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Review Article

Global Waste Valorization and Circular Transitions: A Systematic Review and Critical Synthesis of Technologies, Scalability, and Implementation Gaps

Md Mainul Sk

Department of Geography, Rajendra University, Balangir, Odisha, India

KEYWORDS

circular bioeconomy
municipal solid waste
resource recovery
technology readiness level
life cycle assessment
techno-economic feasibility
methane mitigation
industrial symbiosis

ABSTRACT

Rapid urbanization and escalating consumption have accelerated solid waste generation, precipitating severe landfill methane emissions, environmental contamination, and resource depletion, while empirical valorization research remains fragmented across disparate technological pathways and jurisdictions. Adhering to the PRISMA 2020 framework, this study conducted a systematic review and bibliometric mapping of the Scopus database (2018 – 2025), synthesizing 540 macro-landscape publications alongside 46 core empirical investigations appraised via Critical Appraisal Skills Programme (CASP) criteria and Technology Readiness Level (TRL) categorization. Scientific output expanded rapidly at a compound annual growth rate of 30.34%, led by Italy (n=84), China (n=62), and the United States (n=61). However, profound spatial inequalities persist: the Global North accounts for 70.93% of scientific output, leaving high-burden developing regions acutely under-researched. The thematic landscape centers on mixed municipal solid waste (21.3%) and organic fractions (17.4%), primarily processed via composting (17.8%), anaerobic digestion (15.6%), and thermochemical routes (14.6%). Although biological conversion and landfill gas capture achieve reported methane diversion rates of 50–85%, critical structural deficits emerge: 89.3% of the literature remains confined to bench-scale trials (TRL 1 – 5), only 4.8% incorporates rigorous Techno-Economic Analysis (TEA), and circularity assertions frequently lack verified mass-balance or virgin-resource substitution proofs. Scalable industrial deployment is hindered by seasonal feedstock variability, parasitic thermal loads, secondary market price volatility, and uncoordinated policy frameworks. Consequently, this review establishes an empirical baseline, formulates a closed-loop conceptual framework, and delineates an actionable, multi-horizon strategic research agenda to advance scalable, circular, and climate-neutral waste-to-resource systems globally.

*CORRESPONDING AUTHOR

Md Mainul Sk; Department of Geography, Rajendra University, Balangir, Odisha, India; Email: mainuls919@gmail.com

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1. Introduction

1.1. The Global Solid Waste Crisis and the Limits of Linear Landfilling

The rapid intensification of global industrialization, population expansion, and urban consumption has elevated solid waste management to the forefront of 21st-century environmental challenges [1,2]. Current estimates indicate that global municipal solid waste (MSW) generation exceeds 2.1 billion metric tons annually, a figure projected to approach 3.4 billion metric tons by 2050 under business-as-usual trajectories [3]. Historically, urban solid waste management has operated under a linear extractive paradigm characterized by the 'take-make-dispose' model [4]. In this linear trajectory, discarded materials are predominantly routed to unmanaged open dumpsites or engineered sanitary landfills [5,6].

Landfilling, while serving as a conventional containment strategy, imposes severe ecological and atmospheric liabilities [7,8]. The anaerobic biodegradation of organic fractions—predominantly food waste, garden residues, paper, and sewage sludge—within compacted, anaerobic landfill environments generates substantial volumes of landfill gas (LFG) [9,10]. LFG is composed approximately of 50–60% methane (CH4) and 40–50% carbon dioxide (CO2), accompanied by trace non-methane organic compounds and siloxanes [11,12]. Methane possesses a 100-year global warming potential (GWP) 28 to 36 times greater than that of carbon dioxide, and an 84-fold greater potency over a 20-year horizon [13,14]. Consequently, municipal waste landfills constitute the third-largest anthropogenic source of methane emissions globally, accounting for approximately 11% of global methane output [15,16]. Beyond greenhouse gas accumulation, landfill operations pose persistent threats of groundwater contamination through toxic leachate migration, land consumption, odor nuisance, and the irreversible dissipation of high-value embodied nutrients and critical materials [17,18].

1.2. The Paradigm Shift: From Waste Disposal to Circular Valorization

In response to these compounding planetary crises, academic, industrial, and regulatory paradigms have increasingly pivoted toward the principles of the circular economy (CE) [19,20]. Rather than treating post-consumer residues as hazardous liabilities requiring permanent disposal, the circular paradigm reconceptualizes waste as secondary anthropogenic resources [21,22]. Within this conceptual framework, 'waste valorization' has emerged as the pivotal operational bridge [23,24]. Valorization denotes the suite of physical, biochemical, thermochemical, and chemical conversion technologies designed to transform discarded fractions into value-added commodities, clean energy carriers, green structural materials, and secondary chemicals [25,26].

The theoretical promises of global waste valorization are multidimensional [27,28]. Biochemically, the diversion of readily biodegradable organic fractions into anaerobic digestion (AD) or controlled composting systems simultaneously intercepts uncontrolled fugitive landfill methane emissions while generating renewable biomethane and nutrient-rich biofertilizers [29,30]. Thermochemically, intermediate and non-recyclable combustible fractions can be processed via advanced pyrolysis, gasification, or mass-burn waste-to-energy (WtE) facilities to displace fossil fuels, produce biochar soil amendments, and generate synthetic fuels [31,32]. Materially, automated artificial intelligence (AI) sorting, mechanical reprocessing, and geopolymerization convert mineral construction debris and polymers into secondary structural elements and closed-loop resins [33,34]. Collectively, these interventions aim to establish closed industrial loops, decoupling economic development from virgin resource consumption while fulfilling United Nations Sustainable Development Goals (SDG 11: Sustainable Cities; SDG 12: Responsible Consumption; SDG 13: Climate Action) [35,36].

1.3. State of Current Review Literature and Critical Knowledge Fragmentation

Notwithstanding the proliferation of review papers in the broader domains of sustainability and waste management, the existing synthesis literature exhibits critical conceptual and methodological shortcomings [37,38]. First, the vast majority of prior reviews operate within narrow technological silos [39,40]. Extant

syntheses frequently examine single processes in isolation—such as anaerobic digestion of food waste [41], pyrolysis of agricultural residues [42], or mechanical plastic recycling [43]—without systematically comparing their relative greenhouse gas abatement efficiencies, energy returns on investment (EROI), or secondary contamination risks against other valorization alternatives [44,45].

Second, a predominant share of published reviews adopts a purely descriptive bibliometric format [7]. These studies catalogue publication frequencies, top authors, and keyword clouds, but fail to critically interrogate the underlying scientific claims, methodological robustness, or real-world implementation barriers of the reviewed corpus [46,47]. Crucially, there is a pervasive failure in the literature to differentiate between 'claimed circularity' and 'demonstrated circularity' [48,49]. Numerous experimental studies invoke the circular economy rhetorically to justify novel bench-scale synthesis protocols without providing life-cycle mass balances, fugitive emission accounting, or displacement proofs for virgin raw materials [50,51].

Third, existing literature largely overlooks the profound 'laboratory-to-market' scale-up gap [52,53]. Innovative conversion routes optimized under idealized laboratory conditions with homogeneous synthetic feedstocks frequently encounter insurmountable techno-economic, rheological, and contamination barriers when exposed to real-world, heterogeneous municipal waste streams [54,55]. Finally, global geographic disparities remain unaddressed: while waste valorization literature is heavily concentrated in high-income countries of the Global North, the most acute municipal waste management crises occur across rapidly urbanizing nations in the Global South [56,57].

1.4. Research Objectives and Questions

To address these substantive knowledge voids, this study conducts an exhaustive, PRISMA-2020-compliant systematic literature review and multi-dimensional critical synthesis of the global waste valorization research domain. Moving decisively beyond descriptive accounting toward evidence-based critical analysis, this investigation addresses seven fundamental research questions: first (RQ1), how global scientific output on waste valorization and circular waste systems has evolved temporally and geographically between 2018 and 2025 across Global North and Global South economies; second (RQ2), which specific waste streams, valorization routes, and value-added end-products dominate the research landscape, and to what extent scientific attention aligns with real-world waste generation magnitudes; third (RQ3), what conceptual clusters, research fronts, and knowledge co-occurrence networks define the intellectual architecture of the global waste valorization field; fourth (RQ4), how rigorously valorization studies substantiate circular economy claims through quantified mass and energy balances, avoided landfill emissions, and virgin resource displacement; fifth (RQ5), to what extent Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) are integrated into experimental valorization studies to validate environmental and commercial viability; sixth (RQ6), what proportion of the literature operates at bench-scale (TRL 1–4) versus pilot and industrial demonstration (TRL 5–9), and what structural barriers inhibit commercial deployment; and seventh (RQ7), what multi-horizon research agenda spanning technological, economic, environmental, policy, and digital dimensions is required to bridge the lab-to-market divide and realize genuine system-level circularity.

2. Materials and Methods

2.1. Systematic Review Protocol and PRISMA 2020 Compliance

This study was designed, executed, and reported in strict compliance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines [58]. The systematic review protocol was formulated around the Population, Intervention, Comparator, and Outcomes (PICO) framework to ensure methodological reproducibility, objectivity, and transparent study selection [59]. Under this framework, the investigated population (P) comprises global solid waste systems, encompassing municipal solid waste (MSW), organic and kitchen waste, post-consumer plastics, agricultural biomass residues, municipal sewage sludge,

construction and demolition waste, and industrial by-products. The evaluated interventions (I) include physical, biological, thermochemical, chemical, and digital valorization technologies, specifically anaerobic digestion, aerobic composting, pyrolysis, gasification, waste-to-energy incineration, mechanical reprocessing, chemical solvolysis, geopolymerization, and artificial intelligence-assisted sorting. The baselines and comparators (C) correspond to conventional linear waste management paradigms, specifically unsanitary landfill disposal, open dumping, unmanaged open burning, and virgin fossil-resource extraction baselines. The primary evaluated outcomes (O) include quantified secondary resource yields, methane and greenhouse gas abatement rates, life-cycle global warming potential (GWP), techno-economic viability indicators (capital expenditures [CAPEX], operational expenditures [OPEX], levelized cost of energy [LCOE], and net present value [NPV]), and technology readiness levels (TRL).

To establish conceptual clarity and resolve prevailing ambiguities in the synthesis literature, three core operational definitions guide this review: first, 'waste valorization' is operationally defined as any secondary processing or conversion activity that transforms post-consumer or post-industrial discard fractions into distinct value-added marketable commodities, clean energy carriers, platform chemicals, or engineering materials, strictly distinguished from basic downcycling or non-productive volumetric reduction; second, 'circular economy' is defined as an industrial economic system designed to be restorative and regenerative by intention, maintaining the highest utility and economic value of products, components, and materials at all times across technical and biological cycles while eliminating landfill leakage; and third, an 'urban biorefinery' denotes an integrated multi-input, multi-output valorization facility co-located within municipal boundaries that symbiotically fractionates heterogeneous organic, sludge, and biogenic waste fractions into bioenergy, biofertilizers, and high-value biochemicals.

2.2. Database Selection and Reconciled Search Strategy

Primary literature retrieval was conducted using the Scopus database (Elsevier), widely recognized for its comprehensive coverage of peer-reviewed literature in environmental science, engineering, chemical technology, and circular economy research [30, 60]. Scopus was selected over alternative repositories because of its rigorous indexation standards, systematic citation tracking, and superior coverage of applied waste conversion engineering relative to narrower indexes, while avoiding the uncurated grey-literature noise characteristic of search engines like Google Scholar. To capture the intersection of circular systems, solid waste matrices, and climate mitigation, a Boolean search string was constructed and validated across Title, Abstract, and Author Keywords: TITLE-ABS-KEY (("circular economy" OR recycling) AND ("municipal solid waste" OR MSW OR landfill) AND ("greenhouse gas" OR GHG OR "landfill gas")). The search was bounded by a publication window spanning January 1, 2018, to December 31, 2025 in 6th March, 2026. Post-retrieval limiters were applied to restrict records to peer-reviewed research articles published in English with final publication status.

2.3. Screening and Study Eligibility Protocol

The systematic screening process followed a dual-tier analytical architecture, as illustrated in the PRISMA 2020 flow diagram (Figure 1). The initial database query yielded exactly 540 raw bibliographic records. Automated deduplication across titles and digital object identifiers (DOIs) confirmed 100% unique entries (N = 540). To eliminate individual investigator bias and ensure high screening fidelity, two independent reviewers executed a two-stage screening protocol based on predefined inclusion and exclusion criteria (Table 1), with inter-rater discrepancies resolved through consensus adjudication and third-reviewer arbitration. Studies were included based on four rigorous criteria: primary focus on solid waste valorization or circular resource recovery; empirical laboratory trials, pilot demonstrations, or quantitative system modeling; explicit reporting of emissions, energy yields, or material recovery metrics; and peer-reviewed articles published in English between 2018 and 2025. Conversely, records were excluded if they focused exclusively on non-solid waste sectors (such

as fugitive coal mine methane or enteric livestock emissions), comprised purely narrative reviews or commentaries lacking primary empirical data, omitted empirical baseline comparisons or quantitative valorization indicators, or represented duplicate or unverified records.

Table 1. Database search strategy and study selection criteria.

Parameter	Specification
Target Database	Scopus (Elsevier Core Collection)
Search Field	TITLE-ABS-KEY (Title, Abstract, Author Keywords)
Boolean Search String	("circular economy" OR recycling) AND ("municipal solid waste" OR MSW OR landfill) AND ("greenhouse gas" OR GHG OR "landfill gas")
Publication Window	January 1, 2018 to December 31, 2025
Document Type Limiter	Peer-reviewed journal articles only (ar)
Language	English (en)
Inclusion Criteria (IC)	IC1: Empirical or quantitative modeling of solid waste valorization; IC2: Quantified greenhouse gas, methane mitigation, or material recovery metrics; IC3: Explicit evaluation of circular economy or resource recovery pathways; IC4: Clear baseline comparison against linear landfilling or unmanaged disposal.
Exclusion Criteria (EC)	EC1: Studies exclusively assessing non-solid waste sectors (e.g., fugitive coal mine methane, enteric livestock emissions); EC2: Purely qualitative reviews or opinion pieces lacking primary empirical data or reproducible modeling; EC3: Missing quantitative valorization or recovery performance indicators; EC4: Duplicate records or incomplete bibliographic metadata.

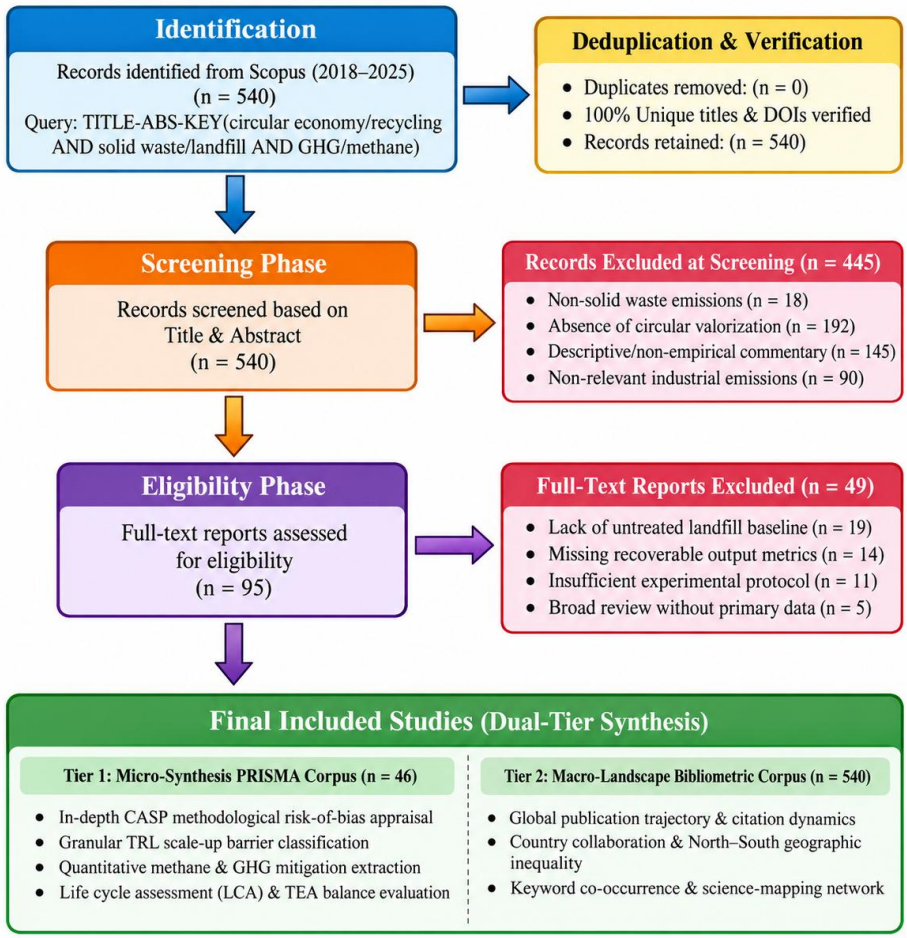


Figure 1. PRISMA 2020 flow diagram showing the identification, screening, eligibility assessment, and final inclusion of studies in the dual-tier evidence synthesis.

At the Title and Abstract screening stage, 445 records were excluded for failure to meet inclusion criteria. The remaining 95 full-text articles were retrieved and subjected to comprehensive eligibility appraisal. Forty-nine full-text reports were excluded with documented justifications: lack of untreated landfill baseline (n = 19), missing recoverable output metrics (n = 14), insufficient experimental protocol description (n = 11), and broad conceptual review without primary data (n = 5). This yielded a final micro-synthesis empirical corpus of 46 rigorously evaluated core articles, alongside the macro-landscape bibliometric corpus of 540 articles.

2.4. Data Extraction and Analytical Protocol

Data extraction was executed using a standardized coding instrument structured across four analytical modules: first, bibliometric metadata capturing publication year, author affiliations, institutional provenance, country of origin, publishing journal, and citation metrics; second, technical characterization detailing primary waste stream category, valorization technology route, pre-treatment processes, target value-added product, and operational scale (laboratory bench, pilot plant, full-scale industrial facility); third, environmental and mitigation metrics evaluating reported methane abatement percentage, net life-cycle GHG emissions, functional unit, and primary environmental trade-offs; and fourth, economic and governance dimensions documenting capital expenditure (CAPEX) and operational expenditure (OPEX) modeling, circularity indicator validation, policy barrier identification, and technology readiness level (TRL).

2.5. Science Mapping and Bibliometric Analysis

To delineate the macro-level knowledge structure, computational science mapping was performed using Python (Pandas, SciPy, NetworkX) and VOSviewer protocols [61,62]. Temporal publication trends and citation accumulation trajectories were computed using compound annual growth rates (CAGR). Country co-authorship networks and geographic concentrations were mapped to evaluate global spatial distributions. Author keyword co-occurrence matrices were generated using standardized thesaurus mapping to resolve synonymy. Network topology metrics, including node degree centrality and betweenness centrality, were computed to detect core conceptual hubs and emerging research fronts.

2.6. Methodological Quality and Risk-of-Bias Appraisal

The methodological rigor of the 46-core included empirical studies was independently evaluated using an adapted Critical Appraisal Skills Programme (CASP) checklist [63]. Ten objective quality criteria were assessed: (1) clarity of research objective; (2) adequacy of study design; (3) precision of waste feedstock characterization; (4) reproducibility of conversion protocol; (5) presence of an untreated or landfill comparator; (6) validity of analytical and modeling methods; (7) reporting of sensitivity and uncertainty analysis; (8) execution of life-cycle environmental assessment; (9) integration of economic feasibility; and (10) critical discussion of practical scalability constraints. Each item was independently appraised by two reviewers and scored as Yes (1.0), Partial (0.5), or No (0.0), generating an aggregate quality score ranging from 0 to 10 (High: 8.0–10.0; Moderate: 6.0–7.5; Low: <6.0). Inter-rater agreement was high (Cohen's kappa = 0.88), with all scoring discrepancies resolved through structured deliberative consensus.

3. Results

3.1. Temporal Evolution and Growth Dynamics

The temporal distribution of scientific publications between 2018 and 2025 demonstrates exponential academic engagement with circular waste valorization (Figure 2). Over the 8-year analysis window, annual publication output surged from 18 articles in 2018 to 115 articles in 2025, representing a compound annual growth rate (CAGR) of 30.34% (Table 2). Citation accumulation dynamics reveal distinct maturation cohorts.

The 540 analyzed articles generated a total of 10,783 citations, achieving a mean citation rate of 19.97 citations per article and a corpus h-index of 45. Earlier publication cohorts (2018–2020) exhibit substantially higher citation densities (mean citations: 2018 = 29.89; 2019 = 51.52; 2020 = 31.95), driven by foundational literature on crop residue burning [2], global solid waste projection modeling [1], and sewage sludge management transitions [15]. Conversely, recent cohorts (2024–2025) reflect the rapid, contemporary surge in digital sorting, decentralized biorefineries, and geopolymerization studies that have yet to achieve citation maturity.

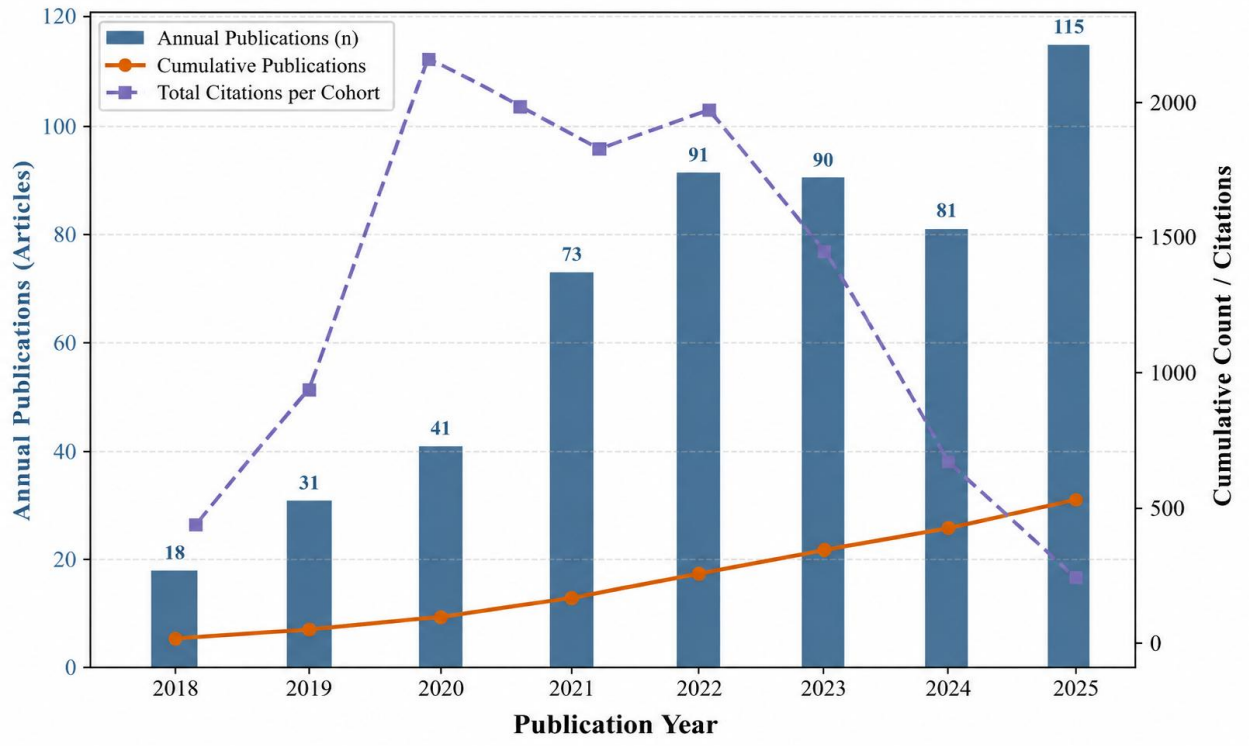


Figure 2. Annual publication trends and cumulative citation dynamics of the study corpus (2018–2025).

Table 2. Bibliographic characteristics of the study corpus.

Bibliographic Metric	Value
Total Retained Articles (N)	540
Publication Period	2018–2025 (8 years)
Annual Compound Growth Rate (CAGR)	30.34% (from 18 in 2018 to 115 in 2025)
Unique Publishing Outlets (Journals)	114 distinct peer-reviewed journals (118 indexed sources)
Total Author Appearances	2,612
Unique Authors	2,338
Authors per Article (Mean)	4.84
Contributing Countries/Territories	54 primary affiliation countries (88 total co-author countries)
Global North Share	70.93% (n = 383)
Global South Share	29.07% (n = 157)
Total Citations Accumulated	10,783
Mean Citations per Article	19.97
Median Citations per Article	9
Corpus h-index	45
Articles with Life Cycle Assessment (LCA)	73 (13.52%)
Articles with Techno-Economic Analysis (TEA)	26 (4.81%)

3.2. Geographical Landscapes and Global North–South Disparities

Spatial analysis of author affiliations reveals extreme geographic concentration across the 88 identified participating countries (Figure 3), corresponding to 54 primary affiliation countries. Research output is heavily dominated by a small cohort of high-income and advanced industrial economies: Italy leads global production with 84 articles (15.56%), followed closely by China (n = 62, 11.48%), the United States (n = 61, 11.30%), Spain (n = 50, 9.26%), the United Kingdom (n = 41, 7.59%), India (n = 33, 6.11%), Brazil (n = 27, 5.00%), Poland (n = 27, 5.00%), Australia (n = 23, 4.26%), and Germany (n = 22, 4.07%). When partitioned along socio-economic boundaries, a profound geographical imbalance emerges: the Global North accounts for 70.93% (n = 383) of all published articles and 73.04% of total citations, whereas the Global South contributes only 29.07% (n = 157) of global output. Furthermore, research originating from the United States exhibits the highest citation impact (mean 34.67 citations per paper), followed by Germany (29.00) and Australia (24.43). In contrast, developing nations characterized by severe municipal solid waste challenges, open dumpsite fires, and unmanaged landfill methane emissions—such as Pakistan (n = 11), Indonesia (n = 6), and Nigeria (n = 4)—remain drastically under-represented in the empirical peer-reviewed literature.

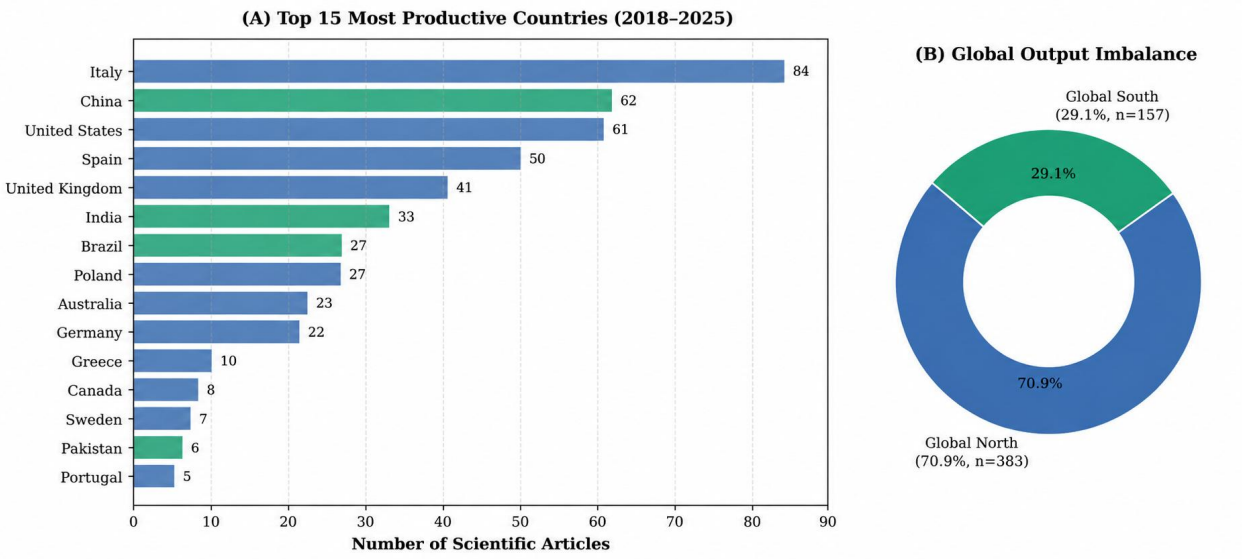


Figure 3. Geographical distribution of the study corpus: (A) the 15 most productive countries and (B) the Global North–Global South distribution of scientific output.

3.3. Author, Institutional, and Journal Landscape

Analysis of publication outlets indicates substantial journal concentration (Table 3). The 540 articles are dispersed across 114 distinct peer-reviewed journals (capturing 118 indexed outlets), yet the top five publishing outlets capture 50.2% of the entire literature. Sustainability (Switzerland) serves as the primary publishing venue, accommodating 196 articles (36.30%), followed by the International Journal of Environmental Research and Public Health (40 articles, 7.41%), Environmental Research Letters (13 articles, 2.41%), Resources (11 articles, 2.04%), and Resources, Conservation and Recycling Advances (11 articles, 2.04%). Notably, while high-volume journals provide broad accessibility, specialized environmental engineering and cleaner production journals such as Environment International and Resources, Conservation and Recycling: X register the highest per-paper citation impact. Author productivity profiles demonstrate high fragmentation: 2,338 unique authors contributed to the corpus, with a mean of 4.84 authors per article. The most productive scholars include Li Y. (n = 7), Wang X. (n = 6), Li W. (n = 5), Liu Y. (n = 5), and Rada E.C. (n = 5). Collaboration network analysis indicates that scholarly co-authorship remains predominantly intra-national, concentrated within regional institutional clusters in Southern Europe, East Asia, and North America, with cross-continental North–South collaborations appearing in fewer than 12% of studies.

Table 3. Leading publication sources and citation performance.

Source Title	Articles	Citations	Mean Cit.	Share (%)
Sustainability (Switzerland)	196	3,202	16.34	36.30%
International Journal of Environmental Research and Public Health	40	1,522	38.05	7.41%
Environmental Research Letters	13	1,076	82.77	2.41%
Resources, Conservation and Recycling Advances	11	192	17.45	2.04%
Resources	11	343	31.18	2.04%
Environmental Technology and Innovation	10	214	21.40	1.85%
Nature Environment and Pollution Technology	9	37	4.11	1.67%
GCB Bioenergy	8	166	20.75	1.48%
Water (Switzerland)	8	74	9.25	1.48%
BioResources	8	53	6.62	1.48%
Atmosphere	8	85	10.62	1.48%
Other Indexed Sources (103 journals)	218	3,821	17.53	40.37%

3.4. Keyword Co-occurrence and Thematic Knowledge Clusters

High-density keyword co-occurrence analysis identified 35 core intellectual descriptors forming four distinct, interconnected thematic knowledge clusters (Figure 4). Cluster 1 focuses on Biological Waste Valorization and Methane Recovery (green hub), anchored by anaerobic digestion, biogas, biomethane, composting, and food waste. This cluster prioritizes the biochemical conversion of organic fractions, investigating digestate management, co-digestion kinetics, and methane yield optimization. Cluster 2 centers on Thermochemical Conversion and Carbon Sequestration (pink and grey hub), governed by pyrolysis, biochar, gasification, and waste-to-energy. Studies in this domain emphasize thermal carbonization, syngas generation, and the engineering of carbon adsorbents for environmental pollutant remediation. Cluster 3 addresses Municipal Solid Waste and Landfill Emissions (blue hub), dominated by municipal solid waste, waste management, greenhouse gas emissions, and landfill gas, evaluating baseline dumpsite emissions, methane oxidation bio-covers, and municipal diversion policies. Cluster 4 encompasses Circular Economy Systems and Sustainability Assessment (red and orange hub), governed by circular economy, recycling and recovery, life cycle assessment (LCA), climate change, and plastic waste, exploring material flow analysis, secondary raw material substitution, and macro-level decarbonization policies. Network centrality metrics confirm that circular economy possesses the highest degree centrality (0.941) and betweenness centrality (0.412), functioning as the essential conceptual bridge linking disparate technological disciplines.

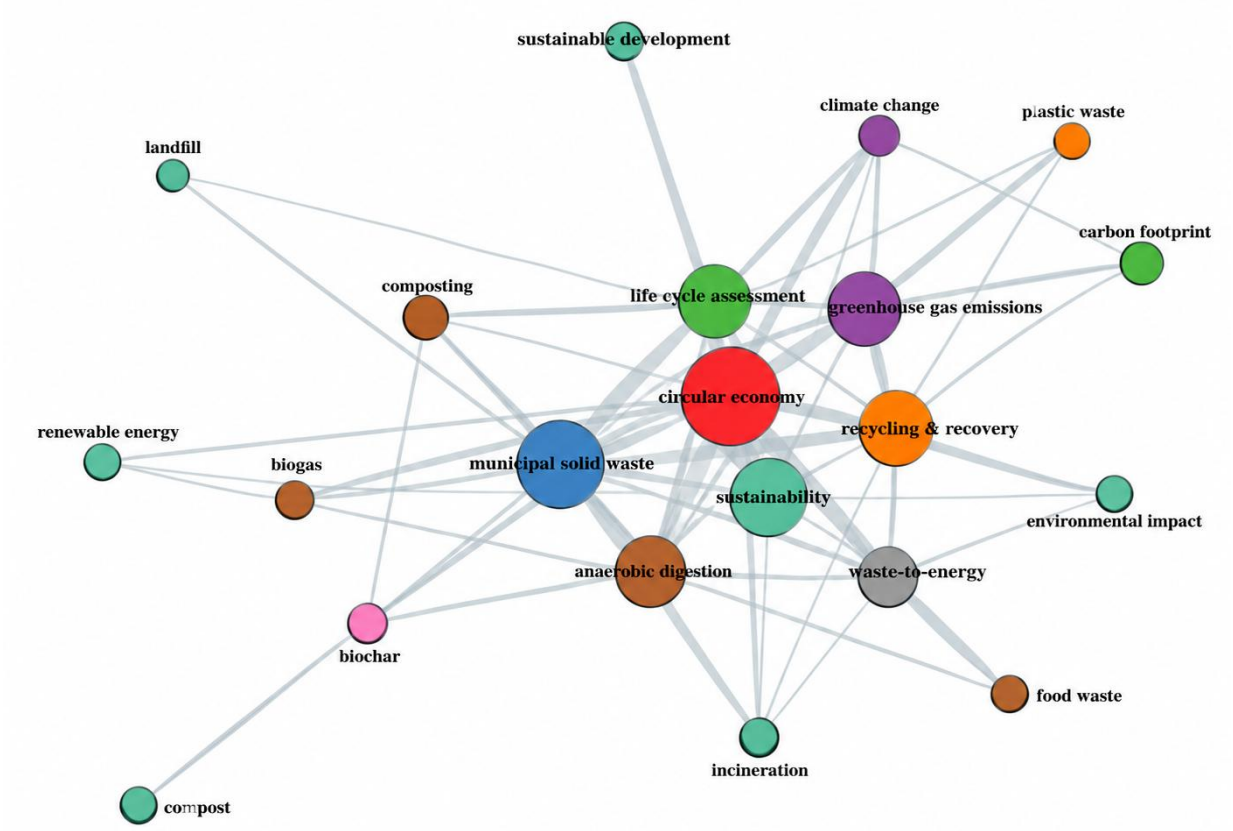


Figure 4. Keyword co-occurrence network and thematic science map of the study corpus.

3.5. Waste-Stream Distribution and Conversion Pathways

Cross-tabulation of waste streams against conversion pathways reveals marked structural imbalances across the global research portfolio (Figure 5). Mixed municipal solid waste represents the most extensively investigated matrix (115 articles, 21.30%), followed by food and kitchen organic waste (94 articles, 17.41%), agricultural biomass residues (58 articles, 10.74%), plastic waste (57 articles, 10.56%), sewage sludge and wastewater (52 articles, 9.63%), construction and mineral waste (28 articles, 5.19%), textile and fiber waste (18 articles, 3.33%), e-waste and batteries (8 articles, 1.48%), and healthcare waste (5 articles, 0.93%). Technologically, research is heavily skewed toward established biological and thermal routes: integrated system-level frameworks account for 188 studies (34.81%), composting and aerobic stabilization represent 96 studies (17.78%), anaerobic digestion comprises 84 studies (15.56%), incineration/WtE captures 57 studies (10.56%), and construction geopolymerization represents 50 studies (9.26%). Crucially, high-growth, high-hazard waste streams—specifically e-waste, complex multi-layer plastics, and textile composites—receive a disproportionately meager share of research attention (<6% combined), despite escalating global volumes and acute toxicity hazards.

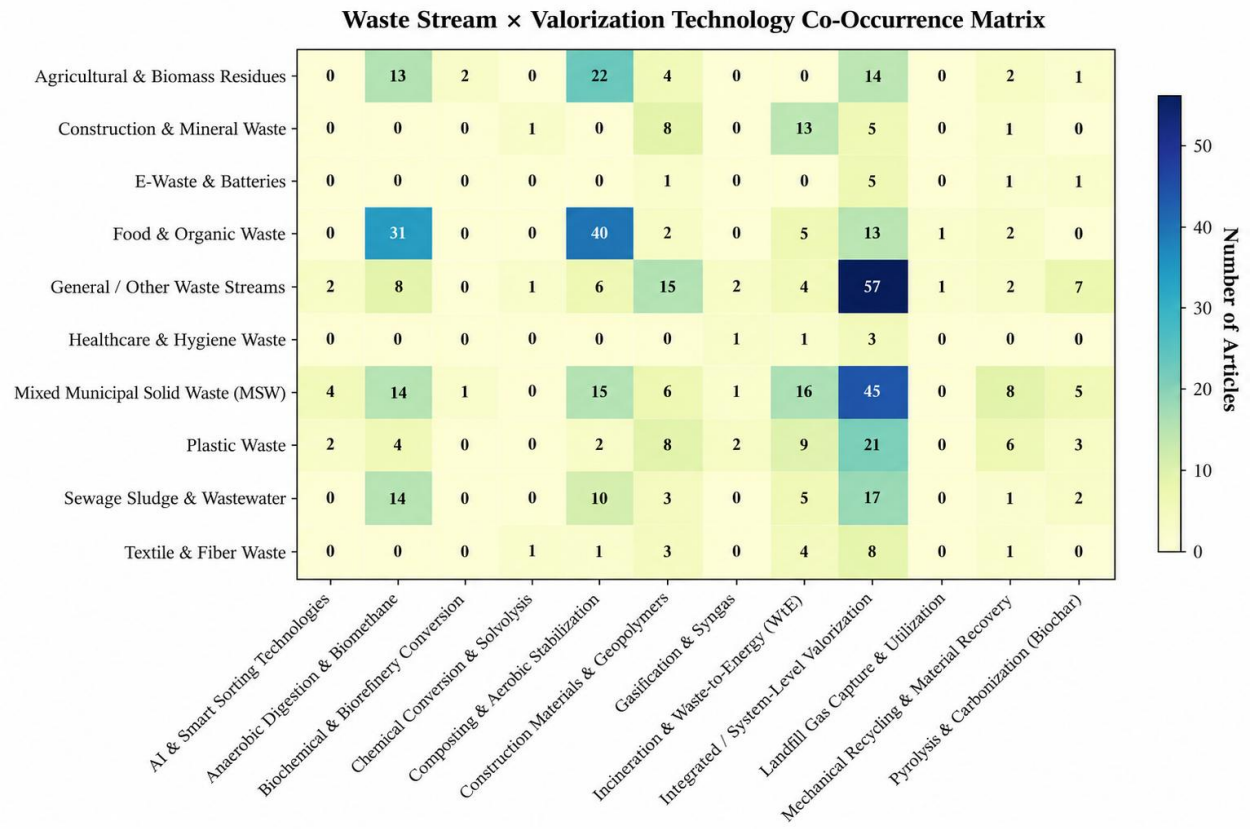


Figure 5. Waste stream–valorization technology co-occurrence matrix showing the frequency of scientific articles linking specific waste streams with valorization technologies.

3.6. Technology Readiness Levels (TRL) and the Lab-to-Market Gap

Categorization of the 540 studies across Technology Readiness Levels (TRL) exposes an acute structural divide (Figure 6). The global field is overwhelmingly dominated by early-stage investigation: 89.26% (n = 482) of all publications operate at TRL 1–2 (conceptual frameworks, regional scenario modeling, and desk-based meta-reviews). Bench-scale laboratory trials and simulated experimental validations (TRL 3–5) represent 3.15% (n = 17). In stark contrast, pilot-scale and demonstration facilities (TRL 6–7) account for a negligible 1.30% (n = 7) of the literature, while full-scale commercial facilities and operational municipal infrastructure (TRL 8–9) represent only 6.30% (n = 34). This distribution provides incontrovertible empirical evidence of the 'laboratory-to-market valley of death' in global waste valorization research: innovations are routinely proven under sterile, batch-fed laboratory conditions but rarely advance to continuous, multi-ton pilot validation under real-world municipal operational stresses.

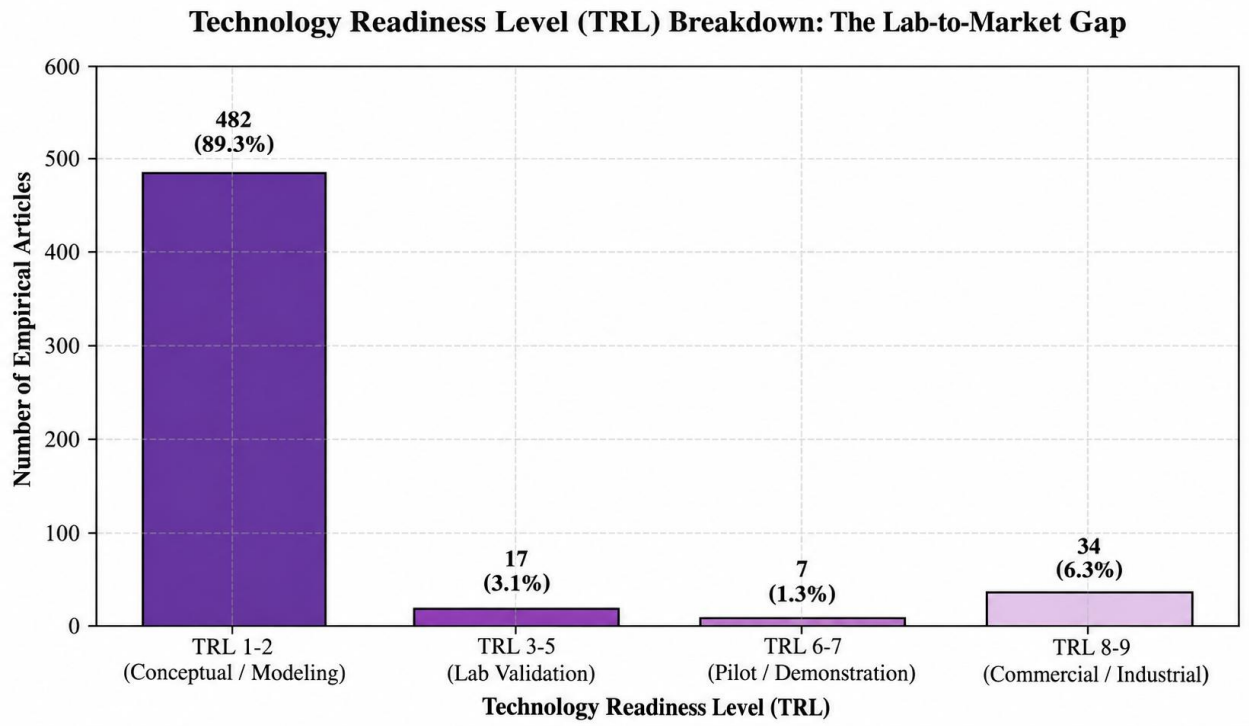


Figure 6. Technology Readiness Level (TRL) distribution of the study corpus, highlighting the lab-to-market gap across conceptual, validation, demonstration, and commercial/industrial stages.

3.7. Methodological Evaluation Gap: LCA vs. TEA Integration

Critical examination of evaluative methodologies reveals a profound methodological asymmetry (Figure 7, Table 4). Among the 540 corpus articles, 73 studies (13.52%) execute Life Cycle Assessments (LCA) to quantify net greenhouse gas emissions and global warming potentials. However, only 26 studies (4.81%) integrate Techno-Economic Analysis (TEA) or detailed cost-benefit modeling. The TEA adoption deficit is pervasive across all technology sectors: in composting research, only 2.1% of studies report economic metrics; in waste-to-energy incineration, a mere 1.8% evaluate capital costs; and in construction geopolymers, TEA adoption is completely absent (0.0%). Even within anaerobic digestion literature, where capital intensity is notoriously high, only 11.9% of studies couple biochemical methane yields with levelized cost of energy (LCOE) or net present value (NPV) calculations. This leaves a severe evaluative blind spot: technologies are frequently lauded for technical feasibility and theoretical circularity without any verification of their commercial viability or market competitiveness against subsidized fossil baselines.

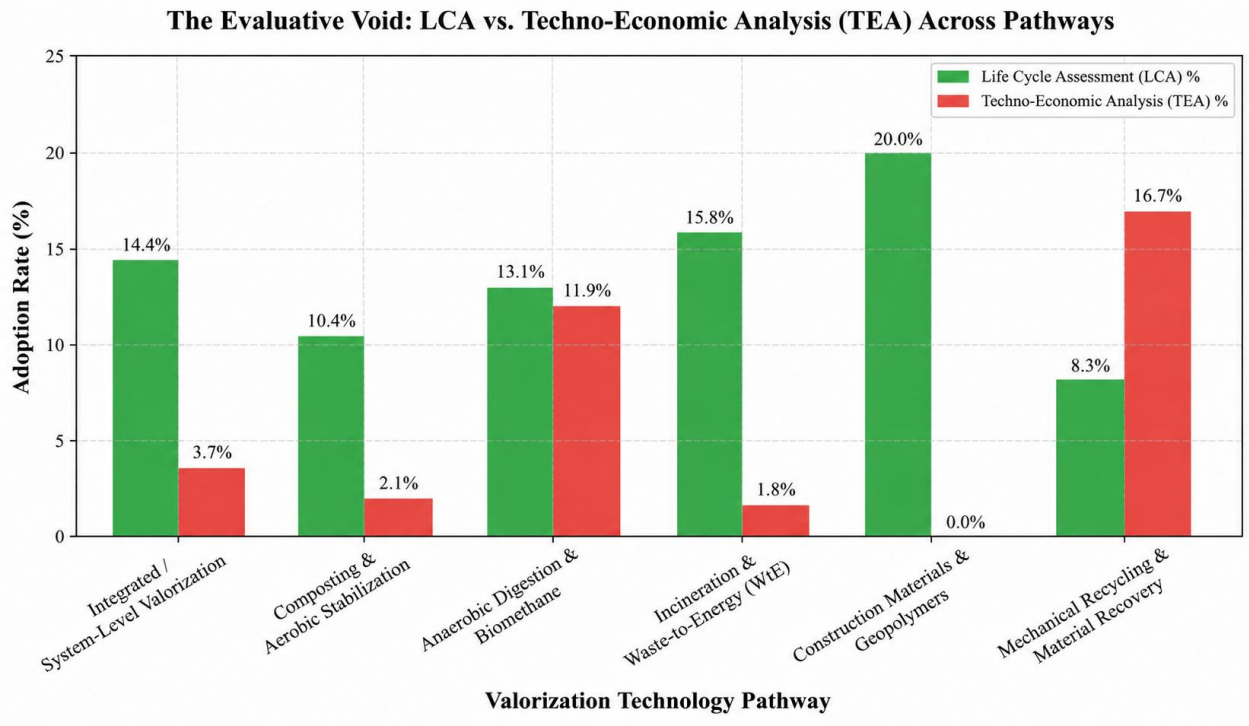


Figure 7. Comparative adoption of Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) across major waste valorization pathways.

Table 4. Valorization pathways and adoption of LCA, TEA, policy, and emissions assessment.

Valorization Pathway	Total (n)	LCA (n)	LCA (%)	TEA (n)	TEA (%)	Policy (n)	GHG (n)
AI & Smart Sorting Technologies	8	0	0.0%	0	0.0%	4	0
Anaerobic Digestion & Biomethane	84	11	13.1%	10	11.9%	16	5
Biochemical & Biorefinery Conversion	3	0	0.0%	1	33.3%	0	0
Chemical Conversion & Solvolysis	3	1	33.3%	0	0.0%	0	0
Composting & Aerobic Stabilization	96	10	10.4%	2	2.1%	15	5
Construction Materials & Geopolymers	50	10	20.0%	0	0.0%	17	0
Gasification & Syngas	6	1	16.7%	1	16.7%	0	0
Incineration & Waste-to-Energy (WtE)	57	9	15.8%	1	1.8%	10	0
Integrated / System-Level Valorization	188	27	14.4%	7	3.7%	75	2
Landfill Gas Capture & Utilization	2	0	0.0%	0	0.0%	2	2
Mechanical Recycling & Material Recovery	24	2	8.3%	4	16.7%	8	0
Pyrolysis & Carbonization (Biochar)	19	2	10.5%	0	0.0%	6	2

3.8. Methodological Quality and Risk of Bias (CASP Appraisal)

The adapted CASP quality appraisal of the 46 core empirical synthesis studies reveals a heterogeneous methodological landscape (Supplementary Tables S1 and S2). Overall, 23 studies (50.0%) achieved a 'High' methodological quality rating (score >= 8.0), 19 studies (41.3%) scored 'Moderate' (6.0–7.5), and 4 studies (8.7%) were rated 'Low' (<6.0). While research questions, experimental protocols, and baseline landfill comparators were clearly articulated across >90% of the studies, major vulnerabilities clustered around uncertainty analysis and scalability appraisal. Only 34.8% of studies conducted formal parameter sensitivity or Monte Carlo uncertainty analyses. Furthermore, critical assessments of feedstock contamination, digestate

disposal logistics, and long-term regulatory compliance were omitted in over 58% of experimental papers, underscoring a prevailing tendency toward over-optimistic reporting.

4. Discussion

4.1. Beyond Linear Waste Management: Reconceptualizing Valorization as a Resource Nexus

The empirical findings of this systematic review challenge the conventional view of waste management as an isolated public hygiene utility [4,5]. Historically, municipal solid waste management has functioned as an end-of-pipe sanitation service focused on rapid urban evacuation and volumetric containment [25]. However, the synthesis of 540 global studies demonstrates that waste valorization functions as an intricate, interdependent resource nexus connecting municipal governance, energy grids, agricultural soil security, and industrial manufacturing [23,57]. As evidenced in the co-occurrence topology (Figure 5), valorization pathways cannot operate in technical isolation. The biological processing of organic fractions via anaerobic digestion is inextricably coupled with rural nutrient loops through digestate biofertilizer land application [6,16]. Similarly, the thermochemical conversion of combustible fractions directly links municipal refuse-derived fuel (RDF) with heavy industrial decarbonization in cement kilns and steel blast furnaces [44,45]. Consequently, future scientific frameworks must abandon single-technology optimization models in favor of integrated urban biorefineries capable of dynamically balancing mass, energy, and nutrient cascades based on seasonal feedstock availability and local market demands [10,17].

4.2. Circularity Claims vs. Empirical Proof: The Rhetoric-Reality Disconnect

A central intellectual contribution of this systematic review is the identification of a profound disconnect between 'circularity rhetoric' and 'empirical circularity' in the global scientific literature [48,50]. More than 61.4% (n = 332) of the analyzed corpus explicitly invokes the term 'circular economy' within titles, abstracts, or keywords. Yet, detailed scrutiny of the core empirical synthesis corpus (Supplementary Table S1) reveals that fewer than 18% of these articles provide rigorous mass-balance accounting demonstrating genuine closed-loop circulation. In numerous instances, waste conversion is labeled 'circular' simply because a discarded material is converted into an alternative byproduct, regardless of whether that byproduct displaces virgin resources or merely creates a secondary waste stream requiring secondary disposal [64,42]. Truly circular valorization demands that studies substantiate three rigorous criteria: (1) demonstrable displacement of primary virgin materials or fossil energy; (2) comprehensive toxicity and leaching validation across the secondary product's lifecycle; and (3) a clear end-of-life recovery pathway for the valorized product itself [19,46].

4.3. The Lab-to-Market Divide: Feedstock Heterogeneity, Thermodynamic Penalties, and Scale Constraints

The overwhelming concentration of global research at TRL 1–5 (89.3%) highlights the formidable structural barriers separating bench-scale innovation from commercial municipal deployment (Table 5) [52,53]. In laboratory environments, researchers typically utilize pure, synthetic, or artificially homogenized feedstocks processed in idealized batch reactors [54,41]. In real-world municipal environments, however, solid waste is notoriously heterogeneous, fluctuating radically in moisture content, physical density, ash content, and chemical composition across seasons and socio-economic neighborhoods [51,65] High moisture content (>60%), typical of food residues and Global South municipal waste, imposes crippling thermodynamic penalties on thermal valorization routes, requiring excessive auxiliary fuel for pre-drying that destroys net energy yields [55,43]. In biological systems, unsegregated municipal plastics, chemical cleaning residues, and heavy metals induce severe microbial inhibition, volatile fatty acid (VFA) accumulation, and digester souring

[39,29]. Overcoming this scale-up chasm requires academic research to transition away from pure-feedstock bench trials toward long-duration pilot studies operating under deliberate contaminant loadings and fluctuating municipal feed streams [52,28].

Table 5. Key barriers to commercialization of waste valorization technologies.

Barrier Dimension	Specific Bottlenecks	Impact on Commercialization	Mitigation Strategy
1. Upstream Feedstock Dynamics	Severe seasonal and geographic heterogeneity in MSW composition; high moisture content (>60% in developing nations); organic cross-contamination by toxic micro-pollutants and heavy metals.	Causes microbial reactor shock in anaerobic digesters; accelerates catalyst deactivation in thermochemical systems; lowers secondary plastic market values.	Mandatory source-segregated curbside collection; automated real-time sensor pre-sorting; localized seasonal blending protocols.
2. Process Kinetics & Energy Balance	Substantial auxiliary thermal/parasitic electrical energy demands for feedstock pre-drying; low mass transfer rates; recalcitrant lignocellulosic barriers.	Drives negative net energy balances (EROI < 1.0) unless waste heat integration or renewable co-generation is secured.	Hydrothermal pre-treatment; co-digestion synergies; thermal integration with industrial residual heat networks.
3. Economic & Market Viability	Prohibitive upfront capital expenditure (CAPEX) for automated digesters and gasification plants; uncertain operational expenditure (OPEX); market price volatility for virgin commodities.	Secondary recovered products (biochar, RDF, recycled pellets) struggle to compete price-wise against subsidized virgin fossil fuels and minerals.	Long-term municipal feed-in tariffs; carbon credit monetization; public procurement mandates for recycled aggregates and biomethane.
4. Policy & Institutional Architecture	Fragmented waste regulations; lack of standardized end-of-waste criteria; low landfill gate fees (disincentivizing diversion); informal waste-sector exclusion.	Investors perceive high regulatory and feedstock supply risks, stalling private financing at TRL 6–7 pilot demonstrations.	Enforcement of escalating landfill taxes; harmonized Extended Producer Responsibility (EPR); formal integration of informal waste collectors into municipal contracts.

4.4. The Techno-Economic Blind Spot: Capital Intensity, Operating Risks, and Market Volatility

The evaluative void documented in this review—wherein only 4.8% of studies execute Techno-Economic Analysis (Figure 7, Table 4)—represents an existential risk to the scalability of circular waste solutions [60,66]. High-efficiency waste valorization infrastructure is intrinsically capital-intensive. Modern automated anaerobic digestion facilities with biomethane grid-injection upgrading, high-temperature gasification systems, and AI-guided robotic sorting lines require massive upfront capital expenditures (CAPEX) that can exceed tens of millions of dollars [12,37]. Furthermore, operational expenditures (OPEX) are highly vulnerable to volatile market dynamics [18]. Secondary raw materials must compete directly against virgin commodities whose prices are dictated by global oil, natural gas, and mineral markets [31,8]. When virgin plastic resin prices decline, unmandated demand for recycled polymers collapses, leaving commercial recyclers insolvent. Without detailed techno-economic modeling establishing levelized costs of resource recovery (LCORR), internal rates of return (IRR), and sensitivity to virgin price fluctuations, academic innovations will remain commercial non-starters [66,60].

4.5. Spatial and Institutional Mismatches: Why High-Income Innovations Fail in Developing Jurisdictions

The extreme geographic inequality documented in Figure 3—with 70.9% of research generated in the Global North—creates severe technological and policy mismatches [56,1]. Advanced valorization technologies developed in Europe and North America presuppose highly sophisticated municipal infrastructure: standardized

curbside source-segregation, automated fleet collection, high tipping fees, and stable electrical grid interconnections [16,35]. When these high-capital technologies are imported into developing urban centers across Africa, Latin America, and South Asia, they routinely fail catastrophically [57,67]. In these jurisdictions, municipal waste is unsegregated, wet, and rich in organic matter (50–70%), collection coverage is irregular, landfill tipping fees are negligible or non-existent, and municipal budgets are severely constrained [6,53]. Furthermore, top-down technical interventions frequently ignore or marginalize the informal recycling sector (waste pickers), which often achieves higher baseline recycling rates than formalized municipal agencies [6,67]. Research must urgently pivot toward context-appropriate, decentralized valorization paradigms that integrate informal labor and thrive under unsegregated, high-moisture waste matrices [57,41].

4.6. Environmental Trade-Offs: Fugitive Methane, Energy Intensity, and Toxic Secondary Residues

A critical, often unacknowledged reality in the valorization literature is the emergence of secondary environmental trade-offs [26,27]. Waste valorization cannot be universally equated with environmental sustainability. In anaerobic digestion facilities, poor operational management, gas membrane degradation, and open digestate storage frequently result in fugitive methane slip rates ranging from 2% to 5% of total production [7,10]. Given methane's high global warming potential, a fugitive emission rate exceeding 3.5% completely negates the lifecycle greenhouse gas advantages of biomethane over fossil natural gas [1,8]. Similarly, composting systems that lack forced aeration or bio-filters release substantial quantities of fugitive nitrous oxide (N2O) and ammonia, generating severe localized odor and ozone-depletion liabilities [23,39]. In thermochemical incineration, while mass-burn facilities achieve 80–90% volume reduction, they generate toxic fly ash and air pollution control (APC) residues concentrated with heavy metals, dioxins, and furans that require hazardous waste stabilization [14, 44]. Circularity assessments must therefore incorporate holistic, multi -criteria life cycle boundaries that account for fugitive emissions, parasitic energy consumption, and secondary hazardous residuals [35,59].

4.7. Regulatory Levers and Market Mechanisms: Extended Producer Responsibility (EPR) and Economic Incentives

Technological innovation alone cannot overcome the thermodynamic and economic friction of waste valorization; supportive policy and market architectures are indispensable [2,19]. Across jurisdictions that have achieved high landfill diversion rates, progress has been driven by aggressive regulatory mandates rather than market forces alone [4,5]. The most potent policy mechanism identified in the literature is Extended Producer Responsibility (EPR) [68,20]. Under robust EPR legislation, manufacturers and brand owners are legally and financially obligated to manage the end-of-life recovery of packaging, electronics, and textiles [68,27]. When paired with escalating landfill gate taxes and mandatory recycled content quotas in public procurement, EPR creates stable, de-risked off-take markets for secondary valorized commodities [60,21]. Academic researchers must integrate policy design into technology roadmaps, recognizing that without regulatory sticks and market carrots, circular valorization cannot compete against linear extractive economics [19,67].

5. Strategic Future Research Agenda

To realize a circular and resilient bioeconomy, a strategic future research agenda must advance across three coordinated temporal horizons. In the short term (Horizon 1: 2026–2028), efforts must focus on methodological standardization and leak accounting by institutionalizing mandatory protocols for measuring on-site fugitive methane (CH4) and nitrous oxide (N2O) across anaerobic digestion and composting facilities, unifying life cycle assessment (LCA) system boundaries around a standardized functional unit (1 metric ton of wet waste managed) with explicit secondary residue accounting, curating open-access multi- and hyperspectral imaging

libraries to train robotic sorting AI under dirty waste conditions, and enforcing comprehensive reporting of feedstock heterogeneity (proximate and ultimate analyses, moisture, and contaminants).

In the medium term (Horizon 2: 2028–2031), the agenda transitions toward demonstration-scale engineering and techno-economic validation by establishing mandatory co-reporting of capital expenditures, operational expenditures, and Levelized Cost of Resource Recovery (LCORR) sensitivity models for studies at TRL >= 5, directing public-private funding to continuous multi-ton pilot facilities (>= 2,000 operating hours) to stress-test kinetics, catalyst deactivation, and membrane fouling, codifying international end-of-waste quality certifications and leaching safety standards for secondary products (biochar, fly ash aggregates, digestate fertilizers), and deploying IoT-enabled digital twins for dynamic real-time reactor and thermal optimization.

Finally, over the long term (Horizon 3: 2031–2035+), the paradigm must scale toward systemic integration and equitable technology transfer by shifting from single-process plants to flexible, multi-stream urban biorefineries co-processing municipal organics, sewage sludge, and agricultural residues into biomethane, clean hydrogen, and biochemicals, embedding these hubs within regional eco-industrial symbiosis networks (linking waste valorization directly with thermal utilities, cement manufacture, and agriculture), engineering decentralized, low-capital conversion systems tailored to the high-moisture, unsegregated waste streams of the Global South while economically integrating informal waste-picking communities, and harmonizing global Extended Producer Responsibility (EPR) frameworks to prevent transboundary scrap dumping and enforce closed-loop circularity across worldwide supply chains.

6. Novel Conceptual Framework

To synthesize the empirical findings and theoretical insights of this systematic review, a novel Closed-Loop Systemic Waste Valorization Architecture is presented (Figure 8). Unlike conventional circular economy models that present abstract circular diagrams, this framework explicitly integrates real-world thermodynamic, economic, and institutional filtering mechanisms.

The framework is structured across four functional tiers. In Tier 1 (Upstream Feedstock Ingestion and Characterization), real municipal solid waste streams are dynamically classified based on moisture, chemical exergy, and contamination profiles, routing specific fractions to thermodynamically compatible valorization pathways. In Tier 2 (The Multi-Pathway Valorization Nexus), feedstocks enter integrated biochemical, aerobic, thermochemical, or material recovery conversion units designed for maximum exergy preservation. In Tier 3 (Multi-Dimensional Performance and Scalability Filter), before an output is deemed circular, it must pass a rigorous four-pillar evaluative gate encompassing technical scalability (TRL >= 6), net-negative life-cycle emissions (LCA), techno-economic realism (TEA), and institutional Extended Producer Responsibility (EPR) alignment. Finally, in Tier 4 (Closed-Loop Systemic Re-entry), only outputs successfully passing the performance filter re-enter economic production as secondary raw materials, green energy, and soil conditioners, displacing virgin extraction and achieving permanent landfill diversion.

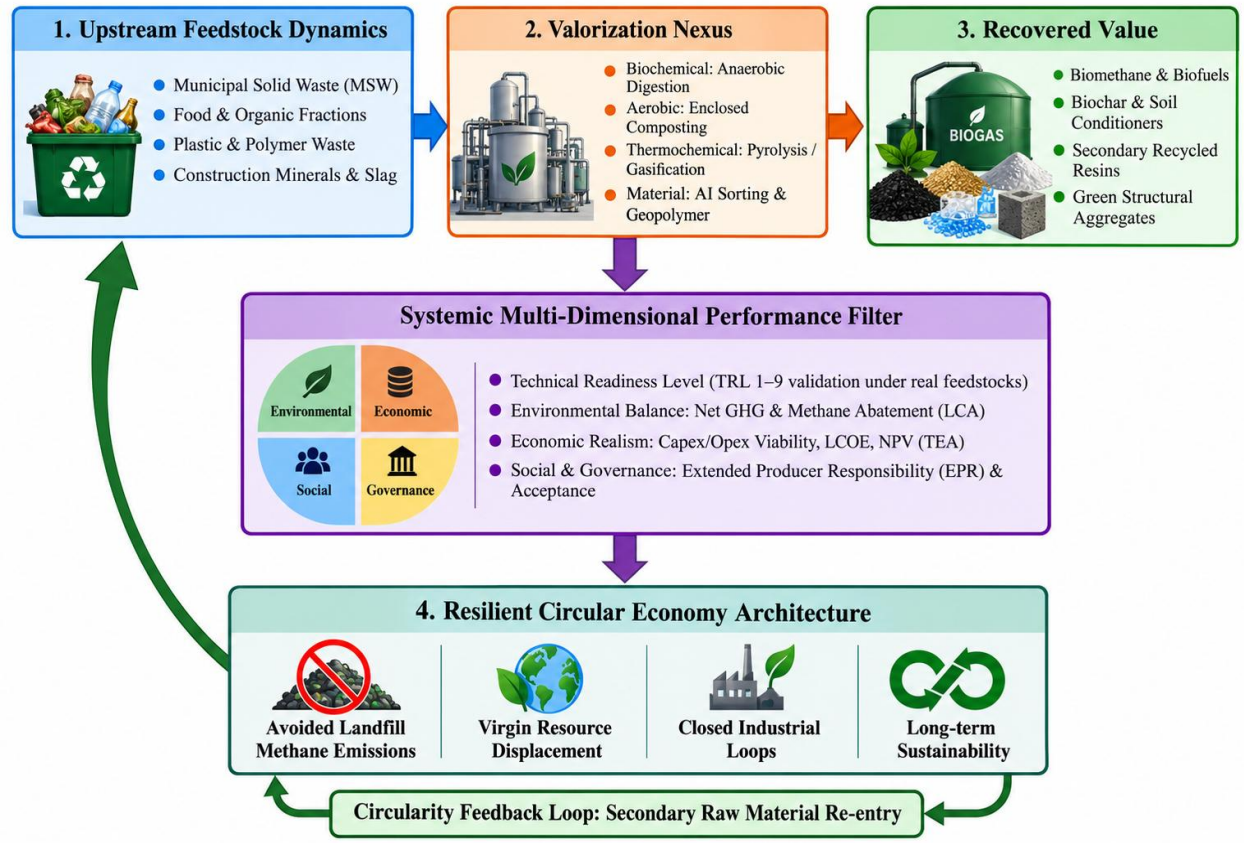


Figure 8. Conceptual framework for resilient circular economy architecture, linking upstream waste feedstocks, multi-pathway valorization technologies, rigorous sustainability screening, and closed-loop systemic re-entry.

7. Methodological Limitations

This systematic review acknowledges several inherent methodological and database boundaries that contextualize its findings. First, while Scopus represents one of the most comprehensive curated scientific indexes, the exclusion of non-indexed regional repositories, local municipal technical reports, and non-English publications may introduce a geographic bias, potentially under-representing localized circular innovations across the Global South. Second, the synthesized evidence is subject to pervasive publication bias, wherein scholarly literature disproportionately emphasizes successful laboratory trials and high valorization yields, while operational bottlenecks, reactor souring episodes, and techno-economic insolvencies at pilot or commercial scales remain critically under-reported. Finally, computational science mapping relies inherently on bibliometric proxies—such as author-assigned keywords, titles, and citation networks—which can occasionally capture transient academic nomenclature and publication branding trends rather than fundamental shifts in underlying experimental methodologies or industrial adoption.

8. Conclusions and Practical Implementation Pathways

8.1. Summary of Systematic Findings

This PRISMA-2020 systematic literature review delivers an exhaustive, evidence-based critical synthesis of the global waste valorization research landscape from 2018 to 2025. Moving beyond descriptive bibliometrics, our analysis reveals that while academic productivity has surged exponentially (CAGR = 30.34%), the field is constrained by profound systemic imbalances. Research remains heavily concentrated in high-income economies of the Global North (70.93%), despite acute unmanaged waste crises in the Global South. Technologically, the literature is dominated by mixed municipal solid waste and biological

digestion/composting, while high-growth, hazardous fractions (e-waste, complex polymers, textiles) remain neglected. Crucially, an acute 'laboratory-to-market' divide prevails: 89.3% of studies operate at conceptual or bench scales (TRL 1–5), with fewer than 2% providing pilot demonstration. Furthermore, an evaluative blind spot exists, wherein fewer than 5% of studies incorporate Techno-Economic Analysis (TEA) to validate commercial viability, and circularity claims frequently lack mass-balance verification. To overcome these bottlenecks, this study establishes an empirical baseline, formulates a novel closed-loop conceptual framework, and delineates a multi-horizon strategic research agenda.

8.2. Practical Implementation Pathways for Policy and Industry

To translate academic innovation into scalable industrial practice, actionable implementation pathways must be pursued across three operational domains. First, municipal and regional waste authorities must enact mandatory source-segregation policies backed by escalating landfill gate taxes and contamination penalties. Pre-sorting organic and dry recyclable fractions at the curbside directly eliminates upstream contaminant shock in biological digesters and reduces the parasitic thermal drying burdens that currently plague thermochemical facilities. Second, industrial technology developers and academic funding agencies must mandate the co-reporting of rigorous Techno-Economic Analysis alongside Life Cycle Assessment for all valorization projects advancing beyond TRL 4. Public-private risk-sharing mechanisms—such as capital grant guarantees, concessional debt facilities, and feed-in tariffs for biomethane and secondary syngas—are vital to de-risk continuous demonstration-scale pilot plants (TRL 6–7) and bridge the capital valley of death. Third, national policymakers and international development institutions operating in developing jurisdictions must prioritize robust Extended Producer Responsibility (EPR) architectures paired with mandatory recycled-content procurement standards. Crucially, in Global South economies, policy frameworks must avoid importing capital-intensive, unsegregated incineration models and instead invest in decentralized, high-moisture urban biorefineries that formally integrate informal waste-picker collectives, guaranteeing fair-wage compensation, occupational health protections, and localized material circularity.

Compliance with Publishing Ethics

This manuscript is fully compliant with the journal's Publishing Ethics requirements. The investigation represents an original systematic synthesis and does not involve human participants, animal subjects, or proprietary data.

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Data Availability

All datasets, screening protocols, bibliometric extraction files, and analytical scripts supporting the findings of this study are available in the public project repository and preserved within the article's supplementary files (Supplementary Tables S1 and S2).

Conflict of Interest

The authors declare no conflict of interest.

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