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Original Article

# Three-Dimensional Printing in Pharmaceutical Formulation and Drug Delivery: A Scientometric Analysis of 2,098 Scopus Documents, 1987–2026

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## ABSTRACT

**Objectives:** Three-dimensional (3D) printing has moved from a laboratory curiosity to a candidate platform for personalised, on-demand medicines, yet the structure of the research literature behind it has not been mapped quantitatively. This study analyses the growth, leading contributors, intellectual base and thematic structure of the Scopus literature on 3D printing and related additive-manufacturing technologies in pharmaceutical formulation and drug delivery. **Materials and Methods:** A Boolean search of Scopus (TITLE-ABS-KEY; subject areas Pharmacology/Toxicology/Pharmaceutics and Medicine; export dated 20 October 2026) returned 2,098 documents published between 1987 and 2027. Keyword co-occurrence (100 nodes, 1,168 edges) and reference co-citation (100 nodes, 4,931 edges) networks were built and partitioned with Louvain community detection in a custom Python pipeline (networkx, scikit-learn, matplotlib), and a simplified Kleinberg-style burst score was computed. **Results:** Output rose from 43 documents in 2017 to 104 in 2018 (141.86% growth) and reached 309 in 2025; 88.6% of all documents appeared from 2018 onward. The corpus has accumulated 90,730 citations (h-index 145). Basit, A.W. (104 documents), Goyanes, A. (81) and Gaisford, S. (72) are the most prolific authors, and University College London and the company FabRx dominate institutional output. India (444 documents), the United States (361) and the United Kingdom (341) lead in volume, but the United Kingdom leads in citations (31,151). The co-citation network resolved into three clusters of foundational printing papers (Q = 0.0604, S = 0.29); the keyword network resolved into four clusters (Q = 0.1343, S = 0.0458). Both modularity values lie below the conventional 0.3 threshold, indicating a diffuse structure, and only the keyword cluster centred on 3D printing and personalised medicine showed a coherent profile (S = 0.4742). **Conclusion:** The field is young, rapidly expanding, concentrated in a small number of groups, and increasingly linked to regulation, point-of-care manufacture and machine learning. Because only 75.4% of the retrieved records explicitly mention 3D-printing terms, results describe a broad "advanced formulation" literature in which 3D printing is the dominant but not the only theme.

**Keywords:** 3D printing; Additive manufacturing; Co-citation analysis; Drug delivery; Personalised medicine; Point-of-care manufacturing; Printlets; Scientometrics

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## INTRODUCTION

Conventional pharmaceutical manufacturing is built around fixed-dose products made in large batches. That model serves most patients adequately but fits poorly for children, older adults, people with rare diseases and anyone whose dose needs frequent adjustment, which is why clinicians and pharmacists routinely split tablets or compound preparations by hand. Three-dimensional (3D) printing, also called additive manufacturing, builds an object layer by layer from a digital design and so allows dose, geometry and internal architecture to be programmed for the individual patient.[1,2] A systematic review of the 2019 to spring 2024 literature identified more than 500 publications on 3D-printed dosage forms spanning oral, parenteral, cutaneous, rectal, vaginal, dental, intravesical and ophthalmic products,[1] which gives a sense of how quickly the topic has grown.

Several milestones explain why interest has accelerated. A 3D-printed *levetiracetam* product for epilepsy became the first printed drug to receive US regulatory approval.[3,4] More recently, a printed *sildenafil* tablet manufactured at the point of care met bioequivalence limits against its marketed originator in a crossover study of 12 healthy volunteers,[5] and reviewers now

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describe printing as moving from feasibility towards practice in hospital, community-pharmacy and industrial settings.[6] At the same time the field faces unresolved questions about quality control, allocation of regulatory responsibility across decentralised sites, and stability and scale-up.[4,7,8]

Printing is not limited to tablets. Printed microneedle arrays are being explored for minimally invasive transdermal and non-transdermal delivery,[9–11] multi-compartment polypills are being designed to simplify complex regimens,[12] and semi-solid extrusion is being applied to paediatric and orodispersible products.[13] A newer strand uses machine learning to predict printability and release behaviour, with the aim of replacing time-consuming trial-and-error formulation work.[14–16] This breadth makes the literature difficult to survey by hand, and it is precisely the kind of heterogeneous, fast-growing body of work for which quantitative mapping is useful.

Narrative reviews of pharmaceutical 3D printing are plentiful, but they differ in scope, are usually organised by technology or dosage form, and are limited by the number of papers an author team can read. They seldom answer structural questions: how quickly has the literature grown, who produces it, which publications form its intellectual base, and which topics are rising or fading? A scientometric analysis answers these questions from the bibliographic record itself and complements, rather than replaces, expert synthesis. To our knowledge no network-based scientometric mapping of this literature has been reported with the scope and data volume used here, although we cannot exclude earlier unpublished or non-indexed work.

This paper therefore asks four questions. (RQ1) How has the volume of Scopus-indexed literature on 3D printing in pharmaceutical formulation and drug delivery evolved? (RQ2) Which authors, institutions, countries and journals contribute most? (RQ3) What intellectual base and thematic clusters can be recovered from reference co-citation and keyword co-occurrence networks? (RQ4) Which references and topics show bursts of attention, and how do they relate to recent external developments in the field?

The analysis uses 2,098 Scopus records retrieved with a single Boolean search and exported on 20 October 2026. Section 2 reviews recent syntheses of the field. Section 3 describes the data and methods, Section 4 reports the results, Section 5 discusses them against recent external literature, and Section 6 concludes with limitations-aware future directions.

## Related literature

Recent reviews show how the field is usually organised. Auel *et al.*[1] grouped more than 500 publications by site of administration and noted that approaches to development remain very diverse. Paccione *et al.*[2] concentrated on oral dosage forms and observed that Fused Deposition Modelling (FDM) is still the most studied technology even as others gain ground. Pan *et al.*[17] argued that printing can support continuous, small-scale manufacturing and so avoid several drawbacks of multi-step oral solid dosage production, while Sierra-Vega *et al.* (2025)[63] emphasised critical process parameters, material attributes and real-time analytical tools needed to assure quality. For early clinical development, Milliken *et al.*[18] concluded that printing is better suited to small adaptive batches than to replacing conventional mass production.

Application-specific reviews add depth. Keerikkadu *et al.*[12] reviewed printed polypills and listed inconsistent production, regulatory approval, scale-up and long-term stability as translational barriers. Three reviews of printed microneedles[9–11] describe expanding fabrication options and flag manufacturing cost, material compatibility and regulatory issues. A review of computational intelligence in printed products[16] covers prediction of printability, optimisation of release rates and structural design, and a regulatory-oriented review[4] stresses the need for harmonised frameworks covering feedstock materials and process parameters.

Within the analysed corpus the most highly cited documents tell a similar story. Reviews on printing in pharmaceutics such as Goole & Amighi, 2016[57], Jamróz *et al.*, 2018 and Aimar *et al.*, 2019 are among the ten most cited items, alongside broader syntheses on oral drug delivery,[19] lipid-based delivery,[20] *polylactic acid* carriers,[21] bioprinting[22] and artificial intelligence.[23] Table 6 lists these documents. Their presence indicates that the retrieved corpus spans printing-specific work and wider formulation science, a point that shapes the interpretation of every network reported below.

What these reviews do not provide is a corpus-level, reproducible picture of growth, authorship, intellectual foundations and thematic drift. The present study supplies this picture and uses it to test whether the clusters and bursts correspond to the developments that the recent expert literature highlights.

# MATERIALS AND METHODS

## Rationale for a scientometric approach

Pharmaceutical 3D printing is interdisciplinary (pharmaceutics, polymer science, engineering, clinical pharmacy and regulatory science), has expanded rapidly, and now includes thousands of papers. Co-citation and keyword co-occurrence networks provide a structured, replicable way to see which works form the shared intellectual base and how topics group together, while burst

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detection highlights terms and references whose usage surged in specific periods.

## Data source and search strategy

Data were obtained from Scopus. The search was run on TITLE-ABS-KEY and limited to the Pharmacology, Toxicology and Pharmaceutics and the Medicine subject areas. The exact query recorded by Scopus was:

*TITLE-ABS-KEY (("3D print*" OR "three-dimensional print*" OR "additive manufacturing" OR "4D print*" OR "fused deposition modeling" OR "FDM" OR "selective laser sintering" OR "SLS" OR "stereolithography" OR "direct powder extrusion" OR "binder jet*") AND ("drug delivery" OR "personalized dosage" OR "polypill*" OR "printlet*" OR "controlled release" OR "implantable" OR "microneedle*" OR "orodispersible film*") AND ("pharmaceutic*" OR "formulation*" OR "medication*" OR "biopharmaceutic*")) AND (LIMIT-TO (SUBJAREA, "PHAR") OR LIMIT-TO (SUBJAREA, "MEDI"))*

The record export was dated 20 October 2026 and contained 2,098 documents (45 fields per record, including abstracts, author keywords, index keywords, affiliations and cited references). No document type, language or date filter was applied beyond the query, so the corpus includes articles (1,237; 59.0%), reviews (679; 32.4%), book chapters (86), editorials[24] and a small number of other types; 2,063 documents are in English and 26 in Chinese. The Scopus export did not include the number of records before the subject-area limit, so a full PRISMA-style flow with exclusion counts cannot be reported; the figure of 2,098 is the number retrieved and analysed. Publication years run from 1987 to 2027. Because retrieval took place in October 2026, the year 2026 is incomplete (292 documents), and 9 documents carry a 2027 date because they were indexed as articles in press (36 documents in total were in press).

## Data preparation

Two preparation steps were applied before analysis, and both are stated because they affect the results. First, for the keyword network only author keywords were used. Scopus index keywords include generic controlled-vocabulary terms such as "article", "human" and "nonhuman" that connect almost every record to every other and, in a first trial run, produced a network with density 0.986 and modularity of 0.078 that carried no thematic information. Spelling variants of the same concept (for example "3D printing", "3-D printing" and "three-dimensional printing"; "fused deposition modeling" and "fused deposition modelling"; "personalized" and "personalised medicine") were merged by a rule-based dictionary, and twelve generic terms were dropped. Second, Scopus reference strings place several authors in one semicolon-delimited block, which a naive split by semicolon misreads as separate references. References were therefore re-segmented on the closing "(year)" token and reduced to a key made of first-author surname, initials, an abbreviated source title and publication year, so that, for example, two different authors named "Wang" are not merged.

## Network construction, clustering and metrics

Analyses were run with a bundled Python script built on networkx, scikit-learn, pandas and matplotlib. It does not use CiteSpace, VOSviewer or Sci2, although the logic is conceptually equivalent to the co-occurrence and co-citation clustering those tools perform. Nodes are keywords (keyword network) or cited references (co-citation network); an edge links two nodes that appear together in the same document, and its weight is the number of such documents. Items appearing in fewer than 12 (references) or 8 (keywords) documents were discarded and the network was capped at the 100 most frequent items to keep it interpretable. Larger networks of 150 nodes and a minimum frequency of 5 were also tried, but they were almost fully connected (density above 0.98) and added no structure.

Clusters were identified with the Louvain algorithm. Modularity (Q) measures how strongly the network divides into groups; values above 0.3 are conventionally taken to indicate meaningful clustering. The silhouette-style coherence score (S) used here is the script's own measure, computed per cluster as (a – b) / max(a, b), where a is the mean weight of edges inside the cluster and b the mean weight of edges leaving it; it ranges from –1 to 1, and the reported S is the size-weighted mean across clusters. It is analogous to, but not identical with, the silhouette score reported by CiteSpace. Cluster labels are the most frequent member items. For each cluster, mean year is the mean publication year of the documents in the export that contain at least one cluster member; it therefore describes when the cluster is being used by the citing literature, not when its cited works were published. Density is the ratio of observed to possible edges.

Burst detection is a simplified Kleinberg-style procedure: each term or reference receives a strength score reflecting a period in which its yearly frequency rises sharply above its own baseline, with begin and end years defining the burst window. A burst indicates a temporal surge of attention, not proof of cause. *Bursts* with very small total frequencies (here 5 to 14 documents) and bursts in the final, incomplete year should be treated as tentative.

Author counts use the Scopus author-name strings, so name homonyms (for example "Zhang J.") can combine different individuals. For institutions, Scopus affiliation strings were grouped into institutions by pattern matching on institution names (for example, the "UCL School of Pharmacy", "Department of Pharmaceutics, UCL School of Pharmacy" and "University College London" variants were counted as one institution, and a document was counted once per institution). Country counts

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were taken from the last element of each affiliation string and counted once per document. Journals were counted from the Source title field. The h-index of the corpus was computed from document citation counts as of the export date.

## RESULTS

### Publication and citation trends

The corpus contains 2,098 documents that together received 90,730 citations, a mean of 43.25 and a median of 13 citations per document, and the corpus h-index is 145. Growth is strongly concentrated in recent years (Figure 1). Fewer than 10 documents a year were retrieved before 2010 (annual counts of 12 in 2010, 16 in 2011, 8 in 2012, 9 in 2013), output then rose to 22 in 2014 and 33 in 2015, and 43 documents appeared in 2017. The sharpest single step is 2018, with 104 documents, an increase of 141.86% on 2017. Counts were stable in 2019 (105; 0.96%) and then grew to 152 in 2020 (44.76%), 204 in 2021 (34.21%), a plateau of 200 in 2022 (-1.96%), 232 in 2023 (16.0%), 252 in 2024 (8.62%) and 309 in 2025 (22.62%). In total 1,859 documents (88.6%) were published from 2018 onward. The 2026 total of 292 reflects retrieval in October and is not a decline; the 9 documents dated 2027 are articles in press.

Citation totals by publication year peak in 2021 (14,903 citations to documents of that year) and fall for later years, which is the usual time-lag effect: recent documents have had less time to be cited, so the apparent drop does not signal declining influence. Of the 2,098 documents, 1,102 (52.5%) carry an open-access flag in the Scopus export.

### Leading authors, institutions, countries and journals

Table 3 lists the ten most prolific authors. Basit A.W. leads with 104 documents and 15,294 total citations, followed by Goyanes A. (81 documents; 13,706 citations) and Gaisford S. (72; 13,650). These three authors are closely associated with the same London research environment and account for far higher citation totals than the authors ranked fourth to tenth, whose totals range from 1,062 to 3,560. The remaining authors in the table are Lamprou D.A., Fatouros D.G., Maniruzzaman M., Repka M.A., Zhang J., Douroumis D., Awad A.. Because Scopus author names are not disambiguated here, entries such as Zhang J. may combine several researchers with the same name.

After grouping the many spelling variants of each institution, the University College London / UCL School of Pharmacy group is the most productive with 124 documents and 15,976 citations, followed by the company FabRx Ltd., UK (88 documents; 14,172 citations) (Table 4). The remaining institutions are the University of Santiago de Compostela, Spain (65), Queen's University Belfast, UK[23] and University of Mississippi, USA.[11] Eight of the ten institutions are in Europe (five of them in the United Kingdom) and two are in the United States, so institutional leadership is geographically concentrated even though country-level output is broader. Note that the unadjusted affiliation list produced by the script splits the same institutions into several entries (for example, UCL appears in three differently written forms), which understates every institution's true total; the grouped counts are therefore the ones reported.

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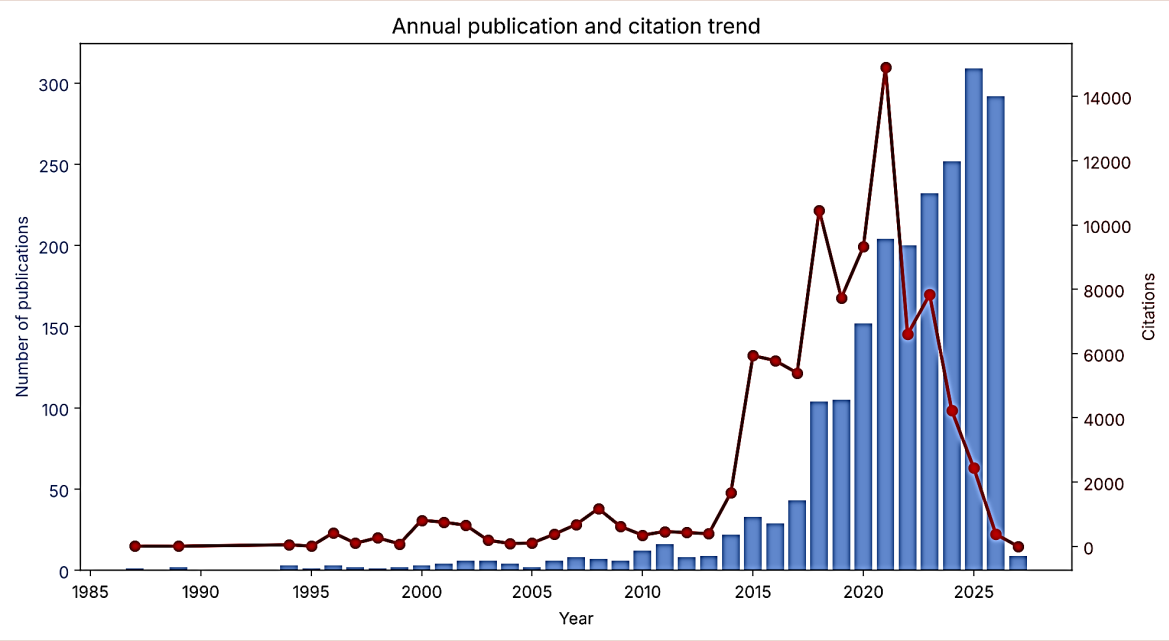


**Figure 1:** Annual number of publications (bars, left axis) and citations (line, right axis), 1987–2027. 2026 is incomplete (data retrieved 20 October 2026) and 2027 documents are articles in press.

*Citations are summed over documents carrying at least one affiliation of the institution and therefore overlap between collaborating institutions.*

By country, India contributes the most documents (444; 8,520 citations), followed by the United States (361; 16,644) and the United Kingdom (341; 31,151) (Table 5). The ranking changes sharply when citations are considered: the United Kingdom's 341 documents have received 31,151 citations, about 91 per document, compared with about 19 per document for India and 46 for the United States, and Spain (125 documents) has accumulated 10,031 citations. China (194), Italy (93), Germany (86) and Saudi Arabia (86) follow. These figures count a document once for each country present in its affiliations, so internationally co-authored papers contribute to more than one country.

Output is concentrated in a few journals. The International Journal of Pharmaceutics published 319 documents, and these have received 22,799 citations, the largest total of any source. Pharmaceutics follows with 225 documents (11,683 citations), then the Journal of Drug Delivery Science and Technology (105), the Journal of Controlled Release (88; 7,501 citations), AAPS PharmSciTech (79) and Advanced Drug Delivery Reviews (50; 7,063 citations). The ten most cited documents are listed in Table 6.

## Network structure

The keyword co-occurrence network (Figure 2) contains 100 nodes and 1,168 edges with a density of 0.236, a modularity of Q = 0.1343 and a weighted mean coherence score of S = 0.0458, and was partitioned into 4 clusters. Q lies well below the conventional 0.3 minimum, so the keyword network should be described as a relatively diffuse structure in which topics overlap heavily; the low S, with three of the four clusters showing negative coherence values, reinforces that most keyword clusters are not cleanly separated from the rest of the network. Only the cluster built around 3D printing itself has a clearly positive coherence (0.4742).

The reference co-citation network (Figure 3) contains 100 nodes and 4,931 edges (density 0.9962), with Q = 0.0604 and S = 0.29, and was divided into 3 clusters. Density this close to 1.0 means that nearly every pair of the 100 most-cited references is co-cited at least once, which is expected when a small number of landmark papers is cited together in many printing papers; it is unusually high compared with typical co-citation maps and it limits how

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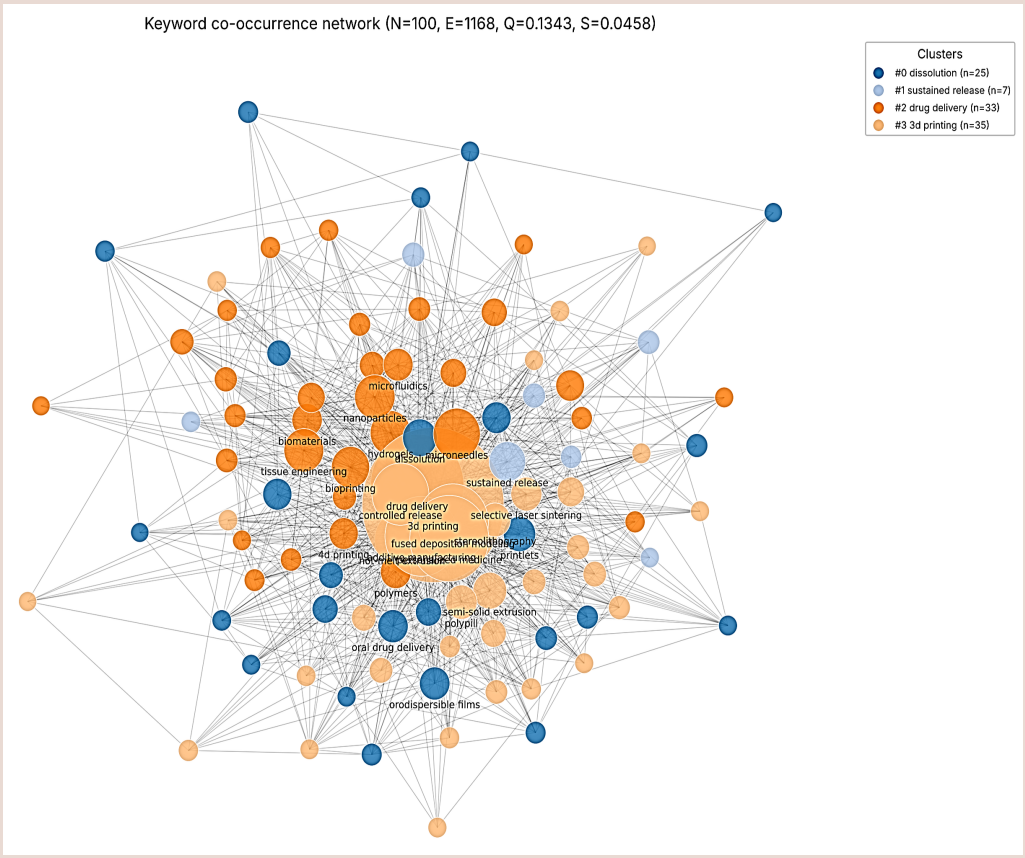


**Figure 2:** Author-keyword co-occurrence network (1987–2027). Node size is proportional to frequency; colour denotes cluster membership. *N* = 100, E = 1,168, density = 0.236, Q = 0.1343, S = 0.0458.

sharply any algorithm can separate groups. The low modularity says the same thing as for keywords: the three groupings reported below are tendencies in a densely interconnected core, not sharp boundaries, and the low S (0.29; below 0.3) is driven mainly by one cluster (#1, S = 0.4263).

## Reference co-citation clusters

*Mean year = mean publication year of the documents in the export that cite at least one member of the cluster. Only the six most frequently cited members of each cluster are listed in the text because the analysis script returns the six highest-ranked members.*

## Cluster #1 (*n*=44; S = 0.4263; mean year 2021.7) – the founding FDM and multi-drug tablet studies

The largest and most coherent co-citation cluster is headed by Goyanes *et al.* (2015a)[58], which examined how geometry affects drug release from printed tablets. Its other leading members are the modified-release aminosalicylate tablets of Goyanes *et al.* (2015b)[59], the fused-filament tablet fabrication of Goyanes *et al.*[25], the five-in-one polypill of Khaled *et al.* (2015a)[61], the multi-drug tablets of Khaled *et al.* (2015b)[62], and the regulator-authored overview of Norman *et al.*[26] on 3D-printed drug products as a new chapter in pharmaceutical manufacturing. The cluster is therefore the field's foundational layer: proof that printed tablets can be made, that their shape controls release, and that several drugs can be combined in one object. With the highest coherence (S = 0.4263) and the lowest mean year of the three clusters, it fits the interpretation of a foundational stream whose papers (2014 to 2017) every later study is expected to cite.

## Cluster #2 (*n*=30; S = 0.1324; mean year 2022.7) – powder-bed printing, polypills and clinical translation

This cluster has a slightly later mean year than the other two (about a year) and is headed by Goyanes *et al.*[27], a single-centre crossover study in which printed isoleucine formulations were prepared for patients with maple syrup urine disease. It also contains two selective laser sintering papers (Fina *et al.*[28]; Fina *et al.*[29]), the multi-layered six-drug polypill of Robles-Martinez *et al.*[30], the translational review of Seoane-Viaño *et al.*[31] on moving printed pharmaceuticals from hype to clinical application, and a review of polymers for extrusion-based printing (Azad *et al.*[32]). The thread connecting them is the move from demonstrating printability to solving clinical and material questions, which accords with the later, more clinically oriented literature discussed in Section 5. Its low coherence (S = 0.1324) shows that these papers are cited

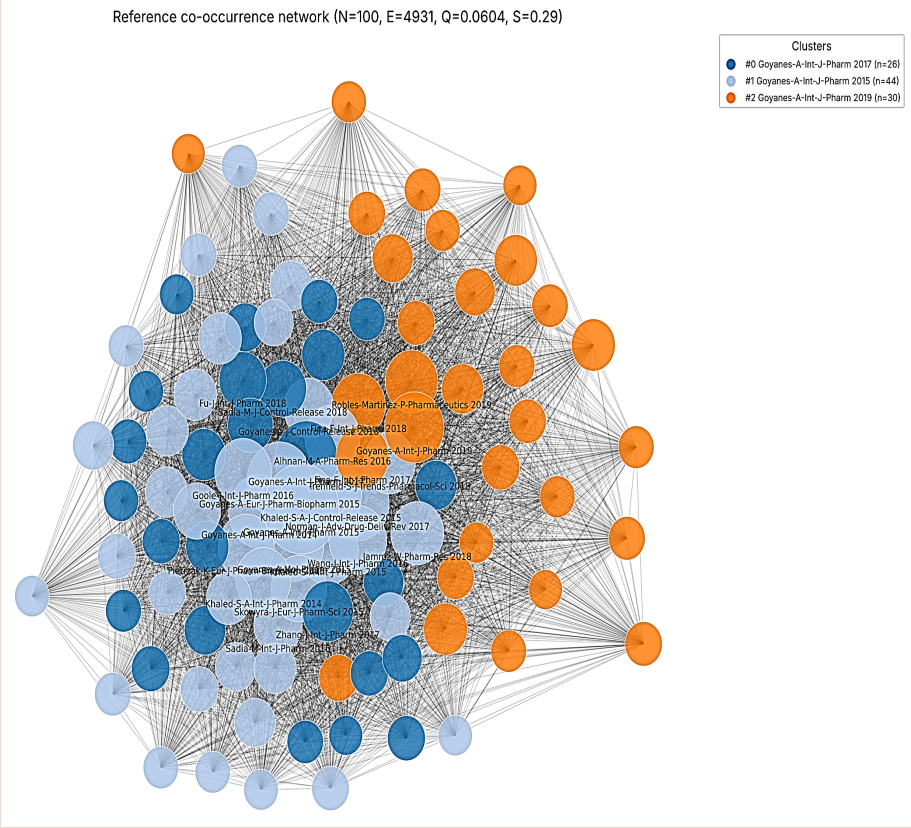


**Figure 3:** Reference co-citation network (1987–2027). Node size is proportional to citation frequency; colour denotes cluster membership. Node labels are first author, initials, abbreviated source and year. *N* = 100, E = 4,931, density = 0.9962, Q = 0.0604, S = 0.29.

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together with the founding studies of Cluster #1 nearly as often as with one another.

### Cluster #0 (*n*=26; S = 0.2412; mean year 2022.0) – extrusion-based processing and release engineering

The leading members are Goyanes *et al.*[33] on modified-release printlets with pharmaceutical-grade excipients, Zhang *et al.*[34] on coupling printing with hot-melt extrusion, Sadia *et al.*[35] on channelled tablets for accelerated release, Kollamaram *et al.*[36] on low-temperature FDM of thermolabile drugs, Chai *et al.*[37] on intragastric floating tablets, and Fu *et al.*[38] on personalised vaginal rings for progesterone. These works address how to process real drugs and excipients (heat sensitivity, hot-melt extrusion, floating and channelled architectures) and how to extend printing to non-oral products. The cluster's S of 0.2412 indicates modest internal consistency. As in the other two clusters, the label is merely the most frequently cited member; the labels are not topic descriptors, and the interpretation above rests on the six highest-ranked members only. Because the script returns only these six members, the remaining 20 members of this cluster, 38 of Cluster #1 and 24 of Cluster #2 are not described, and conclusions are limited accordingly.

A feature common to all three clusters is the dominance of a single research environment: 5 of the 18 listed members have Goyanes as first author, and several others share co-authors with him, Basit and Gaisford. This matches the author and institution rankings in Section 4.2 and implies that the field's intellectual base is, to a notable degree, built on the output of one group and its collaborators.

## Keyword co-occurrence clusters

### Cluster #3 (*n*=35; S = 0.4742; mean year 2022.1) – 3D printing and personalised medicine

The largest and only coherent keyword cluster brings together the core vocabulary of the field: 3D printing, personalised medicine, additive manufacturing, fused deposition modelling, controlled release and hot-melt extrusion. It sums up the technology-and-purpose narrative: fabrication methods for personalised oral products. Its coherence (S = 0.4742) is the highest of any cluster in the study, which supports its reading as the structural centre of the keyword map.

### Cluster #2 (*n*=33; S = -0.1241; mean year 2022.3) – drug delivery platforms and biomedical applications

Its most frequent members are drug delivery, microneedles, hydrogels, nanoparticles, tissue engineering and bioprinting. This cluster collects the printing applications that go beyond the tablet, namely transdermal devices, hydrogel systems, scaffolds and printed living constructs, together with nanoscale carriers that are often discussed alongside them. Its mean year (2022.3) is only marginally later than the other clusters (2022.1 for the core cluster), a difference too small to support a claim about timing, and its negative S (-0.1241) means that these keywords co-occur with the core printing terms at least as much as with one another.

### Cluster #0 (*n*=25; S = -0.2294; mean year 2021.6) – dissolution and oral dosage-form performance

The cluster combines dissolution, printlets, oral drug delivery, orodispersible films, drug release and bioavailability. It captures the performance-testing side of oral printing, the *in vitro* behaviour on which most formulation papers report. Again, a negative S (-0.2294) shows that these topics are entangled with the central printing vocabulary.

### Cluster #1 (*n* = 7; S = -0.3117; mean year 2022.0) – sustained release and implants

This small cluster links sustained release, controlled drug delivery, implants, ocular drug delivery, polyvinyl alcohol and cancer. Because it has only 7 members and the lowest coherence in the network (S = -0.3117), it should be read as a loose collection of release-related terms rather than a distinct research front. All four keyword clusters have mean years between 2021.6 and 2022.3, so keyword clusters do not separate early from late themes; the corpus is dominated by recent output (88.6% from 2018 onward), and cluster mean years inevitably cluster around the recent mean.

## Burst analysis

Table 2a lists the ten strongest reference bursts after removing two malformed items whose keys could not be parsed (they appear as "– 2003" and "– 2004" in the raw output and were excluded rather than guessed at). A column giving the cluster of each burst item is omitted because the analysis script reports only the six highest-ranked members of each cluster and most burst items are not among them. The strongest burst belongs to Fell[39], the

**Table 1: Cluster summary, keyword co-occurrence network (sorted by size).**

| Cluster-ID | Size | Silhouette | *Mean* year | Label (most frequent member) |
|---|---|---|---|---|
| 3 | 35 | 0.4742 | 2022.1 | 3d printing |
| 2 | 33 | -0.1241 | 2022.3 | drug delivery |
| 0 | 25 | -0.2294 | 2021.6 | dissolution |
| 1 | 7 | -0.3117 | 2022.0 | sustained release |

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diametral-compression test for tablet strength, with a strength of 11.2 in 2019 (5 documents). It is followed by Lipinski *et al.*[40] on solubility and permeability estimation (strength 10.8, 2017), Williams[41] on penetration enhancers (strength 8.0, 2023–2024) and Strickley[24] on solubilising excipients (strength 8.0, 2021). An overview of new methods of drug delivery, burst from 2020 to 2023 (strength 8.0).

*Bursts ending in 2026 are subject to the incomplete final year; keywords with five or six documents are tentative.*

The reference bursts do not point to a specific printing technology. Instead they are classic pharmaceutics papers on tablet mechanics,[39] solubility and permeability,[40] solubilising excipients,[24] penetration enhancement,[41] liposomes,[42] solid dispersions,[43] dissolution testing[44] and lipid formulations.[45] Two lines of explanation fit these data. First, printed products raise the same biopharmaceutical questions as conventional ones, so researchers cite established work on solubility, dissolution and excipients when they characterise printed dosage forms. Second, as noted in Section 3.2, around a quarter of the corpus does not mention printing, and these papers belong to the wider formulation literature that the broad query also captured. The data alone cannot separate these explanations. Two items point more directly to the printing literature: El-Egakey *et al.*[46], an early hot-extrusion paper cited in a 2025 burst, which is consistent with growing use of hot-melt extrusion with printing, and Kim[47], on donut-shaped tablets with zero-order release, which burst in 2016 around the time that geometry-controlled release (Cluster #1) became a research focus. Huang & Brazel[48] on burst release in matrix systems (2024–2026) and Marsac *et al.*[49] on drug–polymer miscibility (2024–2026) are likewise consistent with current interest in amorphous and polymer-based printed formulations, although the table does not show this causal link.

The keyword bursts are more varied. The strongest, "transdermal drug delivery system", began in 2023 (strength 17.5), followed by "blood-brain barrier" (2023–2024; 16.5) and "targeted drug delivery" (2024–2026; 12.0). The transdermal burst is consistent with the rise of printed microneedles discussed in Section 5. Several others (*lamivudine*, *diclofenac* sodium, *carbamazepine*, microspheres, nanostructured lipid carriers) are drug- or carrier-specific and are based on only five to seven documents each, so they may represent a few productive papers rather than field-wide trends. The burst for "*sodium lauryl sulphate*" (2019–2020; 6.4) is almost certainly an artefact of the search: "SLS" in the query matches both selective laser sintering and *sodium lauryl sulphate*, and 154 of the 226 records that mention either phrase do not contain any printing term. The same applies to some of the other bursts, which reflect general formulation research captured by the query rather than printing.

## Scope of the corpus

To quantify how much of the corpus concerns printing, titles, abstracts and author keywords were searched for printing-related terms (3D or three-dimensional printing, additive manufacturing, 4D printing, printlets, bioprinting, stereolithography, fused deposition or filament fabrication, direct powder extrusion, semi-solid extrusion, binder jetting, inkjet printing and selective laser sintering). 1,582 of the 2,098 documents (75.4%) matched. The share rises over time: it is 77.9% in 2018 (81 of 104), 71.7% in 2020 (109 of 152), 79.0% in 2022 (158 of 200), 81.0% in 2024 (204 of 252) and 87.7% in 2026 (256 of 292), indicating that the literature has become more tightly centred on printing. The matching documents account for 70,736 of the 90,730 citations (78.0%). These percentages come from a keyword match and are approximate; they are reported to alert readers that the networks above describe a combined printing and advanced-formulation literature.

**Table 2: Top keyword bursts (sorted by strength).**

| Begin | End | Strength | Keyword | Docs |
|---|---|---|---|---|
| 2023 | 2023 | 17.5 | transdermal drug delivery system | 6 |
| 2023 | 2024 | 16.5 | blood-brain barrier | 6 |
| 2024 | 2026 | 12.0 | targeted drug delivery | 12 |
| 2025 | 2026 | 10.8 | *lamivudine* | 5 |
| 2024 | 2025 | 10.71 | microspheres | 7 |
| 2025 | 2026 | 10.33 | *diclofenac* sodium | 6 |
| 2014 | 2015 | 9.33 | controlled-release | 9 |
| 2025 | 2025 | 9.14 | *insulin* | 7 |
| 2026 | 2026 | 8.0 | bone regeneration | 9 |
| 2025 | 2026 | 7.8 | nanostructured lipid carriers | 5 |

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## DISCUSSION

### Phases in the evolution of the field

The data suggest three overlapping phases. The first, up to about 2014, is a period of sparse output, with fewer than 23 documents a year, in which the corpus largely consists of papers on advanced formulation and controlled release that contain printing terms only sporadically. The second, from 2014 to 2018, corresponds to the founding studies of Cluster #1: fused-filament tablets, geometry-controlled release, multi-drug polypills and the first regulatory commentary (Goyanes *et al.*, 2015a[58]; Khaled *et al.*, 2015a.[61] Output rose from 22 documents in 2014 to 43 in 2017 and then more than doubled in 2018. The third phase, from 2018 onward, is one of expansion and diversification, with annual output of 104 to 309 documents and the appearance of the powder-bed, clinical and translational works in Cluster #2.[27,28,31] The sustained plateau in 2021–2022 (204 and 200) followed by renewed growth to 309 suggests that expansion has not saturated.

This arc matches how recent syntheses describe the field. Reviews of oral dosage forms still treat FDM as the most studied technology while noting that other approaches gain relevance,[2] and a broad systematic review needed more than 500 publications to cover just five years of printed dosage forms.[1] The fact that 88.6% of our documents appeared since 2018 is consistent with this picture of rapid recent growth.

### From feasibility to point-of-care manufacture and regulation

The most clinically oriented document among the cluster leaders, the patient crossover study of printed isoleucine formulations,[27] anticipates a theme that now dominates recent external work. Subsequent studies demonstrated that a printed *sildenafil* tablet produced at a hospital met bioequivalence criteria,[5] that pharma-inks can be manufactured by a company and shipped to a distant site where in-line near-infrared spectroscopy checks drug load,[50] and that semi-solid extrusion can be framed in a risk-based quality-by-design scheme for paediatric hospital compounding and early-phase trials.[13] Reviews on clinical trials of printed medicines at the point of care emphasise regulatory barriers, ethical and legal concerns and the need for new manufacturing guidance,[51] and a 2026 synthesis proposes an agenda centred on standardised point-of-care trials, cost and quality benchmarking, and clearer guidance on recalls and labelling.[6] Interviews with national medicines authorities[8] and with Dutch compounding stakeholders[52] show that safety, quality and the regulatory status of prefilled cartridges remain unresolved, and a policy-oriented review reaches similar conclusions for pharmacy practice.[7] A harmonisation-focused review argues for tailored guidance on feedstock materials and process parameters.[4]

**Table 3: Ten most prolific authors (Scopus author names; citations summed over the author's documents in the corpus).**

| Rank | Author | Documents | Total citations |
|---|---|---|---|
| 1 | Basit A.W. | 104 | 15,294 |
| 2 | Goyanes A. | 81 | 13,706 |
| 3 | Gaisford S. | 72 | 13,650 |
| 4 | Lamprou D.A. | 34 | 1,360 |
| 5 | Fatouros D.G. | 30 | 1,685 |
| 6 | Maniruzzaman M. | 29 | 1,062 |
| 7 | Repka M.A. | 27 | 1,818 |
| 8 | Zhang J. | 25 | 1,445 |
| 9 | Douroumis D. | 25 | 1,417 |
| 10 | Awad A. | 23 | 3,560 |

Our network results offer indirect support for this shift but not a direct measurement. The founding-technology cluster remains the most coherent one, and the translational cluster (#2) has a slightly later mean year, but neither keyword nor co-citation clusters isolate regulatory or point-of-care topics as a separate theme. The most likely reason is that regulatory terms occur in few author-keyword lists and that policy papers cite a different set of references from those in the top 100. A targeted bibliometric search on regulatory and clinical terms would be needed to quantify this trend.

### Machine learning and data-driven formulation

Artificial intelligence does not form a separate cluster in the networks, yet it is visible in the citation record: a 2023 review of artificial intelligence in pharmaceutical technology and drug delivery design is the second most cited document in the corpus.[23] External work shows why interest is growing. Machine-learning models trained on formulation composition and characterisation data have predicted selective laser sintering printability with F1 scores up to 88.9% when spectral, thermal and diffraction data are combined,[15] and a deep-learning model later reached 90% printability accuracy while explaining which materials favour sintering.[53] For FDM and hot-melt extrusion, models trained on 1,594 formulations predicted printability and filament properties with 84% accuracy,[14] while genetic-algorithm design produced multi-layer capsules whose release profiles matched targets.[54] A semi-automated pipeline that generates formulations and predicts print parameters printed 80% of the generated formulations successfully and shortened development to a single day,[55] and a recent review covers computational intelligence for customising release.[16] Taken together, this literature indicates that data-driven design is moving from proof of concept to workflow tool, which our keyword data capture only weakly because machine-learning terms are rare among author keywords in a corpus defined by pharmaceutical search terms.

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## Diversification into non-oral applications

The keyword cluster containing microneedles, hydrogels, tissue engineering and bioprinting is not distinguishable by mean year from the other clusters, but the strongest keyword burst is "transdermal drug delivery system" (2023). External reviews confirm rapid activity: reviews of printed microneedles describe the range of printing methods, applications in drug and vaccine delivery, cosmetics, therapy and diagnostics, and ongoing barriers of cost, material compatibility and regulation.[9–11] The corpus also includes highly cited work on bioprinting for regenerative medicine[22] and printing in medical applications,[56] which shows that the boundary between pharmaceutical and biomedical printing is porous. Printed polypills for complex chronic regimens are a related direction,[12] consistent with the early polypill papers at the centre of Clusters #1 and #2 (Khaled *et al.*, 2015a).[61]

## Implications

For researchers, the strong concentration of the intellectual base in one environment means that independent replication, and work from groups outside it, will be valuable for establishing which results generalise. The fact that India, the United States and China produce large volumes but have lower citation counts per document than the United Kingdom and Spain suggests an opportunity for greater international collaboration and for work that addresses the clinical and regulatory questions now cited most. For funders and regulators, the literature's movement towards point-of-care manufacture implies that quality-control methods for small batches, standards for feedstock intermediates and training requirements for hospital pharmacists need as much support as new materials. For journals and indexers, the finding that about a quarter of retrieved records do not concern printing is a reminder that keyword-based retrieval in this field mixes unrelated concepts and that author keyword standardisation (for example "3D printing" versus "three-dimensional printing") would improve retrieval.

**Table 4: Ten most productive institutions after grouping affiliation-string variants (document counted once per institution).**

| Rank | Institution (grouped variants) | Documents | Total citations |
|---|---|---|---|
| 1 | UCL School of Pharmacy / University College London, UK | 124 | 15,976 |
| 2 | FabRx Ltd., UK | 88 | 14,172 |
| 3 | University of Santiago de Compostela, Spain | 65 | 7,212 |
| 4 | Queen's University Belfast, UK | 61 | 2,720 |
| 5 | University of Mississippi, USA | 48 | 2,174 |
| 6 | Aristotle University of Thessaloniki, Greece | 36 | 1,877 |
| 7 | University of Copenhagen, Denmark | 30 | 1,906 |
| 8 | University of Texas at Austin, USA | 29 | 1,394 |
| 9 | University of Greenwich, UK | 23 | 1,362 |
| 10 | University of Nottingham, UK | 21 | 2,583 |

**Table 5: Ten most productive countries (from affiliation strings; a document counts once per country).**

| Rank | Country | Documents | Citations | Citations per document |
|---|---|---|---|---|
| 1 | India | 444 | 8,520 | 19.2 |
| 2 | United States | 361 | 16,644 | 46.1 |
| 3 | United Kingdom | 341 | 31,151 | 91.4 |
| 4 | China | 194 | 7,218 | 37.2 |
| 5 | Spain | 125 | 10,031 | 80.2 |
| 6 | Italy | 93 | 4,673 | 50.2 |
| 7 | Germany | 86 | 3,641 | 42.3 |
| 8 | Saudi Arabia | 86 | 3,555 | 41.3 |
| 9 | South Korea | 59 | 2,427 | 41.1 |
| 10 | Australia | 55 | 2,561 | 46.6 |

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**Table 6: Ten most cited documents in the corpus (Scopus counts at export).**

| Rank | First author | Year | Title | Source | Cited by |
|---|---|---|---|---|---|
| 1 | Tyler B. *et al.* | 2016 | *Polylactic acid* (PLA) controlled delivery carriers for biomedical applications | Advanced Drug Delivery Reviews | 1000 |
| 2 | Vora L.K. *et al.* | 2023 | Artificial Intelligence in Pharmaceutical Technology and Drug Delivery Design | Pharmaceutics | 999 |
| 3 | Alqahtani M.S. *et al.* | 2021 | Advances in Oral Drug Delivery | Frontiers in Pharmacology | 845 |
| 4 | Jamróz W. *et al.* | 2018 | 3D Printing in Pharmaceutical and Medical Applications – Recent Achievements and Challenges | Pharmaceutical Research | 694 |
| 5 | Porter C.J.H. *et al.* | 2008 | Enhancing intestinal drug solubilisation using lipid-based delivery systems | Advanced Drug Delivery Reviews | 669 |
| 6 | Goyanes A. *et al.* | 2015 | Effect of geometry on drug release from 3D printed tablets | International Journal of Pharmaceutics | 649 |
| 7 | Goole J. *et al.* | 2016 | 3D printing in pharmaceutics: A new tool for designing customized drug delivery systems | International Journal of Pharmaceutics | 634 |
| 8 | Aimar A. *et al.* | 2019 | The Role of 3D Printing in Medical Applications: A State of the Art | Journal of Healthcare Engineering | 634 |
| 9 | Vijayavenkataraman S. *et al.* | 2018 | 3D bioprinting of tissues and organs for regenerative medicine | Advanced Drug Delivery Reviews | 617 |
| 10 | Khaled S.A. *et al.* | 2015 | 3D printing of five-in-one dose combination polypill with defined immediate and sustained release profiles | Journal of Controlled Release | 590 |

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## Limitations

Several limitations apply. (1) The data come from a single database, Scopus, and the subject-area limit excludes records in engineering or materials-science journals that do not carry Pharmacology or Medicine classifications, so work from those fields is under-represented. (2) The query is broad, and only 75.4% of the records mention printing terms; the ambiguous acronym "SLS" contributes spurious records and bursts. Results therefore characterise a combined printing and advanced-formulation literature and should not be read as describing printing alone. (3) Modularity (Q = 0.0604 for co-citation and Q = 0.1343 for keywords) lies below 0.3, so the clusters are weakly separated, and the network densities are very high; cluster membership is sensitive to the choice of node cap and frequency threshold, and alternative parameter settings would give different partitions. (4) The script reports only the six leading members of each cluster, so cluster interpretation rests on a minority of members; the remaining members were not inspected individually. (5) The first-author and source key used for co-citation is an approximation: it can merge distinct papers by the same first author in the same journal and year, and reference strings that could not be parsed were dropped. (6) Author and affiliation names are not disambiguated, and institution grouping used pattern matching on names, so some counts may be incomplete. (7) The coherence score S is a custom measure and should not be compared directly with CiteSpace silhouette values. (8) The final year is incomplete and in-press documents carry a 2027 date, so recent trends and any bursts ending in 2026 are provisional; citation counts are subject to time-lag bias against recent papers. (9) The external references used in the Introduction and Discussion were retrieved through a literature search tool that returned first-author names, titles, journals and years but not volume, page or DOI data; their bibliographic details should be completed from the publisher records before submission.

## CONCLUSION

This analysis of 2,098 Scopus documents shows a young literature that has expanded quickly, with 88.6% of its output published since 2018 and 309 documents in 2025 alone. It is concentrated in a small number of research groups, centred on University College London and the company FabRx, and its intellectual base is built on a core of early studies of printed tablets, polypills and release engineering. Network structure is diffuse (Q = 0.0604 for co-citation; Q = 0.1343 for keywords), with the only clearly coherent unit being the central "3D printing and personalised medicine" keyword cluster and the founding co-citation cluster.

Burst patterns largely reflect classical formulation science and, in the case of keywords, a few drug-specific topics and one search artefact. Recent external literature shows that the field is moving towards point-of-care manufacture, regulatory harmonisation, machine-learning-guided design and non-oral applications such as microneedles.

Four directions follow from the findings. First, studies should rerun the analysis on a refined dataset restricted to records that mention printing terms, and with a search string that avoids the "SLS" ambiguity, in order to test how much of the diffuse structure is due to scope. Second, a combined Scopus and Web of Science dataset, with disambiguated author identifiers, would give a more reliable view of leading authors and institutions. Third, targeted searches on regulation, clinical trials and machine learning, which are visible in the external literature but weak in the author keywords of this corpus, would test whether these themes are growing as quickly as the review literature suggests. Fourth, a closer examination of the countries with high volume but lower citation impact, including questions of study design, reporting quality and international collaboration, could show whether the citation gap reflects research questions, methods or visibility.

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