

The Stewart physicochemical approach to acid-base analysis: bibliometric mapping of the literature from 1978 to August 2026

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ABSTRACT

Aims: Since its introduction in 1978, the Stewart physicochemical approach has become an influential framework for acid-base interpretation in critical care, yet to our knowledge the global structure of its literature has not been systematically mapped. This study aimed to perform a comprehensive bibliometric analysis of the international Stewart literature and to identify intellectual landmarks, dominant research clusters, and emerging thematic directions.

Methods: PubMed, Scopus, and the Web of Science Core Collection were searched on 23 August 2026 using an expanded strategy that combined eponymous, conceptual, and parameter-based terms. After deduplication and eligibility screening-with independent duplicate screening of a stratified sample by a second reviewer-1,141 unique publications spanning 1978 to August 2026 were retained. Analyses comprised publication trends, citation analysis, h-Index, Bradford's and Lotka's laws, co-citation, author keyword co-occurrence, country co-authorship, document type, and thematic evolution. Publication trends and document-type composition were analysed in the full corpus, whereas all citation-based, informetric, network, journal-level, keyword, and thematic analyses were performed on the Scopus subset (n=948; 83.1% of the corpus) in VOSviewer, with threshold sensitivity analyses.

Results: Annual output rose from 4.8 publications per year in 1978-1992 to 39.3 per year during 2005-2019 and remained high thereafter (36.6 per year for 2020-2026). The Scopus subset accumulated 26,125 citations (h-Index 74; median 9.0 citations per publication). Stewart's 1983 article was both the most cited publication (1,179 citations) and the most co-cited reference, cited in the reference lists of 416 of the 948 subset records (43.9%). Journal distribution conformed to Bradford's law (20, 77, and 276 journals across the three zones; multipliers 3.85 and 3.58). Author productivity deviated significantly from Lotka's inverse-square law (Kolmogorov-Smirnov D=0.095; critical value 0.032). Co-citation analysis identified three principal clusters-theoretical foundations, clinical application and prognostic markers, and fluid therapy-together with a small dyad representing methodological critique; cluster cores were invariant across thresholds. Country co-authorship comprised 30 countries (density 0.269), with the strongest axis between Canada and the United States. Keyword overlay showed a thematic shift from classical parameters (lactate, mean year 2008.2) toward fluid therapy (2017.9) and acid-base disorders (2016.2).

Conclusion: The Stewart literature represents a mature but evolving research field, transitioning toward outcome-oriented and translational research. Its intellectual structure remains anchored to a small set of foundational references, whilst its collaborative structure is regionally clustered rather than consortium-based. The mapping identifies randomised designs (7.5% of the Scopus subset), economic evaluations (none identified), and inter-country collaboration as underrepresented in the current published record.

Keywords: Acid-base equilibrium, acid-base imbalance, bibliometrics, critical care, fluid therapy, Stewart approach

INTRODUCTION

The regulation of hydrogen ion concentration in body fluids is of fundamental importance in critical care medicine. Whilst the traditional Henderson-Hasselbalch framework has served clinicians for over a century, its limitations in explaining the complex acid-base derangements encountered in the critically ill have long been recognised.^{1,2} Comparative appraisals written from outside the framework's advocacy have reached the same conclusion.^{3,4} In 1978, the Canadian physiologist Peter Stewart proposed an alternative physicochemical model,³

which he subsequently elaborated in his 1981 monograph⁴ and a landmark 1983 publication.⁵

Stewart's approach posits that hydrogen ion concentration is governed by three independent variables: the strong ion difference, the total concentration of non-volatile weak acids, and the partial pressure of carbon dioxide.⁵⁻⁷ This framework was refined by Figge et al.,⁸⁻¹⁰ who quantified the buffering role of serum albumin and phosphate, and by Fencl et al.,¹¹

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who translated it into a bedside diagnostic tool. Kellum^{1,2,12} introduced the strong ion gap as a measure of unmeasured anions and provided influential clinical syntheses of the approach. Over four decades, the Stewart approach has been applied in diverse clinical settings: identifying occult acid-base derangements,^{11,13} evaluating unmeasured anions as prognostic markers,^{14,15} characterising fluid-induced disturbances,^{16,17} and elucidating the role of chloride in acid-base regulation.^{18,19}

The framework has also attracted sustained methodological criticism. Kurtz et al.²⁰ argued that neither the Stewart nor the bicarbonate-centred formulation provides a complete mechanistic account of acid-base regulation, and Doberer et al.²¹ challenged the chemical mechanism proposed for dilutional acidosis. Others have questioned whether the approach improves diagnostic performance sufficiently to justify its computational complexity in routine practice.^{3,4} This continuing debate forms part of the intellectual structure of the field and was therefore treated as within scope in the present analysis.

Despite this substantial body of work, to our knowledge no comprehensive bibliometric analysis of the Stewart acid-base literature has been undertaken to date. Previous reviews have summarised the clinical evidence narratively,^{1,2,17} but none has employed quantitative bibliometric methods-including science mapping, co-citation analysis, and informetric laws-to characterise the intellectual structure, collaborative networks, and thematic evolution of the field. Accordingly, the present study had three objectives, stated in the same order as in the abstract: (i) to identify the intellectual landmarks of the Stewart acid-base literature through citation and co-citation analysis; (ii) to delineate its dominant research clusters through co-citation, keyword co-occurrence, and co-authorship network analyses; and (iii) to trace its emerging thematic directions through temporal overlay analysis. Three databases-PubMed, Scopus, and the Web of Science Core Collection-were used to construct the corpus, and the mapping analyses themselves were performed on the Scopus-Indexed subset, as detailed in the methods.

Main Points

- The Stewart physicochemical approach has produced a mature international literature of 1,141 unique publications across nearly five decades (1978 to August 2026), with an h-Index of 74 and 26,125 citations in the Scopus subset.
- Stewart's 1983 article holds the highest values on both citation measures: it is the most cited publication (1,179 citations) and the most co-cited reference (present in 43.9% of Scopus-subset reference lists; total co-citation link strength 3,624, approximately 1.5 times that of the next reference). International collaboration is regionally clustered, with a dominant Canada-United States axis and an overall network density of 0.269.
- Temporal overlay analysis shows a transition from classical parameter description (lactate, mean publication year 2008.2) toward clinically oriented research on fluid therapy (2017.9), acid-base disorders (2016.2), and the

physicochemical approach itself (2016.1), indicating a shift toward translational and outcome-based applications.

METHODS

Ethics

The study did not require ethics committee approval because it was conducted exclusively on publicly available bibliographic metadata and involved no human participants or identifiable personal data.

Study Design

This was a bibliometric analysis designed to map the global literature on the Stewart physicochemical approach to acid-base analysis. Reporting followed the preliminary guideline for reporting bibliometric reviews of the biomedical literature (BIBLIO),²² which was developed specifically for bibliometric designs; the previously cited STROBE statement was replaced because it addresses observational studies of human participants and is not applicable to a metadata-based design.

Data Sources and Search Strategy

A systematic literature search was performed in three electronic databases-PubMed, Scopus, and the Web of Science Core Collection-on 23 August 2026. The strategy was deliberately broad and combined four families of terms: eponymous designations (Stewart approach, Stewart model, Stewart method, Fencl-Stewart, Stewart-Figge, Figge-Fencl); conceptual descriptors (physicochemical approach, physical chemical approach, physicochemical acid-base, quantitative acid-base); parameter-based terms (strong ion difference, strong ion gap); and the term unmeasured anion combined with acid-base, acidosis, or alkalosis. Terms were searched in title, abstract, and keyword fields, and truncation was applied where supported. The abbreviations SIDa and SIDe were deliberately excluded as free-text terms because case-insensitive matching retrieves large volumes of unrelated records. The Web of Science Core Collection was searched using its default edition selection, and no subject-area limits, filters, or export caps were applied in any database. No restrictions were applied regarding publication date, language, or document type. The complete search strings and the number of records retrieved from each database are presented in [Table 1](#). No systematic search for previously published bibliometric analyses of this literature was undertaken, so the novelty claim rests on the absence of such work known to the authors rather than on a systematic survey.

Deduplication

The search returned 2,559 records (PubMed, n=723; Scopus, n=984; Web of Science Core Collection, n=852). Eight erratum and correction notices were removed at import. Deduplication then proceeded in two stages. First, digital object identifier (DOI)-based matching was applied to the 2,306 DOI-bearing records, yielding 1,013 unique DOIs. Second, the 245 records lacking DOI information-predominantly older publications-were matched on a composite key of publication year (± 1 year) and normalised title, with a minimum string similarity of 0.92; an additional document-type check prevented conference abstracts from being merged with full papers. Ninety-two records were merged at this stage, and two borderline pairs

Table 1. Search strategies and records retrieved from each database		
Database	Search string (fields searched)	Records
PubMed	("Stewart approach"[tiab] OR "Stewart model"[tiab] OR "Stewart method"[tiab] OR "Fencel-Stewart"[tiab] OR "Stewart-Figge"[tiab] OR "Figge-Fencel"[tiab] OR "strong ion difference"[tiab] OR "strong ion gap"[tiab] OR "physicochemical approach"[tiab] OR "physical chemical approach"[tiab] OR "physicochemical acid-base"[tiab] OR "quantitative acid-base"[tiab] OR ("unmeasured anion"[tiab] AND ("acid-base"[tiab] OR acidosis[tiab] OR alkalosis[tiab])))	723
Scopus	TITLE-ABS-KEY("Stewart approach" OR "Stewart model" OR "Stewart method*" OR "Fencel-Stewart" OR "Stewart-Figge" OR "Figge-Fencel" OR "strong ion difference*" OR "strong ion gap*" OR "physicochemical approach" OR "physical chemical approach" OR "physicochemical acid-base" OR "quantitative acid-base" OR ("unmeasured anion*" AND ("acid-base" OR acidosis OR alkalosis)))	984
Web of Science Core Collection	TS=("Stewart approach" OR "Stewart model" OR "Stewart method*" OR "Fencel-Stewart" OR "Stewart-Figge" OR "Figge-Fencel" OR "strong ion difference*" OR "strong ion gap*" OR "physicochemical approach" OR "physical chemical approach" OR "physicochemical acid-base" OR "quantitative acid-base" OR ("unmeasured anion*" AND ("acid-base" OR acidosis OR alkalosis)))	852
Total before deduplication	—	2,559
Search date: 23 August 2026. No date, language, or document-type restrictions were applied. tiab: Title/abstract, TITLE-ABS-KEY, title, abstract, and keywords, TS: Topic search		

were retained as separate records after manual inspection. Deduplication yielded 1,166 unique records.

Screening and Eligibility

All 1,166 unique records were screened on title, abstract, and keyword fields. Records were eligible if they applied, evaluated, extended, taught, or critiqued the Stewart physicochemical framework or its derived parameters. Veterinary and comparative-physiology studies were retained, because the strong ion approach has been developed and validated in parallel in these domains and their exclusion would misrepresent the intellectual structure of the field; publications on renal replacement and replacement-fluid composition were likewise retained where acid-base parameters were analysed within the physicochemical framework. Records in which the search terms appeared only incidentally-most commonly industrial or surface chemistry using the phrase physicochemical approach-were excluded.

Eight records published before 1978 were excluded because they predated Stewart’s seminal publication⁶ and represented retrospective indexing artefacts. Among these eight, one record also met the topical exclusion criterion and is counted once. Seventeen additional records were excluded at the eligibility stage across two screening rounds: a primary round, and a subsequent anchor-based verification round in which every record lacking all of the anchor terms (Stewart, strong ion, Fencel, Figge, unmeasured anion) anywhere in its title, abstract, or keyword fields was re-examined individually. Twenty-five unique records were therefore excluded. The final corpus comprised 1,141 unique publications published between 1978 and August 2026; records indexed in 2026 represent a partial year (January to August). The study flow is summarised in Figure 1.

To quantify the reliability of screening, a second reviewer independently screened a stratified sample of 150 records- all 38 records flagged as potentially off-topic plus a 10% random sample of the remainder-blinded to the first reviewer’s decisions. Overall agreement was 97.3% (Cohen’s κ =0.736;²³ prevalence-adjusted bias-adjusted κ =0.947). Within the flagged stratum agreement was 92.1% (κ =0.753); within the random stratum agreement was 99.1%, where κ was uninformative because that stratum contained almost no exclusions. The four disagreements were resolved by consensus.

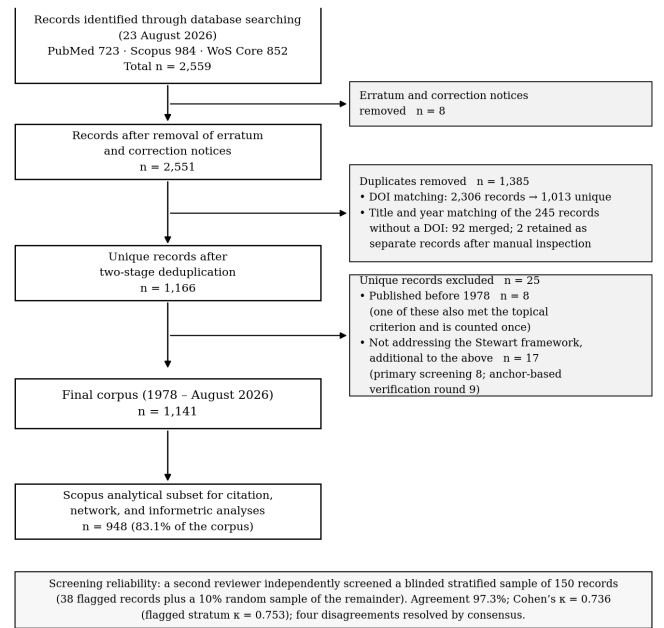


Figure 1. Study flow, from database retrieval to the final corpus of 1,141 publications (1978 to August 2026)

Reference Harmonisation

Preliminary co-citation runs revealed that the same cited work was distributed across multiple network nodes. Two mechanisms were responsible: Scopus delimits author names within a reference string by semicolons, so that a multi-author reference is fragmented and labelled by its final author; and the same work appears with variant journal abbreviations, issue fields, and punctuation. Reference strings were therefore reassembled programmatically, relabelled with the correct first author, and merged across variants that shared publication year and normalised title. This procedure reduced 22,846 raw reference fragments to 14,729 unique cited references; Stewart’s 1983 article alone had been distributed across six separate strings. All co-citation results reported below are derived from the harmonised reference field.

Analytical Datasets

Of the 1,141 corpus records, 948 (83.1%) were indexed in Scopus and constituted the analytical subset used for all citation-based, network, informetric, journal-level, keyword, country, and open-access analyses; publication-trend and document-type composition were computed on the full

corpus, because Scopus provides structured author identifiers, standardised keyword fields, complete reference lists, and normalised affiliation data.²⁴ The full corpus (n=1,141) was used for publication trend analysis, which requires maximal temporal coverage. Journal-level analysis was restricted to the Scopus subset; the previous version of this analysis combined Scopus and Web of Science records after title harmonisation, which introduced an inconsistent denominator and has been abandoned. The representativeness of the subset relative to the full corpus is reported in the results.

Bibliometric Analyses and Software

The bibliometric analysis encompassed performance analysis (publication output, citation distribution, h-Index), science mapping (keyword co-occurrence, co-citation, country co-authorship networks), and informetric laws (Bradford's law of journal scattering²⁵ and Lotka's law of author productivity²⁶). The overall analytical approach followed the methodology described by Donthu et al.²⁴

Network analyses were performed in VOSviewer version 1.6.21 (Centre for Science and Technology Studies, Leiden University, Leiden, the Netherlands)²⁷ using full counting. Thresholds for the primary maps were: co-citation of cited references, minimum 25 citations (99 of 14,729 references met the threshold); author keyword co-occurrence, minimum 10 occurrences (45 of 1,318 keywords; 687 of the 948 records carried author keywords); and country co-authorship, minimum 5 documents (30 of 79 countries). Two thesaurus files were applied—one merging keyword variants (including case and spelling variants, singular and plural forms, and abbreviation-full-term pairs) and one harmonising country names. Because threshold choice can influence cluster structure, each map was recomputed at alternative thresholds (co-citation, 20 and 30; keywords, 5 and 15; countries, 3), and agreement between the resulting cluster solutions was quantified with the adjusted Rand Index.²⁸

Lotka's exponent was estimated by least-squares regression on log-transformed productivity data, and goodness of fit to the theoretical distribution was tested with the Kolmogorov-Smirnov statistic using the procedure described by Pao, with the critical value $1.63/\sqrt{N}$ at $\alpha=0.01$.²⁹ Four analysis periods were defined a priori for descriptive purposes: 1978-1992 (foundational period, from Stewart's first publication to the completion of the Figge-Fencl albumin model^{8,9}), 1993-2004 (methodological refinement, opening with Leith's synthesis³⁰ and Gilfix's bedside translation¹³), 2005-2019 (clinical expansion), and 2020-2026 (recent period, partial final year). These boundaries are descriptive conveniences and were not derived from the data.

Statistical Analysis

No inferential statistical analysis was performed other than the Kolmogorov-Smirnov test of Lotka fit and the agreement statistics reported above. Descriptive bibliometric indicators—including total publication count, citation distribution, h-Index, Bradford zone allocation, and Lotka's law fit—were calculated from the bibliographic data. Journal scatter was assessed against Bradford's law and author productivity against Lotka's law, with goodness of fit for the latter tested

by the Kolmogorov-Smirnov procedure of Pao.^{25,26,29} Annual output for each analysis period was expressed per calendar year of exposure; the final period (2020 to 23 August 2026) contributes 6.6 years. Primary network thresholds—25 co-citations, 10 keyword occurrences, and 5 documents per country—were chosen a priori to yield networks of interpretable size (roughly 30 to 100 nodes) while retaining all structurally central items, and their influence was examined in the threshold sensitivity analyses described below. Study design and population were classified by a rule-based procedure applied to titles, abstracts, and indexed document types: records were assigned to mutually exclusive design categories through an ordered term hierarchy (randomised trial terms taking precedence over prospective, retrospective, and unspecified observational terms, with editorials, reviews, book chapters, conference material, and case reports identified from document-type metadata), and to population categories through species and age terms. A separate term census (cost-effectiveness, cost-utility, cost-benefit, economic evaluation, cost analysis, and quality-adjusted life year) was applied to identify economic evaluations. All non-network computation was performed in Python version 3.12.2 (Python Software Foundation, Wilmington, DE, USA) using pandas version 2.1.4, NumPy version 1.26.4 (NumFOCUS, Austin, TX, USA), and Matplotlib version 3.8.3; tabular summaries were prepared in Microsoft Excel 2019 (Microsoft Corporation, Redmond, WA, USA). Citation counts were extracted on 23 August 2026 and are therefore a cross-sectional snapshot.

RESULTS

Publication Trends and Geographical Distribution

The earliest record in the corpus dated to 1978, the year of Stewart's seminal publication on the independent and dependent variables of acid-base control.⁶ Annual output was 4.8 publications per year in 1978-1992 (n=72), increased to 19.8 per year in 1993-2004 (n=237), and reached 39.3 per year in 2005-2019 (n=589). Output remained at a similar level in 2020-2026 (n=243; 36.6 per year over a 6.6-year exposure to 23 August 2026). The most productive single year was 2013 (n=52), and the 2026 figure (n=30) represents January to August only.

The Scopus subset represented the full corpus closely; the proportion of records falling in each of the four periods differed by less than one percentage point between the corpus and the subset (1978-1992, 6.3% vs 5.8%; 1993-2004, 20.8% vs 20.6%; 2005-2019, 51.6% vs 52.1%; 2020-2026, 21.3% vs 21.5%). The document-type distributions were broadly similar (original articles 65.7% vs 72.5%; reviews 17.2% vs 14.7%; editorials and letters 7.4% vs 6.4%; book material 4.5% vs 5.0%), the largest difference concerning conference material (5.2% vs 1.5%), which reflects meeting abstracts indexed only outside Scopus. The journal distributions also corresponded closely: the ten most productive journals of the two datasets shared eight titles, and the five leading journals were identical in membership and order.

Authors from 79 countries contributed to the Scopus subset. The United States contributed the largest number of publications (n=282), followed by Canada (n=97), Australia (n=86), Germany and Italy (n=67 each), Brazil (n=56), and

the United Kingdom (n=54); Türkiye ranked fifteenth with 19 publications (Table 2; Figure 2). Original research articles constituted 65.7% of the corpus, followed by reviews (17.2%), editorials and letters (7.4%), conference papers and abstracts (5.2%), and book chapters (4.5%); open-access publications accounted for 36.4% of the Scopus subset. Veterinary and comparative-physiology studies made up 250 records (21.9% of the corpus) and experimental animal models published in human-medicine journals a further 38 records (3.3%). The distribution of study designs and study populations is presented in Table 3; no formal economic evaluation was identified.

Table 2. The 15 most productive countries (Scopus subset; full counting)

Rank	Country	Publications	Rank	Country	Publications
1	United States	282	9	The Netherlands	32
2	Canada	97	10	Spain	31
3	Australia	86	11	Czechia	28
4	Germany	67	12	Japan	27
5	Italy	67	13	Austria	24
6	Brazil	56	14	Denmark	24
7	United Kingdom	54	15	Türkiye	19
8	France	35			

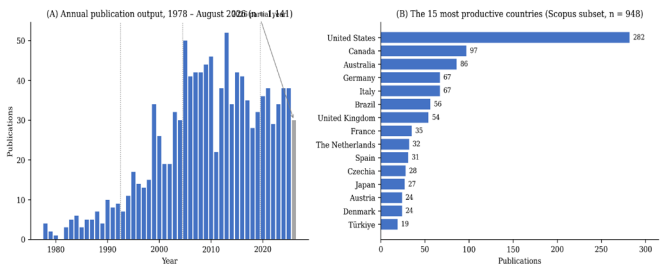


Figure 2. (A) Annual publication output, 1978 to August 2026 (full corpus, n=1,141); the 2026 column represents a partial year. (B) The 15 most productive countries (Scopus subset, n=948)

Table 3. Study design and study population of the Scopus subset (n=948)

Study design	n (%)	Study population	n (%)
Observational, design unspecified	327 (34.5)	Human-adult/general	644 (67.9)
Review	139 (14.7)	Veterinary/comparative physiology	208 (21.9)
Prospective observational	111 (11.7)	Human-paediatric/neonatal	65 (6.9)
Retrospective observational	88 (9.3)	Experimental animal model	31 (3.3)
Randomised controlled trial	71 (7.5)		
Editorial, letter, or note	61 (6.4)		
Experimental (animal or in vitro)	58 (6.1)		
Book chapter	47 (5.0)		
Case report or series	32 (3.4)		
Conference paper	14 (1.5)		

Classification was rule-based, applied to document type, title, abstract, and keyword fields. No formal economic evaluation (cost-effectiveness, cost-utility, or cost-benefit analysis) was identified in the corpus

Journal Distribution and Bradford's Law Analysis

Publications on the Stewart approach were concentrated in a limited number of journals in critical care, anaesthesiology, physiology, and veterinary medicine. The 948 Scopus-Indexed records were distributed across 373 journals. The leading venues were the Journal of Applied Physiology (n=39), Critical Care Medicine (n=29), Critical Care (n=28), Intensive Care Medicine (n=26), the Journal of Critical Care (n=22), and the Journal of Veterinary Internal Medicine (n=20) (Figure 3A). Zone 1 (the core nucleus) comprised 20 journals accounting for 317 publications (33.4% of the subset), Zone 2 comprised 77 journals, and Zone 3 comprised 276 journals. The zone multipliers were 3.85 and 3.58, two mutually consistent values, as Bradford's law requires (Figure 3B).

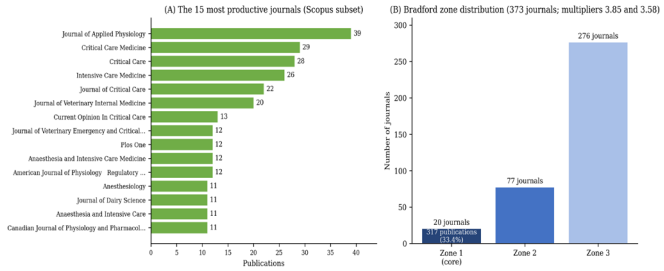


Figure 3. (A) The 15 most productive journals (Scopus subset). (B) Bradford zone distribution of 373 journals

Citation Analysis and h-Index

The 948 Scopus-Indexed publications had accumulated 26,125 citations by 23 August 2026, with a mean of 27.6 and a median of 9.0 citations per publication; 129 publications (13.6%) had not been cited. The h-Index of the subset was 74, indicating that 74 publications had each received at least 74 citations. The 10 most cited publications are listed in Table 4. Stewart's 1983 article⁵ was the most cited publication in the Scopus subset (1,179 citations), followed by the study of Scheingraber et al.¹⁶ on saline-induced hyperchloraemic acidosis (674 citations) and Kellum's review of the determinants of blood pH¹ (403 citations). The Figge-Fencel albumin publications⁸⁻¹⁰ occupied three of the remaining places, and reviews on the clinical importance of chloride¹⁸ and on lactate versus non-lactate acidosis³¹ also ranked among the most cited works.

Co-citation Analysis

Co-citation analysis was performed to identify the intellectual structure of the field by examining how frequently references were cited together.²⁴ Applying a minimum threshold of 25 co-citations to the 14,729 harmonised cited references yielded a network of 99 nodes forming a single connected component, with 4,356 links and a total link strength of 34,373 (Figure 4).

Four clusters were identified. The largest (41 references) comprised the theoretical foundations of the field: Stewart's three primary works,⁵⁻⁷ the Figge-Fencel albumin model,^{8,9} Leith's synthesis,³⁰ and the base-excess literature against which the framework was defined.³² The second cluster (33 references) covered clinical application and prognostic use of unmeasured anions, centred on Fencel et al.,¹¹ Kellum et al.,¹² Gilfix et al.,¹³ Balasubramanyan et al.,¹⁴ and Kaplan and Kellum.¹⁵ The third cluster (23 references) concerned fluid

Table 4. The 10 most cited publications in the Scopus subset (n=948)

Rank	First author, year	Title	Journal	Citations
1	Stewart PA, 1983	Modern quantitative acid-base chemistry	Can J Physiol Pharmacol	1,179
2	Scheingraber S, 1999	Rapid saline infusion produces hyperchloremic acidosis in patients undergoing gynecologic surgery	Anesthesiology	674
3	Kellum JA, 2000	Determinants of blood pH in health and disease	Crit Care	403
4	Figge J, 1998	Anion gap and hypoalbuminemia	Crit Care Med	372
5	Figge J, 1991	The role of serum proteins in acid-base equilibria	J Lab Clin Med	365
6	Figge J, 1992	Serum proteins and acid-base equilibria: a follow-up	J Lab Clin Med	336
7	Gunnerson KJ, 2006	Lactate versus non-lactate metabolic acidosis: a retrospective outcome evaluation of critically ill patients	Crit Care	318
8	Stewart PA, 1978	Independent and dependent variables of acid-base control	Respir Physiol	315
9	Kaplan LJ, 2004	Initial pH, base deficit, lactate, anion gap, strong ion difference and strong ion gap predict outcome from major vascular injury	Crit Care Med	294
10	Yunos NM, 2010	Bench-to-bedside review: chloride in critical illness	Crit Care	287

Citation counts extracted from Scopus on 23 August 2026



Figure 4. Co-citation network of harmonised cited references (minimum 25 co-citations; 99 nodes, 4,356 links)

therapy and iatrogenic acid-base disturbance, centred on Scheingraber et al.¹⁶ and Morgan.¹⁷ A fourth, two-node cluster grouped two comparative appraisals of the traditional and modern approaches.⁴

Stewart's 1983 article recorded the highest values in the network: it appeared in the reference lists of 416 of the 948 subset records (43.9%), and its total link strength (3,624) exceeded that of the next most connected reference (Figge et al.⁹ 1992: 2,398) by approximately 50%. The ten most co-

cited references, with their citing-record counts, total link strengths, and cluster memberships, are listed in Table 5. The two principal published critiques of the framework were themselves nodes within the network, both located in the largest (theoretical) cluster.

Keyword Co-occurrence Analysis and Thematic Evolution

Author keyword co-occurrence analysis was used to explore the conceptual structure of the literature. Applying a minimum frequency of 10 occurrences yielded a network of 45 keywords in six clusters, with 556 links and a total link strength of 2,730 (Figure 5A). The most frequent keywords were acid-base balance (n=263), metabolic acidosis (n=206), strong ion difference (n=205), anion gap (n=107), and Stewart approach (n=106) (Table 6). The clusters grouped, respectively: the anion gap and unmeasured-anion terms; laboratory and blood-gas descriptors; metabolic acidosis with lactate, chloride, and acute kidney injury; acid-base balance with the Stewart approach and fluid therapy; base excess with the classical disorder categories; and the strong ion difference with pH, bicarbonate, and the Henderson-Hasselbalch equation.

Table 5. The ten most co-cited references in the co-citation network (Scopus subset, n=948; minimum 25 co-citations)

Reference	Source	Citing records, n (%)	Total link strength	Cluster
Stewart PA, 1983	Can J Physiol Pharmacol	416 (43.9)	3,624	1
Figge J, 1992	J Lab Clin Med	220 (23.2)	2,398	1
Fencel V, 2000	Am J Respir Crit Care Med	189 (19.9)	2,118	2
Kellum JA, 1995	J Crit Care	176 (18.6)	2,142	2
Figge J, 1991	J Lab Clin Med	161 (17.0)	1,847	1
Balasubramanyan N, 1999	Crit Care Med	135 (14.2)	1,752	2
Leith DE, 1993	Respir Physiol	122 (12.9)	1,356	1
Stewart PA, 1981	Monograph (How to Understand Acid-Base)	118 (12.4)	973	1
Figge J, 1998	Crit Care Med	117 (12.3)	1,460	2
Scheingraber S, 1999	Anesthesiology	114 (12.0)	1,439	3

Citing records: number of subsets records whose harmonised reference lists contain the reference. Clusters: 1=theoretical foundations; 2=clinical application and prognostic markers; 3=fluid therapy and hyperchloremic acidosis. Data extracted 23 August 2026.

Table 6. The 20 most frequent author keywords (minimum 10 occurrences; 687 of 948 records carried author keywords)			
Author keyword	Occurrences	Total link strength	Mean publication year
Acid-base balance	263	579	2011.4
Metabolic acidosis	206	598	2012.1
Strong ion difference	205	521	2010.2
Anion gap	107	352	2010.7
Stewart approach	106	294	2014.0
Strong ion gap	82	271	2011.6
Base excess	71	270	2012.4
Metabolic alkalosis	56	235	2012.4
Acid-base disorders	49	100	2016.2
Lactate	48	146	2008.2
pH	41	138	2010.5
Critical care	38	115	2015.4
Bicarbonate	38	131	2008.5
Electrolytes	33	68	2013.7
Unmeasured anions	33	110	2011.1
Hyperchloraemia	30	111	2011.5
Chloride	29	107	2010.7
Blood gas analysis	26	64	2015.4
Horse	24	43	2011.2
Fluid therapy	23	45	2017.9

To examine how research themes have evolved over time, the same keyword network was visualised using temporal overlay colouring, in which node colour represents the average publication year of each keyword (Figure 5B). Mean publication years ranged from 2007.9 to 2017.9. Classical parameters were associated with the earliest years-strong ions (2007.9), lactate (2008.2), bicarbonate (2008.5), strong ion difference (2010.2), and anion gap (2010.7)-whereas fluid therapy (2017.9), respiratory alkalosis (2017.1), buffers (2016.7), carbon dioxide (2016.6), acid-base disorders (2016.2), the physicochemical approach (2016.1), critical care (2015.4), and acute kidney injury (2014.3) occupied the recent end of the scale. Keywords ranked by mean publication year are presented in Table 7. Because the overlay metric is a mean over the whole indexing period, its upper bound (2017.9) lies well below the final year of the search window even though the subset itself had a mean publication year of 2010.2 (range 1978-2026) and 235 records (24.8%) were published in 2019 or later; the metric summarises where a term’s literature is centred, not when it was last used.

Country Co-authorship Network

To characterise international collaboration patterns in the Stewart literature, country co-authorship analysis was performed on the Scopus subset using a minimum threshold of five publications per country (Figure 6). The network comprised 30 countries organised into seven clusters, connected by 117 links with a total link strength of 275; network density was 0.269 and the mean link strength 2.35. The strongest single collaboration axis was between

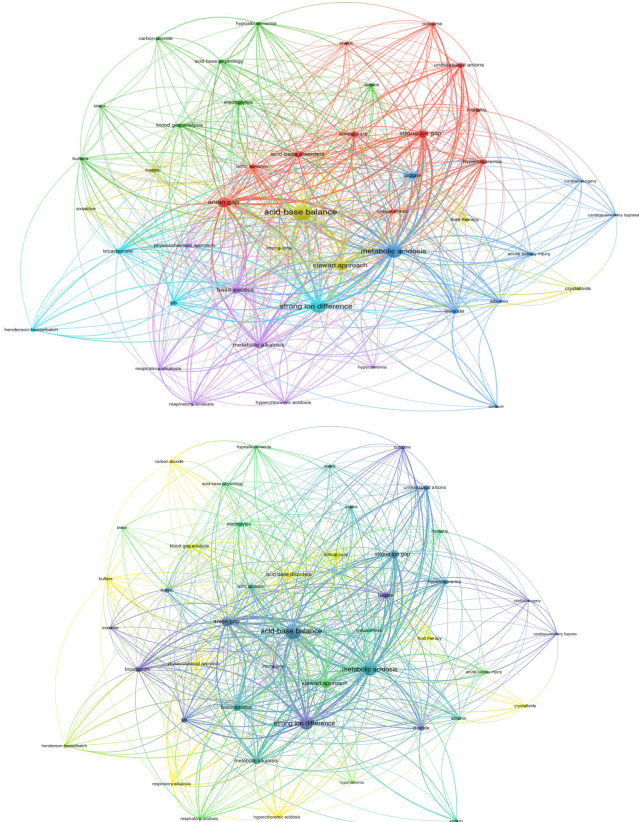


Figure 5. Author keyword co-occurrence network (minimum 10 occurrences; 45 keywords). (A) Cluster view. (B) Temporal overlay, coloured by mean publication year

Canada and the United States (link strength 27), followed by Australia-United States (12), Austria-Germany (8), Germany-United States (8), and Czechia-Italy (7). The United States occupied the most central position (total link strength 98), followed by Canada (49) and Australia (45). A Central European group centred on Germany, with links to Austria, Italy, the Netherlands, Czechia, and Denmark, formed a distinct regional cluster. Türkiye entered the network with 19 publications and links to the Netherlands and the United States, with a mean publication year of 2020-the most recent of any country in the network. Despite broad geographical coverage, network density remained low.

Author-Level Co-authorship Network

Because collaboration was originally described at country level only, an author-level co-authorship analysis was added. Ninety-eight authors had contributed five or more publications to the Scopus subset. Restricted to these authors, the co-authorship network comprised 168 links with a total link strength of 617 and a density of 0.035. The network was highly fragmented: it resolved into 28 components, the largest containing 20 authors (20.4% of the 98), and 12 authors had no co-authorship link to any other author in this group. The most productive authors were Kellum JA (38 publications), Bellomo R (30), Story DA (24), Constable PD (22), Lindinger MI (21), and Langer T and Heigenhauser GJF (18 each). The strongest author-level ties were Langer-Zadek (link strength 12), Maciel-Park (11), Lindinger-Heigenhauser (11), Bellomo-Story (10), and Bellomo-Morimatsu (9).

Table 7. Author keywords ranked by mean publication year (temporal overlay metric)

Mean publication year	Author keywords (occurrences)
2007.9-2009.9	Strong ions (13), lactate (48), bicarbonate (38), exercise (12), cardiopulmonary bypass (10)
2010.0-2011.9	Strong ion difference (205), cardiac surgery (10), pH (41), chloride (29), anion gap (107), outcome (17), unmeasured anions (33), horse (24), hyperchloraemia (30), strong ion gap (82)
2012.0-2013.9	Lactic acidosis (21), metabolic acidosis (206), metabolic alkalosis (56), base excess (71), albumin (16), sepsis (16), shock (11), sodium (10), critical illness (22), mortality (13), electrolytes (33), acid-base physiology (17), hypoalbuminaemia (17)
2014.0-2015.9	Stewart approach (106), acute kidney injury (18), respiratory acidosis (13), blood (10), hyponatraemia (10), hyperchloraemic acidosis (12), Henderson-Hasselbalch (17), blood gas analysis (26), critical care (38)
2016.0-2017.9	Physicochemical approach (19), acid-base disorders (49), crystalloids (13), carbon dioxide (13), buffers (12), respiratory alkalosis (14), fluid therapy (23)

Mean publication years are rounded to one decimal place. The overlay metric is the mean publication year of the records carrying each keyword and is therefore centred on the bulk of a term's literature rather than on its most recent use

**Figure 6.** Country co-authorship network (minimum 5 documents; 30 countries)

Lotka's Law Analysis

The Scopus subset comprised 2,555 unique authors, of whom 2,020 (79.1%) contributed a single publication. The observed distribution deviated substantially from the theoretical curve, particularly in the higher productivity ranges: 286 authors published two items against 505 predicted, 115 published three against 224 predicted, and 98 published five or more against 447 predicted (**Table 8**). The fitted exponent was 2.25, and the Kolmogorov-Smirnov statistic ($D=0.0952$) exceeded the critical value (0.0322) at $\alpha=0.01$ ($p<.001$), so conformity to the inverse-square form was rejected. The deviation persisted after the approximately fourfold expansion of the corpus relative to the previous version of this analysis.

Table 8. Observed author productivity against the distribution predicted by Lotka's inverse-square law (Scopus subset; 2,555 authors)

Publications per author	Observed authors	Predicted by Lotka's law	Observed/predicted
1	2,020	2,020	1.00
2	286	505	0.57
3	115	224	0.51
4	36	126	0.29
≥5	98	447	0.22

Fitted exponent 2.25; Kolmogorov-Smirnov $D=0.0952$ against a critical value of 0.0322 at $\alpha=0.01$, rejecting conformity to the inverse-square form

Sensitivity Analyses

Recomputing each network at alternative thresholds showed that the co-citation structure was robust: thresholds of 20,

25, and 30 co-citations produced networks of 143, 99, and 81 nodes with five, four, and four clusters respectively, and cluster agreement with the primary solution was substantial (adjusted Rand Index 0.688 for the threshold of 20 and 0.730 for the threshold of 30). The six highest-degree references retained identical cluster membership at all three thresholds. The country network was likewise stable (adjusted Rand Index 0.828 between thresholds of 5 and 3 documents).

The keyword network was more threshold-dependent: thresholds of 5, 10, and 15 occurrences produced 94, 45, and 30 keywords in nine, six, and four clusters, with adjusted Rand indices of 0.181 and 0.251 relative to the primary solution. Keyword cluster boundaries are therefore reported descriptively and are not interpreted as stable thematic partitions; the temporal analysis reported above relies on the mean publication year of individual keywords, which is threshold-independent.

DISCUSSION

This bibliometric analysis mapped 1,141 publications on the Stewart physicochemical approach published between 1978 and August 2026. Four findings define the field. First, the literature has matured rather than expanded: annual output rose eightfold between the foundational and expansion periods but has been essentially flat since 2005, and its Scopus-Indexed subset has accumulated a substantial citation base (26,125 citations; h-Index 74). Second, its intellectual structure is unusually concentrated on a single reference-Stewart's 1983 article, which is cited in the reference lists of 43.9% of the Scopus subset. Third, its collaborative structure is regionally clustered, with a dominant Canada-United States axis, and its authorship base consists overwhelmingly of occasional contributors. Fourth, the conceptual content has shifted measurably from parameter description toward fluid therapy, chloride, and outcome-oriented questions.

Growth, Composition, and the Breadth of the Field

The plateau in annual output after 2005 is consistent with a mature rather than a rapidly expanding literature: the field now produces a stable 35-40 publications per year. A distinctive feature revealed by the expanded search is the weight of veterinary and comparative physiology, which contributed 250 of the 1,141 corpus records (21.9%; within the Scopus subset 208 of 948, likewise 21.9%-**Table 3**) and placed

the Journal of Veterinary Internal Medicine, the Journal of Veterinary Emergency and Critical Care, the Journal of Dairy Science, and the American Journal of Veterinary Research within the Bradford core. This is not incidental: the strong ion approach has been developed in parallel in these domains, and Constable's simplified strong ion model was derived in equine plasma before being applied in human medicine.³³ Any account of the field that restricts itself to human critical care therefore understates both its size and its methodological origins.

The distribution of study designs is equally informative. Only 71 of the 948 subset records (7.5%) were randomised controlled trials, and no formal economic evaluation was identified. The evidence base is therefore predominantly observational, and comparative-effectiveness evidence on whether physicochemical interpretation changes management or outcome-remains limited relative to the volume of descriptive work.

Intellectual Structure and the Place of Methodological Critique

The co-citation network resolved into three principal clusters that correspond to recognisable phases of the framework's development: a theoretical nucleus (Stewart's own works, the Figge-Fencel albumin model, and the base-excess literature against which the approach was defined),^{5-10,32} a clinical-application cluster organised around the strong ion gap and its prognostic use,¹²⁻¹⁵ and a fluid-therapy cluster centred on saline-induced hyperchloraemic acidosis.^{16,17} The dominance of Stewart's 1983 article within this structure (total link strength 3,624, approximately 50% above the next reference) is quantitatively unusual for a mature field and indicates the continued prominence of the original formulation within the field's intellectual structure.

An important qualification concerns what co-citation does and does not measure. Two nodes are linked when they appear together in a reference list, irrespective of whether the citing author endorses or rejects them. The presence of Kurtz et al.²⁰ and Doberer et al.²¹ within the network therefore does not indicate agreement; it indicates that the critique of the Stewart framework is conducted inside the same citation community rather than in a separate literature. It also cautions against reading cluster membership as consensus.³³⁻³⁸ The persistence of the debate is real: authors continue to question whether the physicochemical approach adds diagnostic information beyond a well-corrected anion gap,^{3,4} and reviews reach divergent conclusions on the prognostic value of the strong ion gap.^{39,40}

Conceptual Structure and Thematic Evolution

The temporal overlay provides the clearest evidence of the field's reorientation. Terms describing the framework's own machinery are centred in the late 2000s (strong ions 2007.9, strong ion difference 2010.2, anion gap 2010.7), whereas clinically framed terms are centred in the mid-2010s (acute kidney injury 2014.3, critical care 2015.4, physicochemical approach 2016.1, acid-base disorders 2016.2) and fluid therapy is the most recent of all (2017.9). The pattern is consistent with

the citation data: the most cited works of the last two decades concern chloride, fluid composition, and outcome^{18,32} rather than the derivation of the model.

This interpretation rests on the mean publication year of individual keywords rather than on cluster membership, a deliberate choice. Recomputing the keyword network at thresholds of 5 and 15 occurrences produced markedly different partitions (adjusted Rand indices 0.181 and 0.251), whereas the co-citation and country partitions were stable. Keyword clusters in this literature should therefore be treated as descriptive groupings, not as robust thematic communities—a limitation that applies to many keyword-based bibliometric analyses but is rarely tested explicitly.

Collaboration Structure

The strongest collaborative axis in the field links Canada and the United States (link strength 27), more than twice the next strongest tie. Two factors plausibly contribute: Stewart himself worked in Canada, and Canadian comparative and exercise physiology groups have sustained a continuous line of work on strong ion regulation, reflected in the presence of the Canadian Journal of Physiology and Pharmacology in the Bradford core. Australia forms a second hub, and the author-level network shows that this hub rests on recurring dyads within the country and with Japan (Bellomo-Story, link strength 10; Bellomo-Morimatsu, 9) rather than on a single transnational partnership. A Central European group centred on Germany, Austria, Italy, Czechia, and Denmark constitutes a third.

The author-level network reinforces this reading: of the 98 authors with five or more publications, only 20 (20.4%) belonged to the largest connected component, 12 had no co-authorship tie to any other author in that group, and network density was 0.035. Overall country-level network density (0.269) and mean link strength (2.35) are likewise low, indicating that the field has advanced through regional partnerships rather than multinational consortia. This structural observation aligns with the informetric findings: 79.1% of authors contributed a single publication and productivity deviated significantly from Lotka's inverse-square law, so the field lacks the stable core of prolific specialists that typically sustains consortium-scale trials. The two findings are best read together—a dispersed authorship base and a sparse collaboration network are two expressions of the same phenomenon, namely that most contributions to this literature are made by clinicians and physiologists applying the framework locally rather than by dedicated research groups. Türkiye's recent entry (19 publications; mean publication year 2020) is one example of this pattern of distributed, locally initiated contribution.

Informetric Behaviour and Comparison with Other Fields

The field conformed to Bradford's law, with zone multipliers of 3.85 and 3.58 close to the constant multiplier the law predicts, but departed significantly from Lotka's law. This combination reflects orderly journal concentration alongside a dispersed authorship base. Notably, the deviation from Lotka's law persisted after the corpus was expanded approximately

fourfold relative to the previous version of this analysis, indicating that it reflects the structure of the field rather than sampling limitations.

Placing these indicators in context requires comparison with bibliometric analyses of adjacent critical care topics. A bibliometric analysis of machine learning applications in acute kidney injury identified 336 publications with an h-Index of 28 and a mean of approximately 10 citations per publication,⁴¹ and an analysis of sepsis-associated acute kidney injury identified 688 publications to May 2024, drawn from 45 countries and 1,919 authors of whom only 12 (0.6%) had contributed five or more publications, with a recent annual output of approximately 87.5 publications per year;⁴² a further analysis has mapped the broader intersection of acute kidney injury and sepsis over 2004–2024.⁴³ Against these comparators the Stewart literature is larger in volume, markedly higher in citation maturity (h-Index 74; mean 27.6 citations per publication), slower in recent annual output (36.6 per year), and more persistent at author level (98 of 2,555 authors, 3.8%, with five or more publications). Comparable network-density values are rarely reported in these analyses, so the country-level density of 0.269 and the author-level density of 0.035 reported here are offered as reference values for future comparison. The overall pattern is that of a smaller, older, and more slowly renewing field whose foundational works continue to attract citations four decades after publication.

Clinical and Research Implications

Three implications follow. First, the concentration of the field on a small number of foundational references, combined with the low proportion of randomised evidence, suggests that the principal evidential gap lies in comparative studies testing whether physicochemical interpretation alters management decisions or patient outcomes. Second, the evidence on the prognostic value of the strong ion gap is inconsistent across the primary studies that report it: the marker predicted mortality in a pediatric intensive care cohort¹⁴ and outcome after major vascular injury,¹⁵ but showed no prognostic value in a mixed adult medical-surgical intensive care unit,³⁵ and dedicated reviews of the comparative evidence reach the same conclusion of inconsistency.^{39,40} Its use as a stand-alone risk marker therefore cannot presently be recommended without population-specific validation. Third, the computational burden that has limited bedside adoption is increasingly tractable: automated calculation within laboratory information systems and decision-support tools would allow physicochemical parameters to be generated alongside conventional indices, which would in turn make the comparative studies described above feasible at scale.

Stewart's 1981 monograph⁷ is not indexed in any of them and therefore cannot appear in the citation analysis, although it does appear as a cited reference within the co-citation network; conversely, a known-item check confirmed that seven of the eight foundational works of the field were retrieved by the search strategy.

Limitations

This study has several limitations. First, coverage is bounded by the three databases searched.

The corpus also depends on the phrase set used; although the search strategy was substantially expanded during revision, variant designations of the framework that share no term with the strategy may still be absent. Second, citation-based, network, and informetric analyses were restricted to the 948 Scopus-Indexed records (83.1% of the corpus), because records unique to PubMed or the Web of Science Core Collection lack the structured reference, keyword, and affiliation fields these analyses require. The subset closely matched the full corpus in period and document-type distribution, but it is not identical to it, and indicators derived from a single database should be interpreted as database-specific rather than absolute. The findings constrained by this subsetting are the h-Index and all citation indicators, the citation ranking in Table 4, the Bradford zone allocation, the Lotka distribution, the co-citation network, the author keyword analyses, and both the country and author co-authorship networks.

Third, citation counts are a cross-sectional snapshot taken on 23 August 2026 and favour older publications; the 2026 figures represent a partial year. Self-citations were not excluded from the citation counts, the h-Index, or the co-citation network, and citation counts reflect only citing sources indexed in Scopus. Fourth, author keywords were available for 687 of the 948 subset records, so the keyword analysis describes the indexed subset of the literature, and its cluster structure proved threshold-dependent, as reported above. Fifth, reference harmonisation was performed programmatically; although it resolved the principal fragmentation artefacts, residual variant strings below the co-citation threshold cannot be excluded. Sixth, study design and population were classified by rule-based text analysis rather than full-text review, so the categories should be read as an approximate profile of the corpus. Seventh, country attribution rests on author affiliation rather than on where the work was actually performed, and full counting credits a publication to every contributing country, which favours collaborative output. Eighth, the four period boundaries were set by the authors rather than derived from the data, and the grouping of keywords in Table 7 is a presentational convenience rather than a measured partition. Finally, no language restriction was applied, but all three databases index English-language journals preferentially, so non-English contributions are probably under-represented.

Finally, the prespecification status of the study should be stated plainly. The eligibility criteria, the dataset assignments, and the analysis periods were prespecified before the corpus was rebuilt, whereas the search strategy was broadened, the reference-harmonisation procedure was introduced, and the network thresholds were settled during this revision in response to peer review. A conceptual limitation deserves separate mention: co-citation and co-occurrence analyses measure association, not endorsement or scientific validity. High citation counts identify influential works, not correct ones, and the clusters described here should be read as maps of how the literature is organised rather than as assessments of the evidence it contains.

CONCLUSION

Across nearly five decades, the Stewart physicochemical approach has generated a literature of 1,141 publications, whose

Scopus-Indexed subset (n=948) carries 26,125 citations and an h-Index of 74, spanning human critical care, anaesthesiology, and-to a greater extent than previously recognised-veterinary and comparative physiology. Output peaked during 2005-2019 (39.3 publications per year; single-year maximum 52 in 2013) and has remained essentially stable since. The field is intellectually concentrated, with Stewart's 1983 article cited in the reference lists of 43.9% of its Scopus-Indexed subset; informetrically orderly at journal level (a 20-journal Bradford core; multipliers 3.85 and 3.58) but dispersed at author level (79.1% single-publication authors, with significant deviation from Lotka's law); and collaboratively fragmented rather than consortium-based: 30 countries are connected by only 117 links in seven clusters (density 0.269), the network being carried by the United States, Canada, Australia, Germany, and Italy, whilst at author level 28 separate components were identified among the 98 most productive authors. Its conceptual centre of gravity has moved from parameter description toward fluid therapy, chloride, and acute kidney injury, with four co-citation clusters and six keyword groupings describing its present structure. The principal gap is evidential rather than descriptive: fewer than 8% of subset publications report randomised designs, none reports an economic evaluation, and comparative evidence on whether physicochemical interpretation changes clinical decisions and patient outcomes-increasingly feasible as automated calculation reduces the bedside computational burden-remains the least developed element of the published record.

ETHICAL DECLARATIONS

Ethics Committee Approval

The study did not require ethics committee approval because it was conducted exclusively on publicly available bibliographic metadata and involved no human participants or identifiable personal data.

Informed Consent

Since this research is a bibliometric study, it did not require informed consent.

Peer Review Process

This manuscript was subject to external peer review.

Conflict of Interest

The authors declare no conflicts of interest related to this study.

Financial Disclosure

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Author Contributions

Concept: MK, GGÇ; Design: MK, GGÇ; Control: MK, GGÇ; Resources: MK, GGÇ; Materials: MK, GGÇ; Data Collection and/or Processing: MK, GGÇ; Analysis and/or Interpretation: MK, GGÇ; Literature Review: MK, GGÇ; Writing the Article: MK, GGÇ; Critical Review: MK, GGÇ.

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