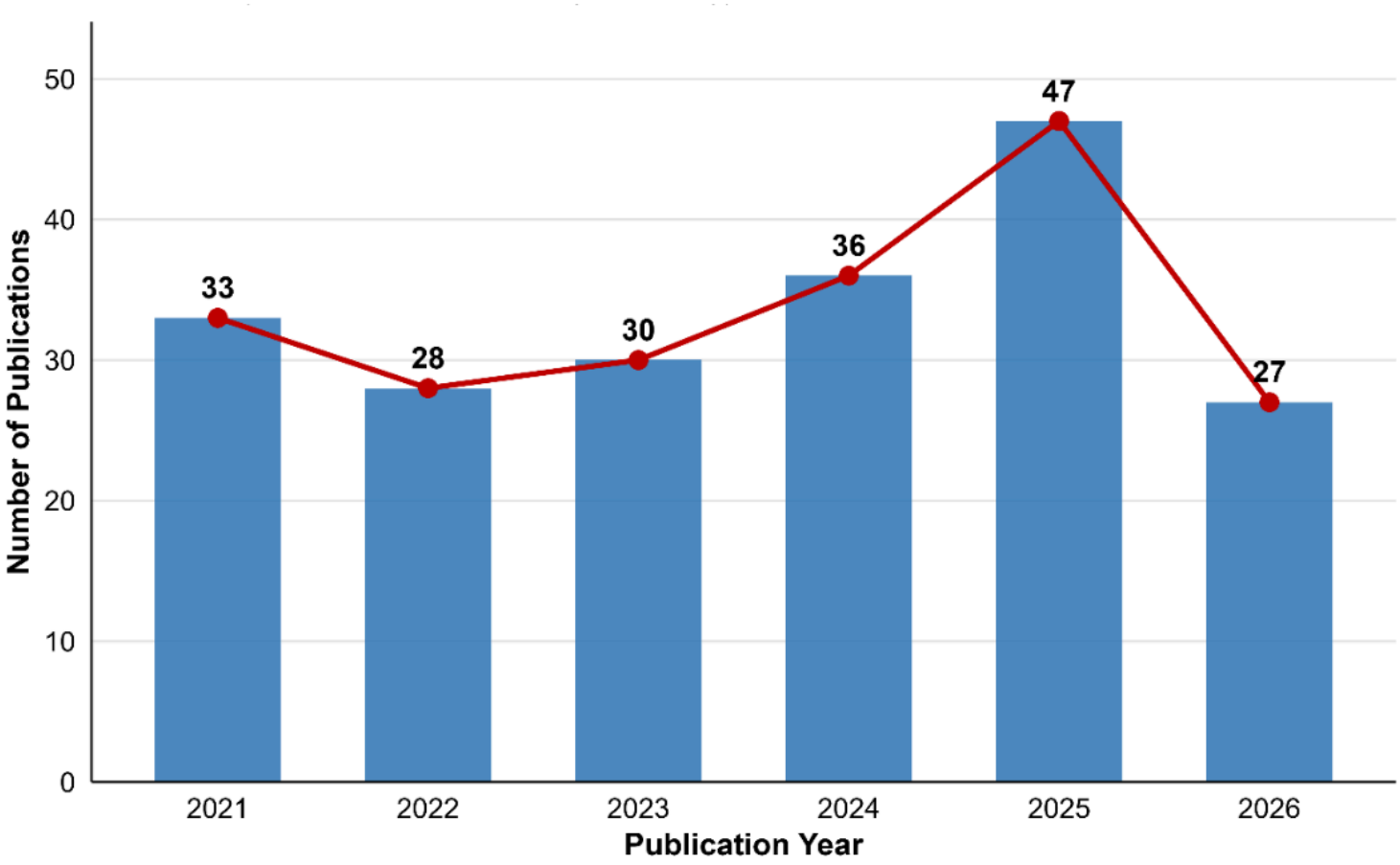


Figure 2

Annual scientific production on liquid and water-soluble fertilizer research indexed in Scopus (2021-2026); note that 2026 coverage is limited to January-June.

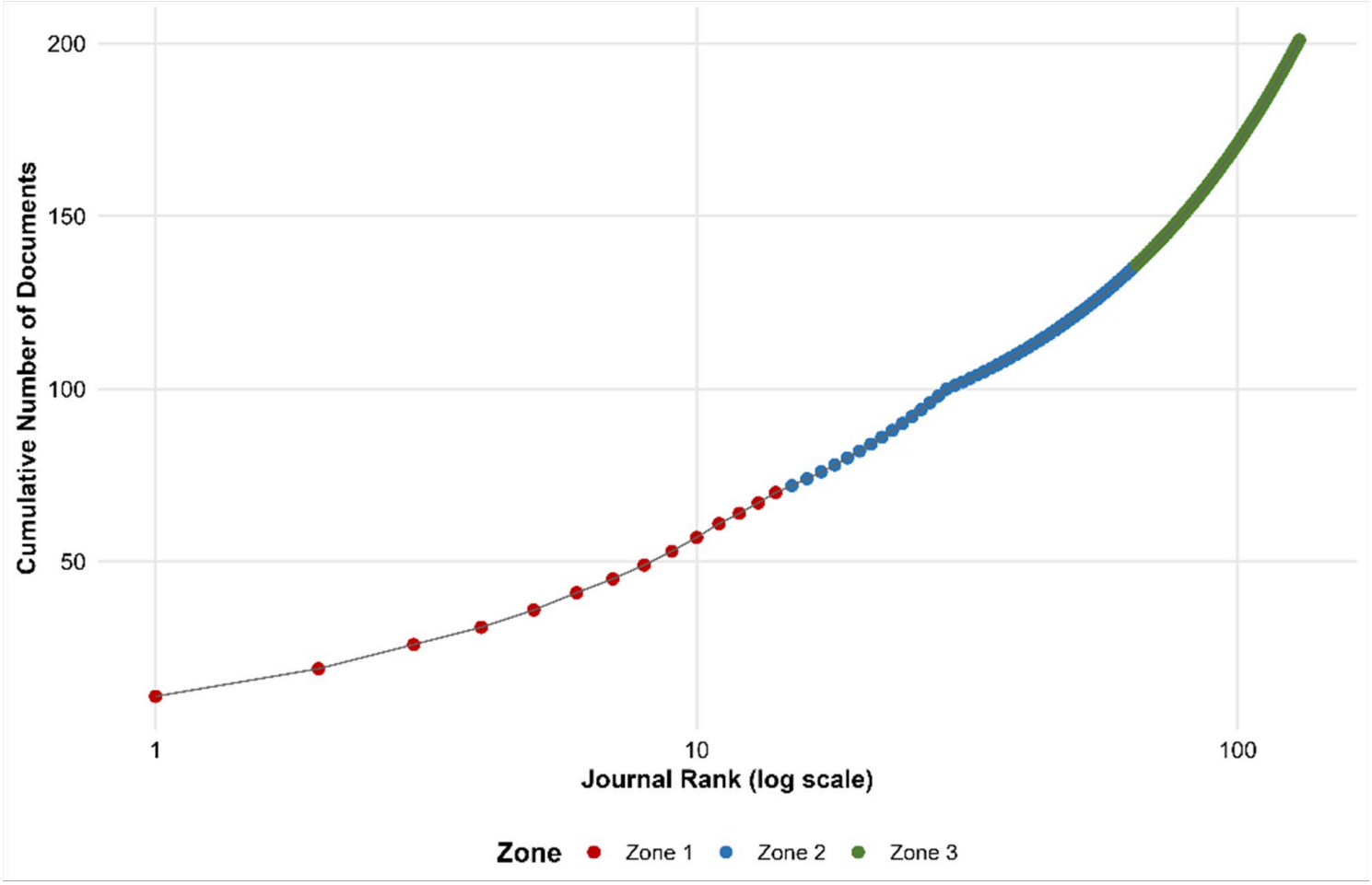


Figure 3

Bradford's Law analysis of journal productivity, partitioning the source set into Zone 1 (core, n = 14), Zone 2 (n = 50), and Zone 3 (n = 66).

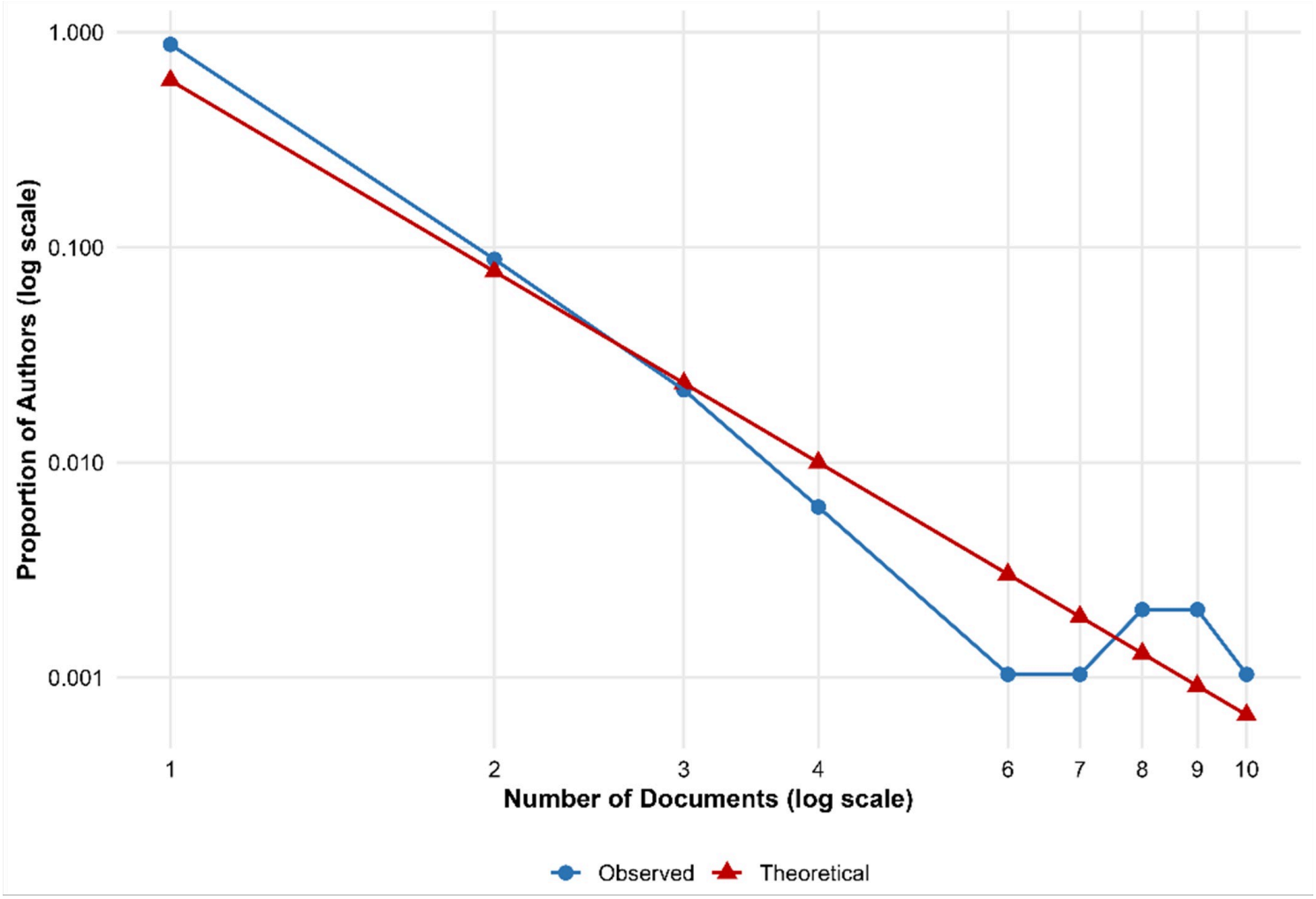


Figure 4

Author productivity distribution compared with the theoretical Lotka's Law curve (Beta = 2.95; R^2 = 0.933; Kolmogorov–Smirnov p = 0.037).

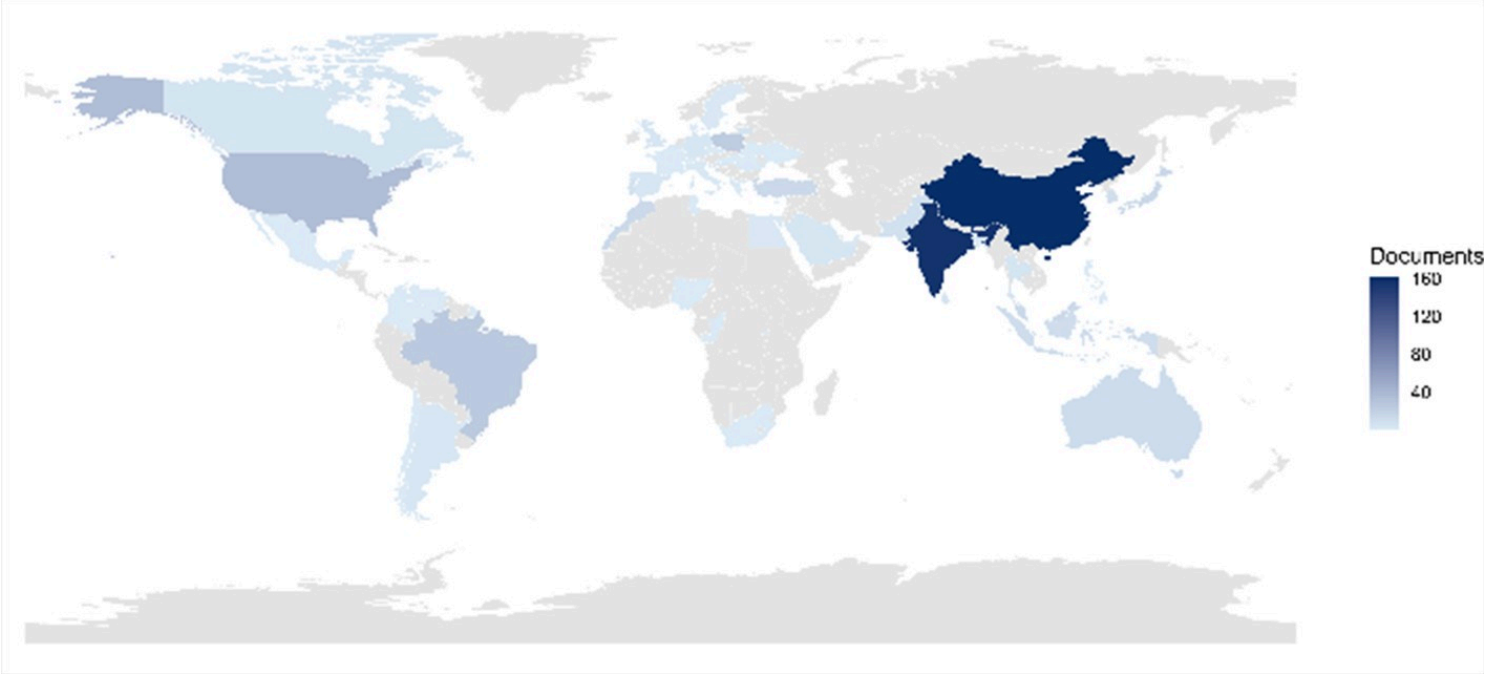


Figure 5

Country scientific production (choropleth map; full counting of all co-authors' countries).

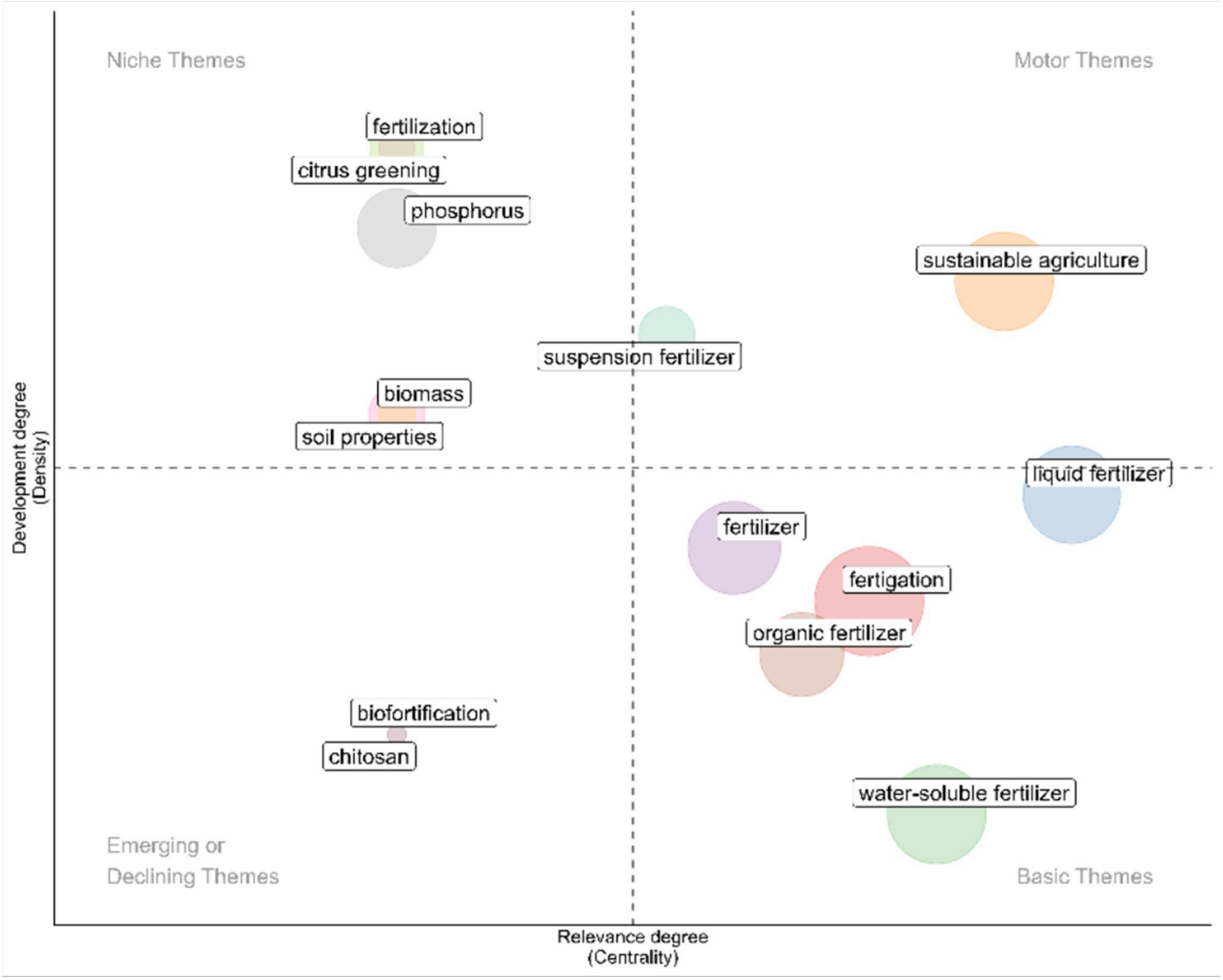


Figure 6

Thematic strategic diagram of author keywords, plotted by centrality (x-axis) and density (y-axis).

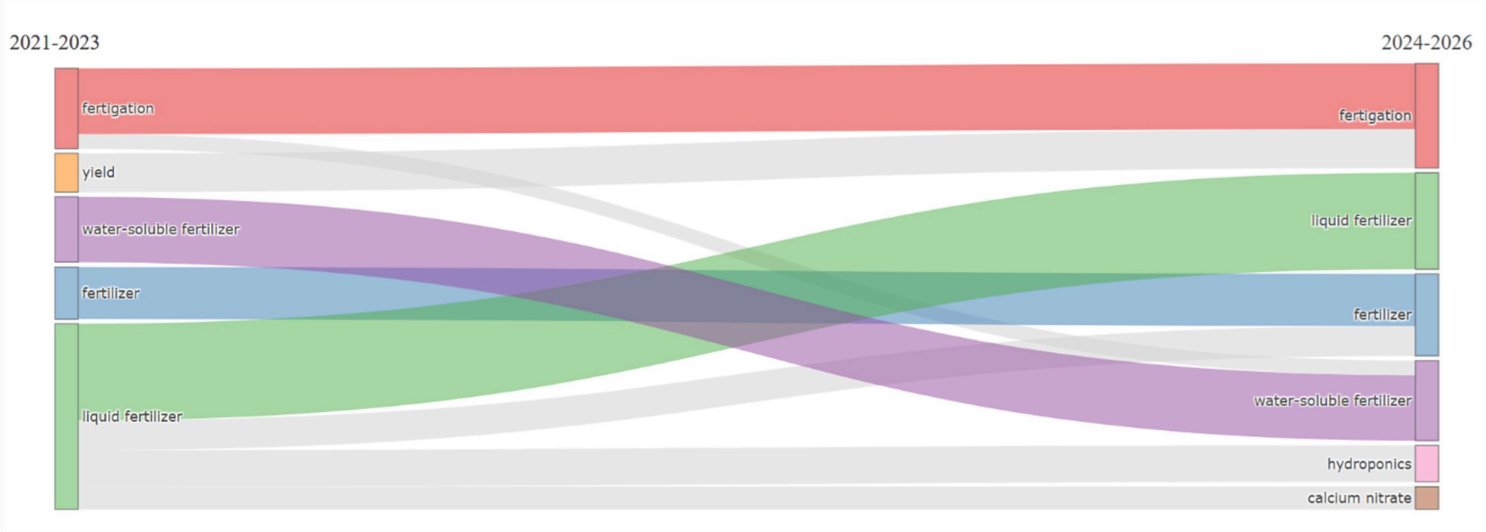


Figure 7

Thematic evolution of author keywords between 2021-2023 and 2024-2026, visualized as a Sankey diagram; link width is proportional to lineage strength.

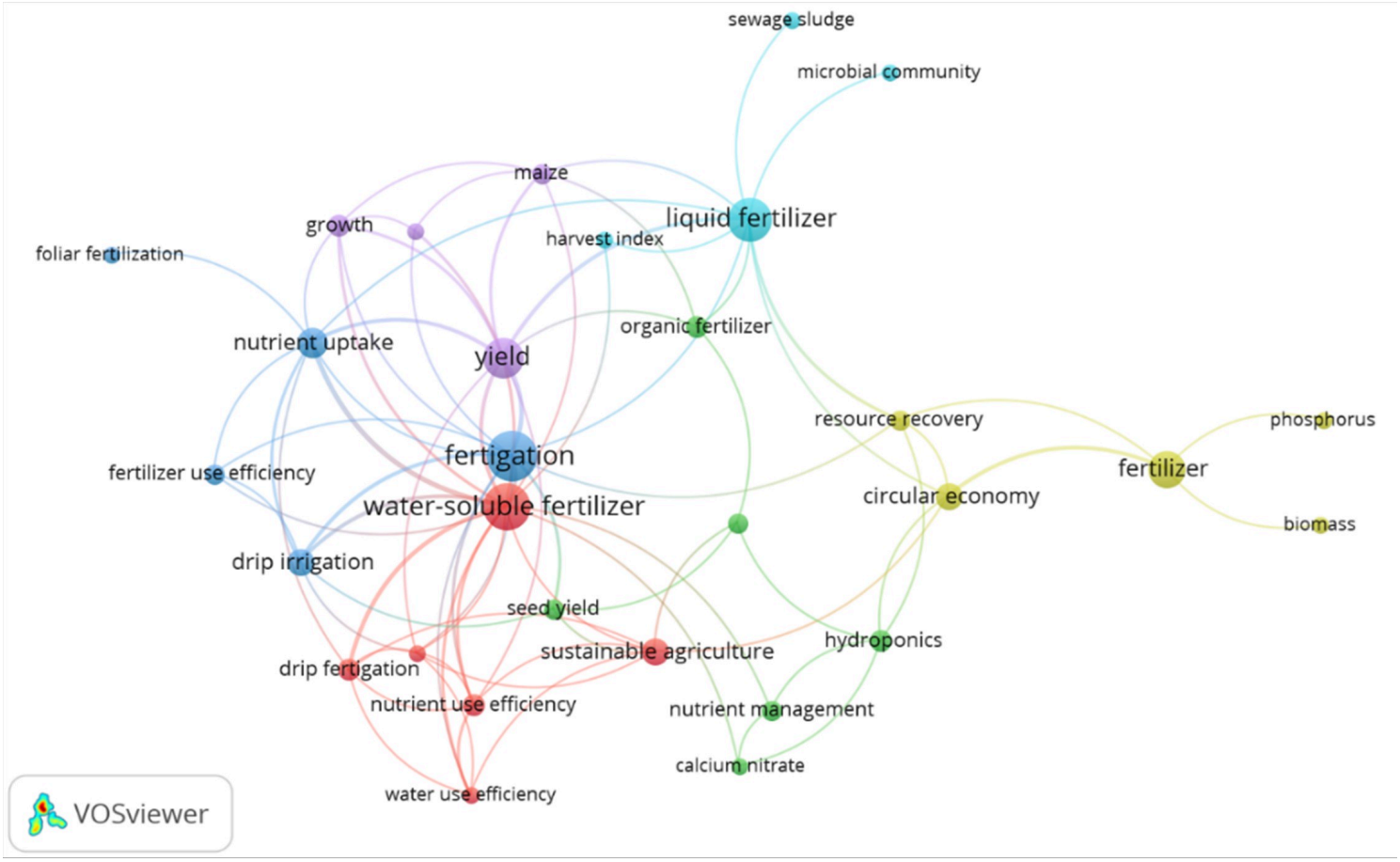


Figure 8

Keyword co-occurrence network (VOSviewer; author keywords, full counting, minimum occurrence = 3; six clusters, 30 items, 81 links).

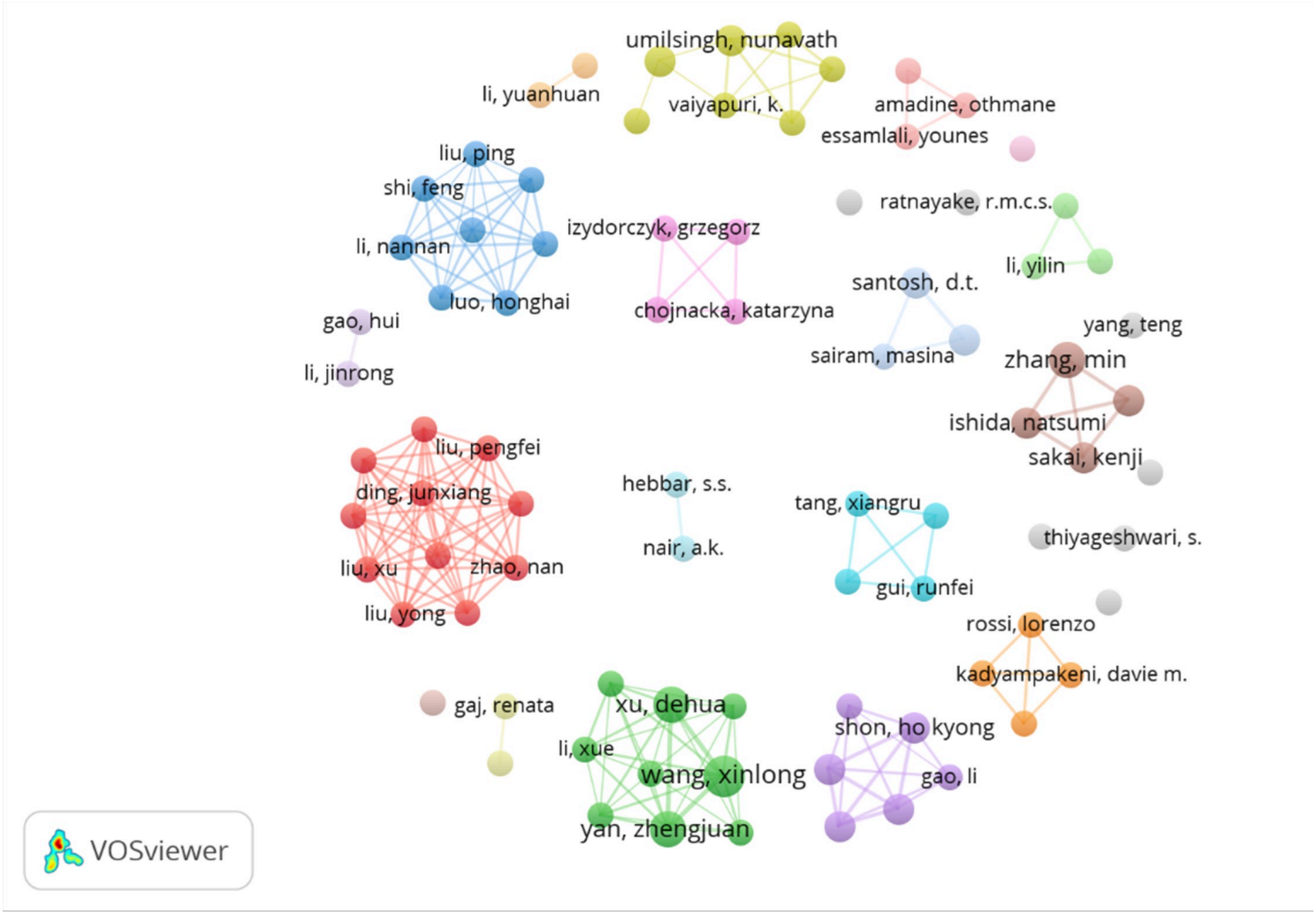


Figure 9

Author collaboration network (VOSviewer; co-authorship, minimum 2 documents/author; 83 items, 25 clusters, 181 links).

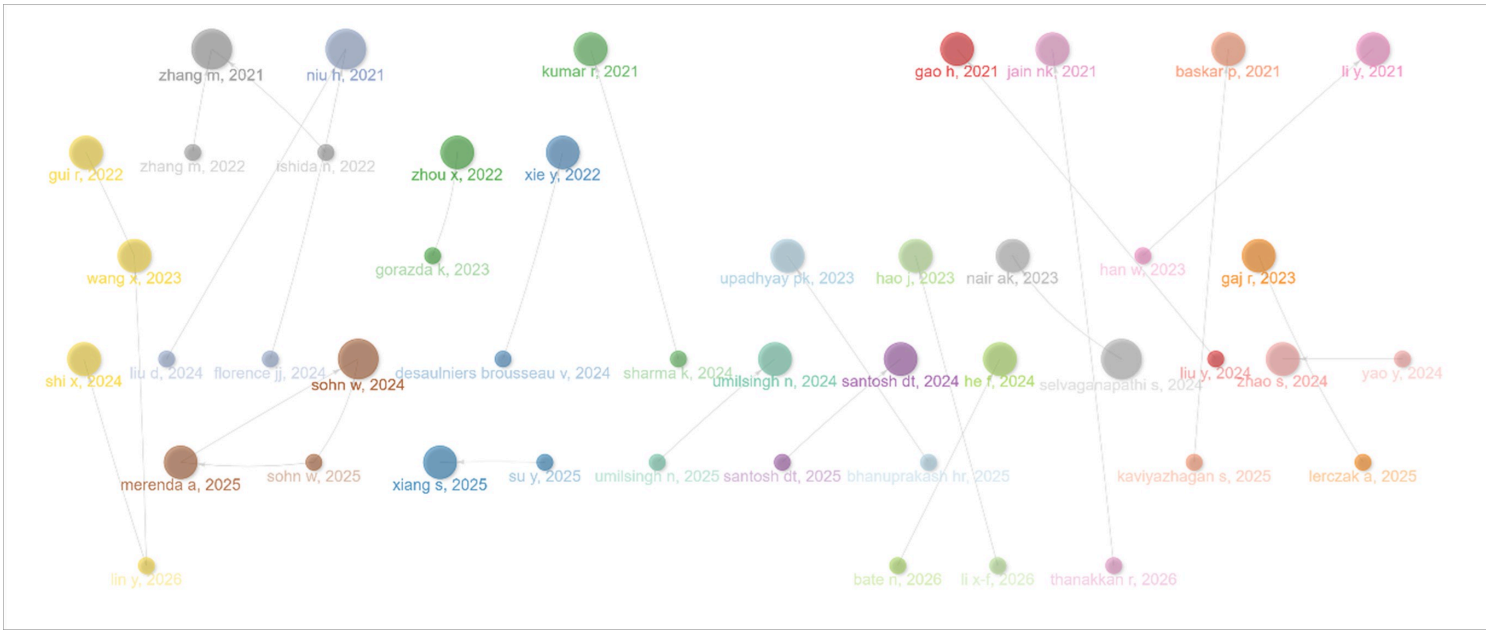


Figure 10

Historical direct citation network of the 45 documents participating in at least one intra-corpus citation (bibliometrix historiograph; author-year-source matching; 23 cited documents, 26 links).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- FileS1SearchQueryandPRISMALog.docx
- FileS2ScopusforVOSviewer201.csv
- FileS3RScripts.R.r
- FileS4SupplementaryFigures.docx