Clean Technologies and Environmental Policy (2026) 28:89
https://doi.org/10.1007/s10098-026-03419-6

REVIEW

Conversion of municipal biowaste into value-added products toward a circular bioeconomy: bridging the gap between laboratory-scale and full-scale implementation

José Manuel Alejandro Cerdán[1] · Tatiana Kimura Kodama[2] · G. H. D. Oliveira[1,3] · Lucas Tadeu Fuess[1] · Júlia Fonseca Colombo Andrade[3] · Aldo Roberto Ometto[2]

Received: 27 January 2025 / Accepted: 12 January 2026

Abstract

Scaling-up municipal biowaste conversion technologies to industrial levels is essential for advancing clean and sustainable technologies and addressing significant technical, economic, and environmental challenges associated with urban organic waste management. Studies that explore technological gaps across the upstream, midstream, and downstream processing stages of biorefineries are critical for transforming biowaste into value-added products. This study aims to fill these gaps through a systematic literature review following the PRISMA guidelines and utilizing the Technology Readiness Level (TRL), which enabled the selection of 88 cases subsequently analyzed using descriptive and content analysis. The main findings show that anaerobic digestion has achieved full commercial maturity (TRL 9), while acidogenic fermentation remains mostly at TRL 6–7, and other pathways such as microbial protein or holocellulase production are still at early stages (TRL 3–4). High-value products, including polyhydroxyalkanoates (PHA) and succinic acid, are clustered at TRL 6–7, typically demonstrated at pilot scale, whereas hydrochar from hydrothermal carbonization has progressed up to TRL 8–9. Companies and projects confirm the feasibility of integrating biological, chemical, and thermal pathways into biorefineries, spanning a wide range of TRLs and showcasing their potential within the circular bioeconomy. Key gaps persist in scaling downstream processes for product purification, reducing costs, addressing feedstock variability, and optimizing pretreatment. By synthesizing experimental evidence with industrial demonstrations and sustainability assessments, this study provides a comprehensive perspective on how municipal biowaste can be converted into both non-fuel bioproducts and biofuels, thereby supporting circular bioeconomy strategies for future environmental policies.

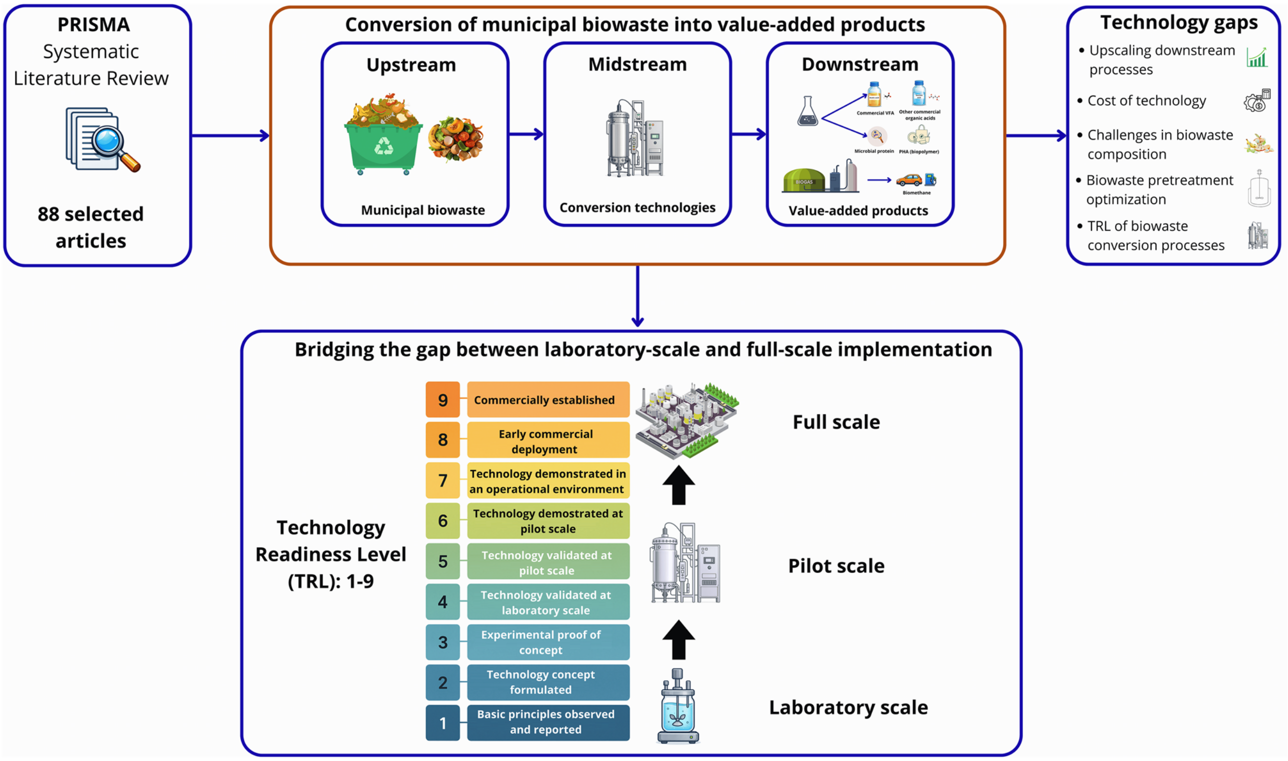
✉ José Manuel Alejandro Cerdán
jcerdan@usp.br

[1] Laboratory of Biological Processes, Center for Research, Development and Innovation in Environmental Engineering, São Carlos School of Engineering, University of São Paulo (USP), 1100, João Dagnone Ave., Santa Angelina, 13563-120 São Carlos, SP, Brazil

[2] Department of Production Engineering, São Carlos School of Engineering (EESC), University of São Paulo (USP), Av. Trab. São-Carlense, 400, 13566-590 São Carlos, SP, Brazil

[3] Solid Waste Study and Research Center (Neper), São Carlos School of Engineering, University of São Paulo, 400, Trabalhador São-Carlense Ave., 14566-590 São Carlos, SP, Brazil

Graphical Abstract



Keywords Biorefineries · Circular bioeconomy · Technological gaps · Technology readiness level (TRL) · High-value products

Introduction

The rapid expansion of urban cities and growing populations have turned municipal solid waste (MSW) into a critical challenge for public health and environmental sustainability. Approximately 2.3 billion tons of MSW is generated annually worldwide (UN-Habitat 2023; UNEP 2024). The biological and biodegradable fraction accounts for approximately 46% of the global MSW by weight (Chavan et al. 2022). The proportion of organic material in MSW exhibits stark regional disparities: In high-income Organization for Economic Cooperation and Development (OECD) countries, it constitutes only 27–30% of the total waste stream (Ricci-Jürgensen et al. 2020). The contribution of organic waste in the Global South, particularly in regions such as Latin America and the Caribbean, exceeds 50%, representing the highest proportions globally (Kaza et al. 2018; Savino et al. 2018). In lower-income countries within these regions, food waste contributes between 56 and 75% of the organic waste stream in MSW (Savino et al. 2018). The "municipal biowaste" category encompasses garden and park waste, food and kitchen waste from households, offices, restaurants, wholesale markets, catering services, retail establishments, and similar waste from food processing facilities (European Commission 2018).

Inadequate municipal management, such as insufficient sorting of the organic materials, hinders effective treatment (Raj et al. 2023). Combined with low recovery rates, significant portions of waste are disposed of through open dumping and burning (Savino et al. 2018). Molina-Peñate et al. (2022) note that, unlike other organic waste streams, municipal biowaste is characterized by high instability, complexity, and heterogeneity, making the selection of appropriate recovery and valorization routes challenging. Thus, segregation and characterization are essential to the comprehensive processing (Hanc et al. 2011).

Contemporary waste management approaches have moved beyond traditional end-of-pipe treatment, focusing instead on recovering valuable resources from urban metabolism, a concept known as the urban biocycle (Ellen MacArthur Foundation 2017; Venkata Mohan et al. 2020). This approach emphasizes transforming waste into valuable resources, often described as "waste to value," by recovering essential elements and materials that can be reintegrated into production systems. These resources can yield value-added products, such as food, animal feed, bio-based materials, and bioenergy within a waste biorefinery, potentially generating positive socio-economic impacts on regional and local levels (Clauser et al. 2021). The increasing interest in utilizing municipal biowaste as a resource for generating multiple value-added products can be effectively realized through an integrated biorefinery. Developing integrated waste biorefineries is crucial to advancing the circular bioeconomy by efficiently utilizing biowaste resources, reducing waste volumes, and minimizing environmental impacts (Leong et al. 2021). This strategy not only addresses specific waste management issues but also offers a promising solution to broader global challenges, including environmental sustainability and food security.

Emerging technologies for waste biorefineries, currently in laboratory and pilot trial stages, are adapted for full-scale implementation (Chavan et al. 2022). Advances in valorization technologies offer significant potential for the sustainable conversion of municipal biowaste into high-value-added products in biorefineries (Asunis et al. 2022). Once these technologies are validated and optimized at the laboratory scale, the next step involves developing pilot plants to further validate the process and gather data simulating industrial-scale conditions (Piccinno et al. 2016). However, scaling of laboratory technologies to industrial level remains challenging, and bridging this gap will be essential in the coming years (Ahmed et al. 2023). Identifying key technological and non-technological obstacles in scaling-up is particularly important given the global landscape of emerging technologies (Shah et al. 2022). This research is crucial in addressing this gap and advancing the field of waste management.

One of the most significant barriers to adopting new biorefinery technologies is the uncertainty surrounding their economic feasibility, especially for those focused on high-value-added products that typically involve long-term development and higher initial costs (Budzianowski 2017; Tsagkari et al. 2016). Many of these processes remain in the early research and technology maturity stages. The technology readiness level (TRL) often begins lower when producing value-added products from waste (Almeida et al. 2023) due to the complex processes and innovative methods required for optimization and yield improvement, such as product recovery and downstream processes. Conversely, technologies focused on lower-value, high-volume products, like bioenergy or biofuels (Stegmann et al. 2020) tend to operate at higher TRLs, as they are more established and accessible to implement at industrial scales (Stafford et al. 2017).

Despite significant studies in mapping emerging technologies along TRL stages, such as those reported by Suárez Valdés et al. (2024) within a portfolio of 25 innovative technologies for biowaste treatment from a circular bioeconomy perspective, important aspects remain underexplored. These include the evaluation of emerging technologies at early stages of development (e.g., TRL < 5) and comprehensive sustainability assessments of the upscaling process for converting biowaste into value-added products, encompassing studies on techno-economic evaluations, life cycle assessments, economic analyses, and social dimensions. To overcome this lack of information and complement previous studies, the objective of this study is to comprehensively address the gap between laboratory-scale and full-scale implementation by covering all phases of technology readiness levels in the conversion of municipal biowaste into value-added products, ranging from lower- to higher-value outputs within a circular bioeconomy. To achieve this main objective and respond to existing scientific gaps, the present study is guided by the following research questions (RQ):

- RQ1: What theoretical frameworks have been applied to study the conversion of municipal biowaste into value-added products?
- RQ2: Which conversion technologies have been demonstrated in real-world commercial settings, and what lessons can be drawn from these cases?
- RQ3: What are the sustainability implications (economic, environmental, and social) of scaling-up biowaste conversion technologies?
- RQ4: Which value-added products and technologies are trending across laboratory, pilot, and industrial scales, and what is their TRL?
- RQ5: What gaps remain in scaling-up emerging technologies, and how can these be addressed to foster industrial implementation?

The novelty of this study lies in narrowing the identified technology gaps in scaling-up from laboratory-scale to full-scale implementation, by analyzing experimental studies that highlight the limitations and propose ways to overcome these challenges in biowaste conversion into value-added and high-value products from technology maturity levels (emerging and advanced) within the biorefinery context. It aims to demonstrate the value of investing in small-scale research to narrow the technological gap and advance the field through scalable innovations.

Methods

Systematic literature review methodology

The Systematic Literature Review (SLR) was conducted to investigate the conversion of municipal biowaste into value-added products, focusing on biorefineries. This method was

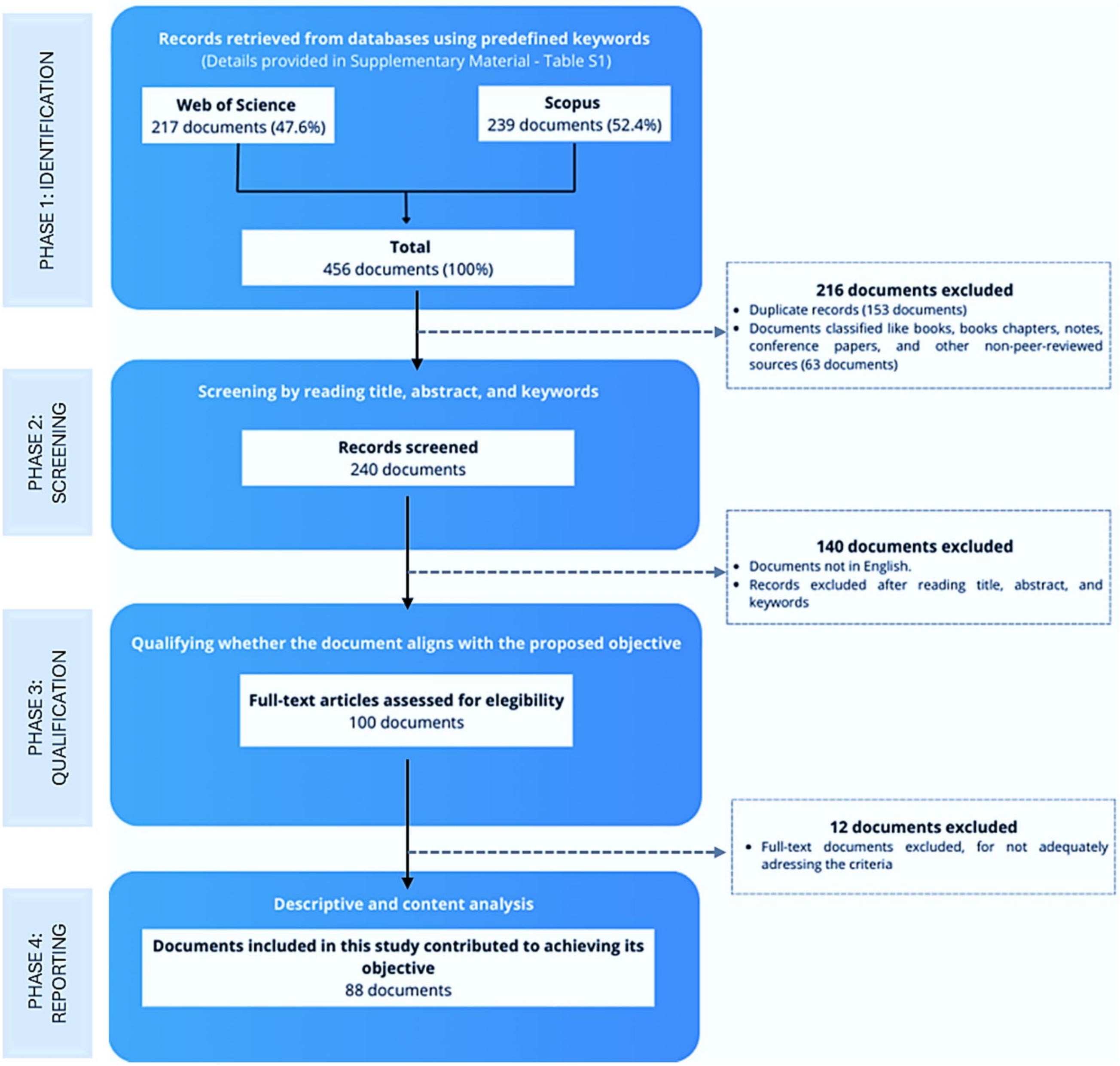


Fig. 1 Steps used in performing the systematic literature review (SLR) based on the Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA) protocol

chosen for its structured and replicable approach, ensuring rigor, transparency, and reliability (Denyer & Tranfield 2009; Tranfield et al. 2003). The research protocol followed the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 (Moher et al. 2009) and incorporated methodologies from Denyer & Tranfield (2009) and Kitchenham (2014).

The SLR was organized into four phases aligned with the PRISMA protocol (Fig. 1): (i) phase 1—identification of relevant literature from databases; (ii) phase 2—screening based on inclusion and exclusion criteria; (iii) phase 3—eligibility assessment focusing on study quality; (iv) phase 4—reporting of results. This structured process enhances the review's robustness and validity, offering reliable and trustworthy insights into biowaste valorization and its application in biorefineries.

Phase 1: identification

This phase focused on defining the keywords and selecting the databases for systematic review. Initially, the study by Molina-Peñate et al. (2022) served as a foundational reference for determining the initial set of keywords. Subsequently, an exploratory investigation was conducted to refine the keywords through a preliminary literature review on topics including "Biorefineries," "municipal solid waste," "urban solid waste," "value-added," and other related terms. These steps established keywords to target documents containing these terms in the title, abstract, and/or keywords. As a result, different combinations of main keywords were used to generate specific search strings, such as: Biorefiner*AND value-added AND ("Municipal solid waste" OR "Urban solid waste"); Biorefiner* AND (Biomaterial* OR Bio-material*) AND ("Municipal solid waste" OR "Urban solid waste"); and Biorefiner* AND ("Bio-based product*" OR "Biobased product*" OR Bioproduct*) AND ("Municipal solid waste" OR "Urban solid waste"), among others. The complete list of search strings applied, along with the corresponding number of results obtained for each, is found in Supplementary Material (Table S1).

The databases selected for the systematic search were Web of Science and Scopus, chosen for their robust repositories of peer-reviewed publications, which ensure high-quality research outputs (Pranckutė, 2021). Using both databases is recommended to achieve more comprehensive coverage of the scientific literature (Lim et al. 2024). PubMed was not considered due to its primary focus on clinical and biomedical sciences (Xu et al. 2025), while Google Scholar, although extensive, indexes grey literature and non-peer-reviewed sources and lacks the advanced filtering tools required for systematic reviews (Halevi et al. 2017).

The systematic search across selected databases yielded 456 documents (see Supplementary Material, Table S1). After exporting to BibTeX and processing with Bibliometrix, 153 duplicates were removed, leaving 303 unique records. Further screening excluded 63 non-peer-reviewed sources, including books, chapters, and conference papers. In total, 240 peer-reviewed articles were retained for Phase 2 of the analysis.

Phase 2: screening

During the screening phase, titles, abstracts, and keywords were evaluated based on the following criteria:

- Inclusion criteria: documents were included if they addressed municipal waste, such as food and kitchen waste from households, offices, restaurants, wholesale markets, canteens, caterers, retail establishments, and comparable waste from food processing plants, all of which fall under the category of municipal biowaste as defined by the European Commission (2018). Additionally, studies focusing on technologies for converting biowaste into value-added products were considered relevant (Clauser et al. 2021; Stegmann et al. 2020). English-language documents were selected to ensure a comprehensive understanding of the current global research trends and to facilitate effective communication within the international scientific community (Englander 2019). Moreover, previous evidence indicates that including English-only publications seems to be a reliable methodological shortcut that introduces minimal language bias on the overall conclusions of systematic reviews (Nussbaumer-Streit et al. 2020).
- Exclusion criteria: Documents that focused solely on methane burning, landfill combustion, incineration, and composting were excluded, as these processes occupy lower positions in the biomass value cascade within the framework of a circular bioeconomy (Venkatesh 2022). Studies that did not specifically address municipal biowaste were also excluded.

After applying these inclusion and exclusion criteria, 140 documents were excluded from the initial 240, resulting in 100 documents retained for Phase 3.

Phase 3: qualification

At this stage, the documents were read in full, and only those aligned with the study's objective were selected. Thus, 12 documents were excluded; after completing this stage, 88 documents were selected for analysis. The *Biblioshiny* package in RStudio was also employed in this phase to perform descriptive analyses of the selected documents, enhancing the analytical process and facilitating the generation of robust data visualizations. The details of this analysis are provided in Supplementary Material**.**

Phase 4: reporting

In this phase, the findings from Results and Discussion section were analyzed using content analysis, a qualitative method recognized for its flexibility (Braun & Clarke 2006). The 88 reviewed studies were classified using a coding scheme (F1-F88) into four categories (Krippendorff 2004), as presented in Supplementary Material (Table S2). To ensure reliability, each author independently reviewed and validated the coding of the studies, thereby reducing subjectivity and enhancing the robustness of the categorization process. A description of each category is provided below.

- Conceptual reviews: articles presenting theoretical frameworks and engaging in conceptual discussions, offering foundational insights and defining key concepts, ensuring readers are well informed.
- Case studies: Studies focusing on prospective technology assessments and scaled-up evaluations for industrial-level biowaste conversion provide practical insights into

technological feasibility and applications, equipping you with actionable knowledge.

- Sustainability assessment studies: Research encompasses techno-economic analyses, life cycle assessments, and social impact indicators. This category adopts a comprehensive perspective on sustainability, addressing technical, economic, environmental, and social dimensions, thus reassuring you about the thoroughness of the research and supporting evidence-based decision-making for sustainable practices.
- Experimental cases: Studies investigating biowaste conversion technologies at laboratory, pilot, and full scales contribute to an understanding of their scalability and practical performance.

Additional records identified through other sources

In line with the recommendations of Rethlefsen & Page (2022) about minimizing potential gaps inherent to the PRISMA methodology, additional sources were consulted to identify studies beyond structured database searches. These sources encompassed real-world commercial and non-commercial cases, including EU-funded projects from various calls, initiatives, and projects under the Circular Bio-based Europe Joint Undertaking (CBE JU 2025), previous studies compiling information on state-of-the-art and mapping circular technologies such as Suárez Valdés et al. (2024) and Fabbri et al. (2018), hand searches of key journals, and other relevant publications not systematically indexed in bibliographic databases. These complementary strategies were particularly important, given the predominance of early-stage research in the field, while also emphasizing high-TRL and commercially implemented technologies. All records identified through these approaches were tracked and ultimately included, thereby strengthening both the comprehensiveness and robustness of the review and ensuring its up-to-date coverage.

Results and discussion

Analysis of conceptual reviews

This section thoroughly analyzes 34 scholarly articles investigating theoretical frameworks and methodological advancements for valorizing municipal biowaste into value-added products. The focus was to elucidate the essential principles, methodologies, and technological pathways for effectively upscaling these conversion processes from laboratories to industrial applications. The articles were systematically organized into 6 thematic domains (Supplementary Table S3), each representing a critical aspect of biowaste valorization: (i) waste-to-energy & conversion technologies, focusing on strategies for transforming organic waste into valuable bioenergy and commodity chemicals, including biofuels, biogas, biohydrogen, and other renewable energy products; (ii) circular economy & biorefinery models, emphasizing on the integration of circular economy principles into waste management and biorefinery systems; (iii) waste feedstock and biomass utilization, which explores the potential of diverse biowaste types as feedstocks for bioenergy and biochemical synthesis, examining their chemical composition and suitability for various conversion technologies; (iv) bioproducts and high-value chemicals, targeting the extraction and synthesis of biochemicals and bioplastics from biowaste, with an emphasis on isolating compounds of high commercial and industrial value; and (v) techno-economic and environmental assessment research and review, focusing on assessing biowaste conversion technologies' economic feasibility and environmental impact.

The thematic domain studies on waste-to-energy & conversion technologies cover key themes: (1) conversion of biowaste into biofuels and bioenergy, including biodiesel from waste cooking oil, bioethanol, biodiesel, biohydrogen, biomethane, and bioelectricity (Barampouti et al. 2019; Foo et al. 2022; Poggi-Varaldo et al. 2014); (2) chemical production, renewable energy, and bioproducts from food supply chain waste (Ahmed et al. 2023; Xiong et al. 2019); (3) microalgae cultivation on food waste digestate (Tawfik et al. 2022); (4) MSW utilization for biofuels and renewable chemicals in biorefineries (Narisetty et al. 2023); and (5) technological advancements in MSW conversion to sustainable energy (Raj et al. 2023).

The studies of the role of circular economy and biorefinery models were explored through diverse pathways: (1) transitioning from linear waste management to circular economy models, emphasizing resource recovery and bioenergy production from biodegradable and non-biodegradable waste (Kumar et al. 2023; Velvizhi et al. 2020); (2) advancing biorefinery systems for sustainable waste valorization (Haddadi et al. 2018; Maina et al. 2017); (3) developing biorefinery concepts, including bioconversion of organic waste streams into value-added products and bioplastics (Mishra et al. 2022; Moodley & Trois 2022); and (4) utilizing frameworks like fuzzy cognitive maps to analyze bioeconomy transitions and identify barriers and policies for circular bioeconomy implementation (Morone et al. 2021).

The studies within the thematic domain of waste feedstock and biomass utilization examine various aspects of waste conversion and resource recovery: (1) biomass availability and bioenergy conversion processes, including agricultural residues, municipal solid waste, and aquatic biomass, with a focus on biofuels and power generation in India (Negi et al. 2023); (2) the global variability in food waste chemical composition, along with its valorization through integrated biorefineries and technologies focused on converting food

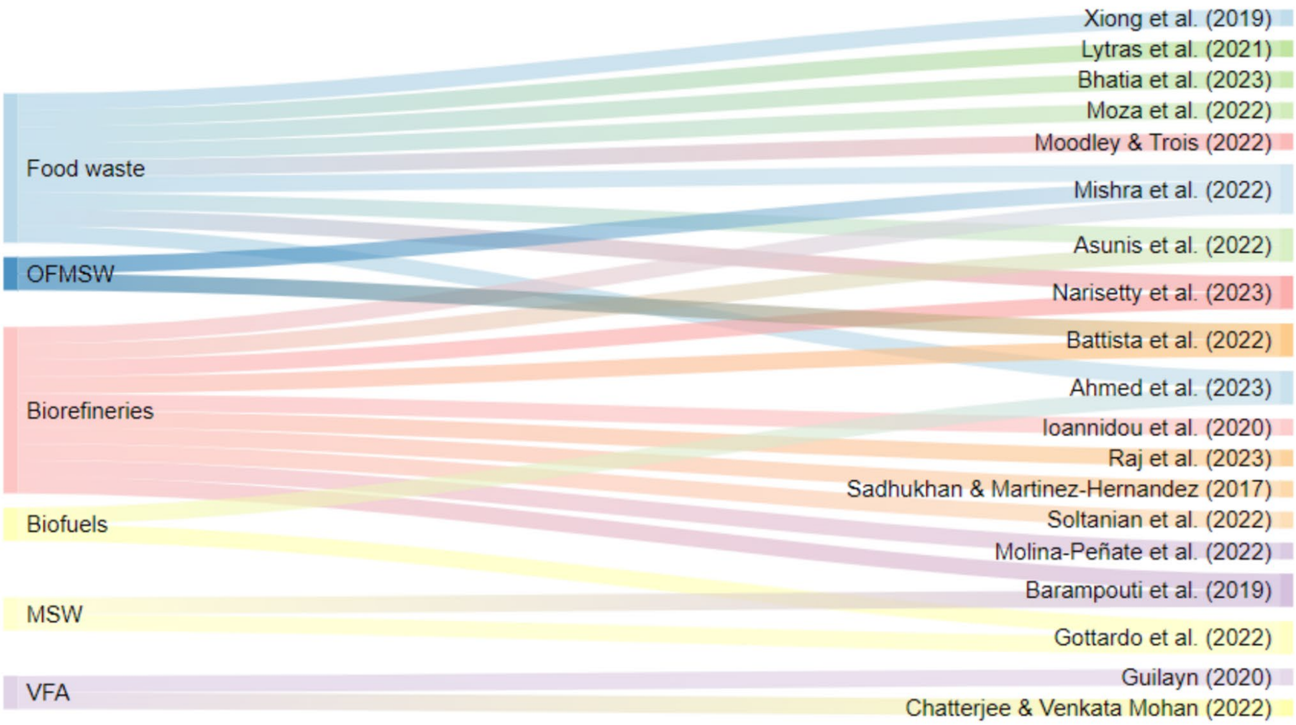


Fig. 2 Sankey diagram showing relationships between six most prominent key insights and their respective references

waste into biofuels, compost, and bioplastics, highlighting their environmental benefits in reducing greenhouse gas emissions (Bhatia et al. 2023; de Abreu et al. 2023; Lytras et al. 2021); (3) valorizing digestates from urban and centralized anaerobic digestion (AD) plants to produce biofuels, biochar, and organic fertilizers (Guilayn 2020); (4) the integration of bioconversion technologies for converting the organic fraction of municipal solid waste (OFMSW) into biofuels, chemicals, and other bioproducts (Molina-Peñate et al. 2022); (5) and wet explosion as a thermochemical pretreatment for lignocellulosic biomass to improve conversion efficiency (Biswas et al. 2015).

The bioproducts and high-value chemicals theme addresses aspects of bioprocessing and biorefinery innovations: (1) production of volatile fatty acids (VFA) (Asunis et al. 2022; Battista et al. 2022; Gottardo et al. 2022) and polyhydroxyalkanoates (PHA) (Gottardo et al. 2022) from food waste; (2) challenges in converting food waste into high-value VFA (Moza et al. 2022); (3) yeast and fungi's role in producing biofuels and chemicals (Chatterjee & Venkata Mohan 2022); (4) bioethanol production from non-food crops and waste biomass (Duque et al. 2021); and (5) valorization of AD from MSW for high-value bioproducts (Cesaro 2021).

Techno-economic and environmental assessments theme focus on: (1) material flow and sustainability analyses of novel mechanical biological chemical treatment systems for comprehensive MSW valorization (Sadhukhan & Martinez-Hernandez 2017); (2) techno-economic and life cycle assessments of biorefinery concepts using OFMSW as feedstock, demonstrating potential for profitable and sustainable bio-based product production (Ioannidou et al. 2020); and (3) evaluations of waste-to-energy technologies like AD, incineration, and gasification, emphasizing energy efficiency and environmental performance through exergetic approaches (Soltanian et al. 2022).

The Sankey diagram (Fig. 2) visually represents the connections between key insights and their respective references, offering a clear and structured overview of the significant trends and connections in the literature, enabling an efficient and interactive exploration of the relationships among the most prominent insights identified in the dataset. The diagram focused on the six most prominent key insights, carefully selected for their relevance and frequency across the references, including topics such as food waste, biorefineries, VFA, biofuels, MSW, and OFMSW.

The findings highlight that food waste and OFMSW are the most studied sources for the production of value-added products. Biorefineries emerge as an integrative concept capable of transforming these residues into renewable products through advanced technologies such as AD and acidogenic fermentation. The references analyzed span a variety of approaches, ranging from a comprehensive overview of technologies for food waste utilization, which convert it into

Table 1 Case studies on biorefinery both real-world applications and prospective scenarios

Type of case study	Country	Area of application	Main focus	Input analyzed	Type of processes analyzed	Main products analyzed	Type of biorefinery	Reference
Real-world application	Brazil	Campus of the UFPE	Pilot-scale implementation of waste conversion technology for bioproducts	Used cooking oil, pruning residues, and food waste	Transesterification plant, AD unit, and composting facility	Biodiesel, biogas, organic compost and 1,3-propanediol	Integrated biorefinery	de Sousa et al. (2022)
Prospective	USA	Sheridan County, Kansas	Optimize the lowest-cost biomass blend (carbohydrates and ashes) to meet conversion specifications for a biorefinery	Three-pass stover, two-pass stover, switchgrass, miscanthus, grass clippings and an MSW fraction	Preprocessing, solar drying and size reduction, blending and storage, enzymatic and dilute-acid deconstruction, and biological conversion of sugars into hydrocarbons	Biochemical product (hydrocarbons)	Biochemical conversion biorefinery	Roni et al. (2018)
Prospective	Italy	Tuscany	Comparing the environmental performance of a PHA-producing biorefinery from OFMSW with conventional methods using LCA	OFMSW	Comparison between (i) the baseline scenario (high TRL), including pretreatment, dry AD, biogas upgrading to biomethane, and solid digestate composting, and (ii) the alternative scenario (low TRL), consisting of the baseline scenario + PHA production	PHA, Biomethane, and fertilizers	Dry anaerobic biorefinery	Rossi et al. (2022a, b, c)
Prospective	Kingdom of Saudi Arabia	Makkah	To assess the potential of a biorefinery to convert waste into energy	OFMSW	AD, transesterification, pyrolisis, refuse derived fuel (RDF)	Biogas, glycerol, biodiesel, liquid fuel oil, RDF pellets	Waste-based biorefinery or waste-to-energy (WTE) facility	Nizami et al. (2017)
Prospective	Italy	NS	Use fuzzy cognitive maps to analyze Italy's bioeconomy transition, focusing on OFMSW and identifying barriers and policies for circular bioeconomy	OFMSW	NS	NS	Urban Waste-based biorefinery	Morone et al. (2021)

Table 1 (continued)

Type of case study	Country	Area of application	Main focus	Input analyzed	Type of processes analyzed	Main products analyzed	Type of biorefinery	Reference
Real-world application	Italy	Southern Italy	Technological improvements and microbiological analysis to optimize biogas production in an AD plant (full-scale)	OFMSW	AD	Biogas and Biomethane	Anaerobic biorefinery	Le Pera et al. (2022)
Prospective	EU-28 countries	NS	Techno-economic evaluation of succinic acid production using the OFMSW as feedstock	OFMSW	Fermentation	Succinic acid	Integrated biorefineries using Industrial and Food Supply Chain Side Streams (IFSS)	Ioannidou et al. (2020)
Prospective	Netherlands	Region of Moerdjjk	To assess the environmental impacts of treating OFMSW and pig manure for energy and product recovery using LCA on two modeled scenarios	OFMSW and pig manure	AD in co-digestion systems combines OFMSW and pig manure using Dranco® thermophilic technology, an advanced and commercially established biotechnological process	Electricity, heat, compost, and nutrients	Anaerobic biorefinery	Moretti et al. (2018)
Prospective	Italy	Three macro-areas: North, Center, and South and Islands	Optimize the sizing and location of biorefinery plants, as well as assess the impact of these technologies in terms of energy production and CO_2 emissions reduction	SS, OFMSW, agricultural and livestock waste, and food industry waste	Thermo-valorization and AD	Bioenergy	Second-generation (2G) biorefinery	Demichelis et al. (2019)

Table 1 (continued)

Type of case study	Country	Area of application	Main focus	Input analyzed	Type of processes analyzed	Main products analyzed	Type of biorefinery	Reference
Real-world application	Netherlands, Germany, Spain, Italy, Denmark, and UK	Plants: Holsworthy Biogas, Cassington AD, Biocel, Twence Fermentation, Meerlanden, ZAK, Ecoparc 2, An anonymous plant in Italy, Aikan Showcase	Compare wet and dry AD processes	MSW and FW	AD	Biogas, Digestate (liquid or solid/compost), Refuse-Derived Fuel (RDF)	Anaerobic biorefinery	Angelonidi & Smith (2015)

NS, not showed; FW-, food waste; AD, anaerobic digestion; SS, sewage sludge

valuable products (Bhatia et al. 2023) to techno-economic and life cycle assessments to evaluate biorefinery concepts, using OFMSW as feedstock for production (Ioannidou et al. 2020). Moreover, recent studies (Ahmed et al. 2023; Narisetty et al. 2023) emphasize the potential of biorefineries to integrate within a circular economy model.

Analysis of case studies

The reviewed case studies underscore the significant strides made in biorefinery applications for municipal biowaste conversion, elucidating the promising potential to convert waste streams into valuable resources. This review categorizes studies into two main types: prospective (projecting future scenarios) (Oliveira et al. 2018) and real-world applications (reporting practical experiences in facilities) (Darvishi-Harzevili & Hiligsmann 2018), showcasing the adaptability of biorefineries in both strategic and operational contexts. Table 1 summarizes these studies, detailing the countries, type of biorefinery, input types, and main products associated with each case.

Prospective studies have examined comparative scenarios between consolidated technologies, such as AD (Moretti et al. 2018; Rossi et al. 2022a, b, c), and emerging technologies aimed at waste-to-energy (WTE) conversion (Nizami et al. 2017) or the production of high-value bioproducts, such as succinic acid (Ioannidou et al. 2020). For instance, Nizami et al. (2017) assessed a biorefinery in Makkah, Saudi Arabia, integrating AD, transesterification, pyrolysis, and RDF for MSW-to-energy conversion. Similarly, Rossi et al. (2022a, b, c) applied LCA in Italy to compare a baseline scenario with high TRL (AD with biomethane upgrading and digestate composting) with an alternative scenario (low TRL) including PHA production, finding that at the current TRL, the baseline strategy outperforms the novel PHA route on an environmental basis. In addition, Morone et al. (2021) employed fuzzy cognitive maps to analyze the bioeconomy transition in Italy, focusing on OFMSW and policy barriers, while Demichelis et al. (2019) optimized the sizing and location of biorefinery plants in the same country, emphasizing energy gains and CO_2 reduction. Beyond Europe, Roni et al. (2018) developed a biomass blending model in Kansas, USA, to optimize local feedstocks such as corn stover for biochemical conversion.

Real-world applications provide tangible evidence of the practical implementation of integrated biorefineries, demonstrating how innovative technologies can be unlocked alongside consolidated ones. As an illustrative case, de Sousa et al. (2022) reported the establishment of an experimental biorefinery of organic solid wastes at the Federal University of Pernambuco (UFPE), a pilot-scale facility that processes 40 L of used cooking oil, 2,500 kg of yard waste, and 750 kg of food waste daily into biodiesel, biogas, organic compost, 1,3-propanediol, and electricity. The facility integrates a transesterification plant, an anaerobic digester, and a composting unit. Biodiesel production achieves a 93% conversion rate, while biogas generation averages 0.584 ± 0.176 Nm^3 per kg of volatile solids, with methane comprising 50% of the output. The compost produced meets organic fertilizer standards, and the facility is designed to serve the equivalent of a small city in Northeastern Brazil. Other real-world applications focus on improving single consolidated technologies. In this context, Le Pera et al. (2022) optimized an industrial AD plant in Italy for biogas, emphasizing the importance of process adjustments to enhance yields. Angelonidi & Smith (2015) compared wet and dry digestion plants for MSW, evaluating performance across different AD configurations.

Adaptation to regional contexts is essential, with supportive policies on waste collection and infrastructure needed for sustainable biorefinery operations (Morone et al. 2021; Nizami et al. 2017). Real-world applications in Brazil and Italy (de Sousa et al. 2022; Le Pera et al. 2022) underscore the importance of policy support for affordable biorefinery technologies, particularly in smaller urban settings. As such, biorefineries emerge as pivotal players in sustainable production and consumption. Positioned at the core of the circular economy, they transform municipal waste into biofuels and high-value products. Despite the challenges of scaling and process adaptation, developing effective and sustainable biorefinery systems globally remains crucial. To complement the real-world applications identified through the SLR case studies, Sect. "Highlighting real-world commercial and non-commercial demonstration cases" is added to highlight commercial and non-commercial demonstration cases for companies and projects with different scale-up TRL, with a specific focus on innovative technologies that diverge from conventional approaches.

Sustainability assessment studies

This section highlights studies that evaluate the sustainability of technologies for converting municipal biowaste into valuable products, focusing on the environmental, economic, and social impacts of biorefinery processes. Sustainability assessment tools offer a comprehensive analysis of both the benefits and challenges, guiding the design of biorefineries to optimize positive impacts while mitigating potential drawbacks (Solarte-Toro & Cardona Alzate 2021). Key methodologies employed include Techno-economic assessment (TEA), which focuses on the economic feasibility of these processes, Life cycle assessment (LCA), which evaluates the environmental impacts throughout the technology's lifecycle. Other studies incorporate specialized approaches in social indicators and other indicators of sustainability (Supplementary Table S4). These tools and methodologies offer a holistic perspective on optimizing urban biowaste conversion technologies for sustainable outcomes, serving as a guide for future technological development and implementation.

Sustainability assessment studies typically employ a range of techno-economic indicators, including net present value, internal rate of return, payback period, and capital costs to assess the economic viability of different biorefinery systems. For instance, studies on municipal organic waste such as those by Musharavati et al. (2024) and Ladakis et al. (2022) highlight the potential of converting OFMSW into biodiesel, bioethanol, and other valuable products, demonstrating their economic competitiveness. Moreover, LCA is used to quantify environmental impacts, such as global warming potential, human toxicity, and resource depletion, across various waste-to-product conversion scenarios, providing a holistic view of the sustainability of these technologies.

The most recurring environmental hotspots identified for biowaste conversion into value-added products can be found in processes such as energy supply (e.g., grid-mix electricity), transportation, and waste disposal, which account for more than 70% of the contribution to fine particulate matter formation, freshwater eutrophication, marine eutrophication, terrestrial acidification, and fossil and metal depletion (Ladakis et al. 2022). Similarly, Khoshnevisan et al. (2020) highlighted that energy-related processes (e.g., electricity mix, heat demand, hydrogen production), biogas upgrading versus combined heat and power (CHP) allocation, and energy-intensive digestate treatment dominate the environmental burdens across climate change, human health, ecosystem quality, and resource depletion categories.

Other life cycle studies that focused on specific categories such as Global Warming Potential (GWP) and Abiotic Depletion Potential (ADP) of OFMSW-based biorefineries for succinic acid production have reported that 56% of the total GWP is associated with the high natural gas demand for OFMSW drying, while both the oil/fats extraction and succinic acid production stages contribute almost equally (~47% each) to fossil resource depletion. More comprehensive studies, such as Ioannidou et al. (2023), demonstrated that OFMSW-based biorefineries are strongly influenced by energy supply, with a shift from grid to renewable electricity reducing some impact categories including GWP, ADP fossil, Acidification Potential (AP), and Eutrophication Potential (EP) by up to 60%, but increasing Human Toxicity Potential (HTP) due to heavy metals in photovoltaics. Process-specific hotspots include sodium hydroxide (NaOH) use in succinic acid fermentation, enzyme production for hydrolysis (EP), diol inputs and steam demand in polyester polyol production, ε-caprolactone in Hot Melt Adhesives (HMAs) formulation, and potassium hydroxide (KOH) consumption in biosurfactant formulation. In summary, acidification and eutrophication potential are largely driven by emissions from energy production, use of digestates and fertilizers, and release of gaseous pollutants (SO_2, NO_x, NH_3, H_2S) during composting and AD processes. These latter were identified in several studies (Escamilla-Alvarado et al. 2017; Ma et al. 2024; Moretti et al. 2018; Rossi et al. 2022a, b, c; Sadhukhan et al. 2016).

Regarding techno-economic and environmental evaluations, some studies also integrate social indicators to assess the broader societal impacts of waste-to-value conversion technologies. For instance, Ioannidou et al. (2020) incorporated human rights, safety, and social acceptability into their analysis of bio-based polymer production from food waste-derived feedstocks. This multidimensional approach ensures that the adoption of biotechnologies for biowaste conversion not only provides economic and environmental benefits but also contributes positively to social welfare. The sustainability outcomes of these assessments, as seen in studies by Ioannidou et al (2023), underscore the potential of biorefineries to offer a sustainable alternative to traditional waste management practices, reducing greenhouse gas emissions, promoting resource recovery, and supporting a circular bioeconomy.

In relation to the above, the common techno-economic bottleneck identified across the studies focuses on high capital and operational costs associated with complex biorefinery processes, particularly for lignocellulosic biomass and advanced waste-to-energy technologies (Demichelis et al. 2020; Sadhukhan & Martinez-Hernandez 2017). A significant challenge lies in the technical complexity and energy intensity of pretreatment, hydrolysis, and downstream separation and purification steps (Demichelis et al. 2020; Ioannidou et al. 2020; Ma et al. 2024; Waqas et al. 2023). Economically, many bioenergy and bioproduct pathways, such as bio-succinic acid and single-cell protein (SCP) production, demonstrate low profitability or struggle to compete with fossil-based counterparts without external incentives or higher market prices (Elyasi et al. 2021; Escamilla-Alvarado et al. 2017; Ioannidou et al. 2020). Furthermore, the low TRL of some innovative bioproduct extraction methods hampers their economic viability compared to more mature, conventional waste management strategies, and overall profitability is highly sensitive to fluctuating chemical costs, product selling prices, and energy utility expenses (Elyasi et al. 2021; Sadhukhan et al. 2016).

Analysis of experimental studies

Technologies for the conversion of biowaste into value-added products

Recent trends in the literature reveal a growing interest in diverse technologies for converting municipal biowaste into value-added products. The content analysis from experimental studies obtained from SLR is based on a relatively small pool of articles (n = 32) published between 2013 and 2024. These findings are further complemented by additional insights not captured through the PRISMA process (Sect. "Highlighting real-world commercial and non-commercial demonstration cases"). Considering this limited dataset, the analysis should be interpreted as reflecting exploratory trends rather than providing exhaustive coverage of all current technologies. Within this scope, anaerobic conversion processes, such as acidogenic fermentation, microbial fermentation by specific species, and AD, emerge as the most frequently employed individual technologies in experimental studies (Fig. 3).

The analysis of biowaste conversion studies demonstrates a notable shift toward adopting multiple conversion technologies. Studies that evaluated more than one technology, as indicated by the "More than one" category, account for 44% of studies analyzed. Within this category, anaerobic digestion emerges as the most predominant, accounting for 38% of the cases, followed by acidogenic fermentation (17%), aerobic feast–famine regime (10%), ethanolic fermentation (10%), and other technologies (24%). These results emphasize a growing trend toward integrated approaches in biowaste conversion, reflecting an increasing focus on combined solutions to improve efficiency.

The diverse array of conversion technologies discussed emphasizes the necessity for further investigation into integrated systems that capitalize on multiple technological pathways (Haddadi et al. 2018). Such approaches are essential for enhancing both the efficiency and the overall value of biowaste-derived products as they progress from laboratory settings to full-scale implementation. Nevertheless, it is important to note that expanding the range of bioproducts derived from biowaste conversion could potentially affect the economic return of biorefinery processes. The production of smaller quantities of each bioproduct may not generate sufficient revenue to cover the higher production costs associated with diversification (Barragán-Ocaña et al. 2023; Solarte-Toro & Cardona Alzate 2023).

The screening of outputs from municipal biowaste conversion reveals various value-added products, which can be classified based on their economic potential and market relevance as high-value products. For this study, the classification of high-value-added products follows the framework proposed by Budzianowski (2017), which groups them into six categories: (1) biopharmaceuticals, (2) biocosmetics, (3) bionutrients, (4) biochemicals, (5) biofertilizers, and (6) biomaterials.

Regarding the occurrence of the specific products evaluated across the studies, the main value-added products evaluated were VFA, methane, and bioethanol (Fig. 4). Notably, 36% of the occurrences specifically highlight

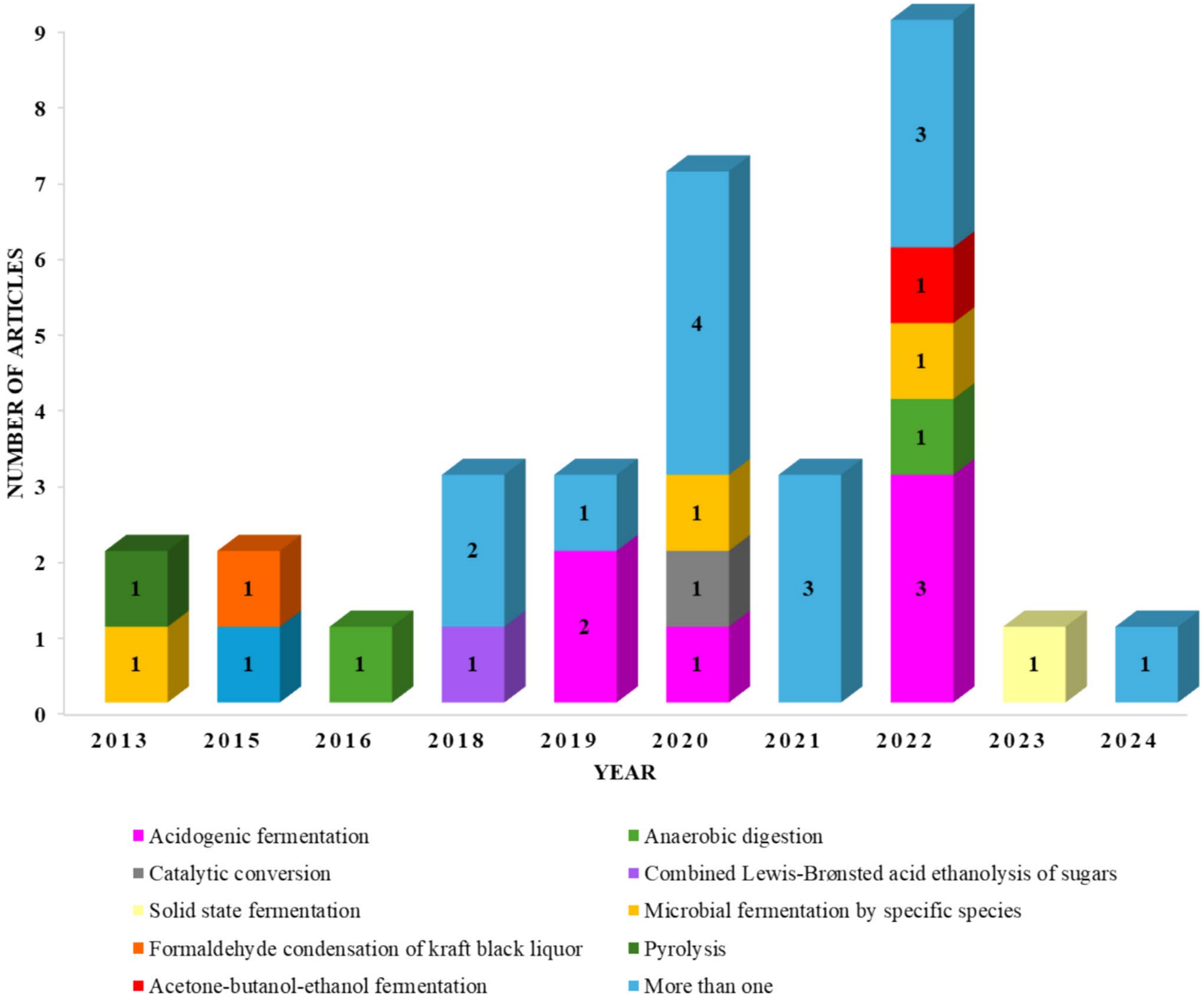


Fig. 3 Trends in biowaste conversion technologies from 2013 to 2024

high-value-added products, including PHA, butanol, acetone, triacylglycerol, 2,3-butanediol, lactic acid (HLA), and others. The findings of this review highlight the growing interest in utilizing municipal biowaste as a valuable resource for generating a range of high-value bioproducts.

Although the identified high-value products are currently produced on a small market volume (low-volume products), they possess significant market potential, positioning them as ideal candidates for biorefineries. The most promising high-value products typically combine large market volumes with medium to high selling prices, enhancing their economic viability (Budzianowski 2017). In other words, integrating high-value products coproduced with bioenergy or biofuel (low-value products) with sufficiently high yields significantly improves the economic performance of biorefineries, resulting in high-profit margins (Budzianowski & Postawa 2016).

Technology readiness level for non-fuel bioproducts and biofuel conversion

The assessment of technology readiness level (TRL) for various biowaste conversion technologies and their potential for upscaling is crucial for the development of waste biorefineries (Gnansounou & Pandey 2017). The maturity of emerging or advanced technologies can be classified into nine levels, as defined by NASA (2017). This scale ranges from 1 (basic research) to 9 (fully operational and market-ready). Based on the stage within the research, development, and demonstration cycle, TRL levels are typically categorized into four stages (Stafford et al. 2017), as follows: (1) research and development (TRL1–TRL4), (2) pilot and demonstration (TRL5–TRL7), (3) early commercial deployment (TRL8–TRL9), and (4) commercially established (TRL9). Table 2 and Table 3 present an overview of technology

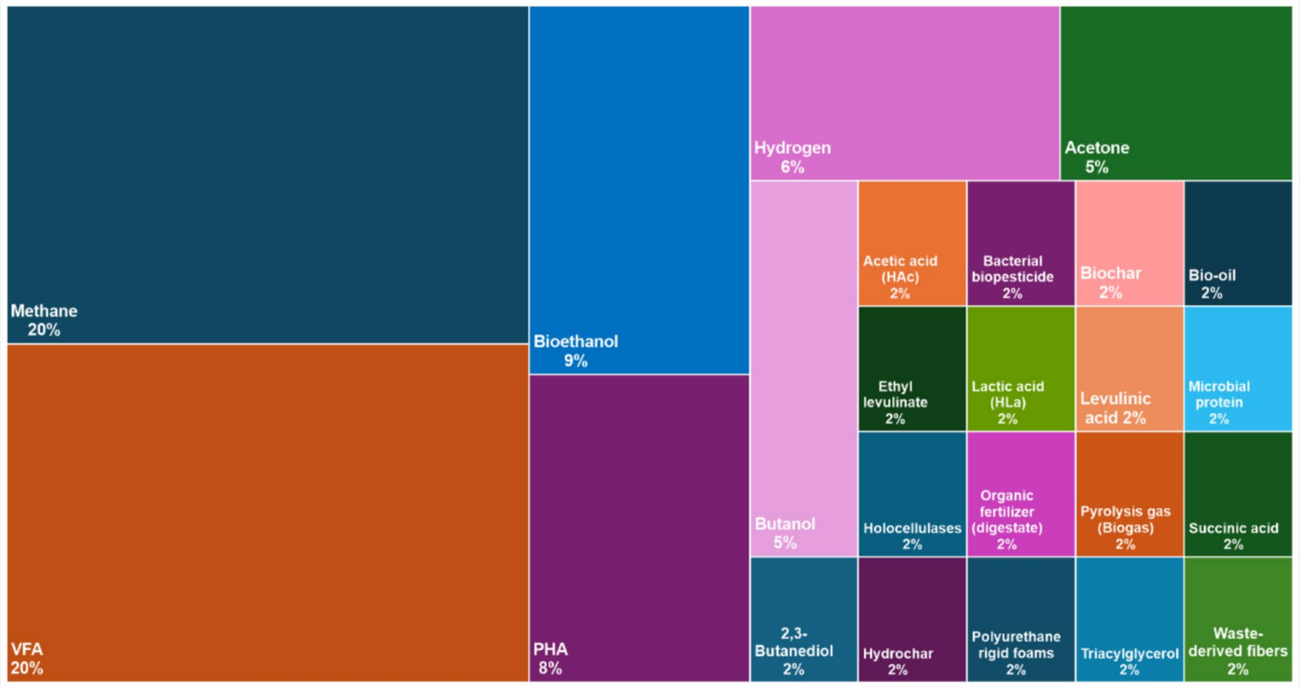


Fig. 4 Distribution of value-added products from municipal biowaste conversion technologies

readiness levels for the bioconversion technologies evaluated for municipal biowaste valorization.

Non-fuel bioproducts conversion technology readiness Based on the analyzed studies, non-fuel bioproduct conversion technologies have been found to generate a wide array of value-added products that can serve as renewable alternatives to those produced from non-renewable sources (Table 2). These products include plastics, fertilizers, lubricants, industrial chemicals, and adsorbents (Tijjani Usman et al. 2022). Several non-fuel bioproduct conversion technologies remain in the Research and Development stages (TRL 1–4), while others are advancing to pilot and demonstration stages (TRL 5–7).

The main bioproducts identified and categorized in this research as chemical building blocks include organic acids and carboxylate derivatives, such as VFA, acetic acid, succinic acid, levulinic acid, and lactic acid. Each of these bioproducts plays a crucial role in various industrial applications (Kim et al. 2018). Experimental studies focused on converting biowaste into VFA are generally conducted at the laboratory and pilot scales, with separation of individual acids typically occurring at the laboratory scale. According to prior research, the TRL for acidogenic fermentation technologies using mixed cultures varies with the extent of bioproduct purification achieved during downstream processing, reaching TRL 6–7 (European Commission 2019; Prado-Rubio et al. 2020). In contrast, acid extraction processes are rated at TRL 3–4 (Tönjes et al. 2025).

In this study, the TRL for municipal biowaste conversion into VFA mixtures (non-separated acids) was estimated at around TRL 6–7, as supported by findings from the various studies (Begum et al. 2016; Cheah et al. 2019; Gianico et al. 2021; Moretto et al. 2019; Moretto et al. 2020a, b; Papa et al. 2020; Rossi et al. 2022a, b, c; Serra-Toro et al. 2022; Tayou et al. 2022; Valentino et al. 2018; Vidal-Antich et al. 2022). Succinic acid conversion (Ladakis et al. 2022) in recent years scaled up to TRL 6–7, showing a close alignment between its Manufacturing Readiness Level (MRL) and TRL (Smanski et al. 2022). Likewise, lactic acid production (Probst et al. 2015) has also been reported at TRL 6–7 (WASTE2FUNC 2024), with successful demonstrations of conversion from food waste derived from agriculture, the food industry, supermarkets, and restaurants. The catalytic conversion of waste to levulinic acid (Dutta et al. 2020) has advanced further in some cases: bagasse-based processes have reached TRL 7–8, whereas processes using other agricultural residues remain at TRL 5–6 (Patil 2024), with research ongoing to improve extraction efficiency.

Bioproducts categorized as biopolymers, including PHA, lead to potential for developing biodegradable materials as alternatives to petrochemical plastics (Rodriguez-Perez et al. 2018). Experimental research on converting biowaste into PHA (Allegue et al. 2020; Moretto et al. 2020a, b; Papa et al. 2020; Valentino et al. 2018) has been conducted at both laboratory and pilot scales, primarily using microbial enrichment strategies that alternate phases of substrate excess and

Table 2 Overview of technology readiness levels for non-fuel bioproducts conversion from municipal biowaste

Reference	Scale	Input	Pretreatment	Conversion technology (process)	Main product(s)	Value-added product[1]	High-value-added product[1]	Technology Readiness Level (scale of maturity)	Technology Readiness Stage
(Begum et al. 2016)	Laboratory Scale	FW	Combined thermal and chemical	AD (Single-stage and two-stage)	VFA	✓	N/A	6–7	Pilot and Demonstration
(Ladakis et al. 2022)	Laboratory Scale	OFMSW	Enzymatic hydrolysis	Fermentation by *Actinobacillus succinogenes*	Succinic acid	✓	✓	6–7	Pilot and Demonstration
(Allegue et al. 2020)	Laboratory Scale	FW	Thermal hydrolysis	AD	Digestate	✓	✓	9	Commercially Established
				Photofermentation with purple phototrophic bacteria	PHA	✓	✓	6–7	Pilot and Demonstration
					Microbial protein	✓	✓	3–5	Pilot and Demonstration
(Dutta et al. 2020)	Laboratory Scale	Lignocellulosic waste fraction	Physical	Catalytic conversion	Levulinic acid	✓	N/A	5–8	Early Commercial Deployment
(Qin et al. 2024)	Laboratory Scale	FW	Physical and enzymatic	Epoxidation and oxirane ring-opening	Polyurethane rigid foams	✓	✓	3–4	R&D
(Escamilla-Alvarado et al. 2013)	Laboratory Scale	OFMSW	Physical and washing	Fermentation by *Cellulomonas flavigena* PR-22 and *Trichoderma reesei* MCG 80	Holocellulases	✓	✓	3–4	R&D
(Moretto et al. 2019)	Laboratory Scale	FW and biological sludge	Thermal	Acidogenic fermentation	VFA	✓	N/A	6–7	Pilot and Demonstration
(Moretto et al. 2020a, b)	Pilot Scale	MSW and WAS	Thermal	Acidogenic fermentation	VFA	✓	N/A	6–7	Pilot and Demonstration
				Aerobic feast-famine regime	PHA	✓	✓	6–7	Pilot and Demonstration
(Moretto et al. 2020a, b)	Pilot Scale	Biological sludge and OFMSW	Thermal and non-thermal	Acidogenic fermentation	VFA	✓	N/A	6–7	Pilot and Demonstration
				Aerobic feast-famine regime	PHA	✓	✓	6–7	Pilot and Demonstration
(Molina-Peñate et al. 2023)	Laboratory Scale	Digestates from OFMSW and SS	Physical, thermal and Enzymatic hydrolysis	Solid-state fermentation by *Bacillus thuringiensis*	Bacterial biopesticide	✓	N/A	3–4	R&D
(Agarwal et al. 2013)	Laboratory Scale	Cellulosic municipal waste	NS	Pyrolysis	Biochar	✓	N/A	5–9	Early Commercial Deployment

Table 2 (continued)

Reference	Scale	Input	Pretreatment	Conversion technology (process)	Main product(s)	Value-added product[1]	High-value-added product[1]	Technology Readiness Level (scale of maturity)	Technology Readiness Stage
(Ko et al. 2015)	Laboratory Scale	CEFW and MSWF	Chemical and thermal	Formaldehyde Condensation of Kraft Black Liquor	Waste-derived fibers	✓	N/A	3–4	R&D
(Dornau et al. 2020)	Laboratory Scale	OFMSW	Thermal and Enzymatic hydrolysis	Fermentation by various microbial species	Triacylglycerol	✓	✓	3–4	R&D
(Vidal-Antich et al. 2022)	Laboratory Scale	WAS and Synthetic Food Waste	Physical	Acidogenic fermentation	VFA	✓	N/A	6–7	Pilot and Demonstration
(Gianico et al. 2021)	Laboratory Scale	Food waste	Thermal	Acidogenic fermentation	VFA	✓	N/A	6–7	Pilot and Demonstration
(Serra-Toro et al. 2022)	Laboratory Scale	Synthetic waste and OFMSW	Pre-fermentation	Acidogenic fermentation	VFA	✓	N/A	6–7	Pilot and Demonstration
(Parmar & Ross 2019)	Laboratory Scale	Various types of organic wastes	Thermal	HTC	Hydrochar	✓	N/A	6–7	Pilot and Demonstration
(di Bitonto et al. 2018)	Laboratory Scale	Various types of organic wastes	Mechanical and thermal	Combined Lewis-Brønsted acid ethanolysis of sugars	Ethyl levulinate	✓	N/A	3–4	R&D
(Tayou et al. 2022)	Pilot Scale	MS and FW	Thermal hydrolysis	Acidogenic fermentation	VFA	✓	N/A	6–7	Pilot and Demonstration
(Cheah et al. 2019)	Laboratory Scale	FW	Biological	Acidogenic fermentation	VFA	✓	N/A	6–7	Pilot and Demonstration
(Rossi et al. 2022a, b, c)	Pilot Scale	OFMSW	Physical and preservation	AD	VFA	✓	N/A	6–7	Pilot and Demonstration
(Valentino et al. 2018)	Pilot Scale	OFMSW	Mechanical	Acidogenic fermentation	VFA	✓	N/A	6–7	Pilot and Demonstration
				Aerobic feast-famine regime	PHA	✓	✓	6–7	Pilot and Demonstration
(Probst et al. 2015)	Laboratory Scale	Biowaste	Physical	Lactic acid fermentation	Lactic acid (HLa)	✓	✓	6–7	Pilot and Demonstration
					Acetic acid (HAc)	✓	✓	6–7	Pilot and Demonstration
(Papa et al. 2020)	Laboratory Scale	OFMSW	Mechanical and mixing	AD	VFA	✓	N/A	6–7	Pilot and Demonstration
				Aerobic feast-famine regime	PHA	✓	✓	6–7	Pilot and Demonstration

Table 2 (continued)

Reference	Scale	Input	Pretreatment	Conversion technology (process)	Main product(s)	Value-added product[1]	High-value-added product[1]	Technology Readiness Level (scale of maturity)	Technology Readiness Stage
(Rossi et al. 2022a, b, c)	Laboratory Scale	OFMSW	Physical	Acidogenic fermentation	VFA	✓	N/A	6–7	Pilot and Demonstration

N/A, not applicable; NS, not showed; MS, Municipal secondary sludge; WAS, waste activated sludge; CEFW, rice straw cellulosic ethanol fermentation waste; MSWF, municipal solid waste derived fiber; R&D, research and development

[1] The classification was based on Budzianowski (2017)

scarcity, commonly known as the aerobic *feast–famine regime*, to select and enhance PHA-storing microorganisms for polymer accumulation (Fradinho et al. 2016; Huang et al. 2018). Recent studies, such as Izarra et al. (2025), indicate that these bioprocesses have reached TRL 6–7, reflecting demonstration in relevant operational environments. Conversely, polyurethane rigid foam, a polymer produced through epoxidation and oxirane ring-opening reactions, with a key role in industrial applications for construction and insulation (Fridrihsone et al. 2020), remains at a lower TRL 3–4, as reported by Qin et al. (2024).

A novel second-generation microbial protein production approach, known as single-cell protein (SCP), involves upcycling various biowastes into protein-rich biomass (Li et al. 2023). According to Sekoai et al. (2024), this technology is currently at low-to-intermediate TRL (3–5); although still predominantly at the laboratory scale (Allegue et al. 2020), some pilot-scale demonstrations have been reported, but large-scale industrial implementation has not yet been achieved. While distinct from SCP, one related study by Escamilla-Alvarado et al. (2013) explored the use of organic waste and digestates for the production of holocellulases, enzymes of high industrial value, which also remains at an early development stage (TRL 3–4).

Bioproducts such as soil amendments (biochar) produced via pyrolysis, hydrochar obtained through hydrothermal carbonization (HTC), and organic fertilizers (e.g., digestate) produced via AD are primarily applied in agriculture to enhance soil quality and reduce dependence on synthetic fertilizers (Parmar & Ross 2019). A recent report by Möllersten (2022) indicates that the TRL for converting organic waste into biochar through pyrolysis ranges from 5 to 9. In the case of hydrochar, UKIERI (2022) places hydrothermal carbonization technologies at TRL 6–7, although some emerging technology companies, such as *Ingelia HTC technology*, have already demonstrated the process at a commercial scale, reaching TRL 9 (Ciceri et al. 2021). In the case of organic fertilizers, digestate from anaerobic digestion processes is a fully commercialized product with a consolidated TRL 9 (Allegue et al. 2020), as further supported by findings from Rizzioli et al. (2023).

In summary, this study identified 32 occurrences of non-fuel bioproducts obtained from municipal biowaste. Figures 5 and 6 illustrate the distribution of occurrences of non-fuel bioproducts across TRL ranges. The heatmap (Fig. 5) shows that VFA and PHA dominate at intermediate TRL levels (6–7), while other products such as digestate, biochar, succinic acid, lactic acid, acetic acid, microbial protein, and fibers appear at various stages of maturity. The percentage distribution (Fig. 6) confirms that most occurrences are concentrated at TRL 6–7 (68.8%), reflecting technologies at pilot or demonstration stages, followed by

Table 3 Overview of technology readiness levels for biofuel conversion from municipal biowaste

Reference	Scale	Input	Pretreatment	Conversion technology (process)	Main product(s)	Value-added product[1]	High-value-added product[1]	Technology Readiness Level (scale of maturity)	Technology Readiness Stage
(Cesaro et al. 2020)	Laboratory Scale	OFMSW	Thermo-chemical (formic acid)	Acidogenic fermentation (Dark fermentation)	Hydrogen	✓	N/A	TRL 3–5	Pilot and Demonstration
(Begum et al. 2016)	Laboratory Scale	FW	Combined thermal and chemical	AD (Single-stage and two-stage)					
					Methane	✓	N/A	TRL 9	Commercially Established
(Allegue et al. 2020)	Laboratory Scale	FW	Thermal hydrolysis	AD	Methane	✓	N/A	TRL 9	Commercially Established
				Photofermentation with purple phototrophic bacteria					
					Hydrogen	✓	N/A	TRL 3–5	Pilot and Demonstration
(Moretto et al. 2020a, b)	Pilot Scale	Biological sludge and OFMSW	Thermal and non-thermal	AD	Methane	✓	N/A	TRL 9	Commercially Established
(Agarwal et al. 2013)	Laboratory Scale	Cellulosic municipal waste	NS	Pyrolysis	Pyrolysis gas	✓	N/A	TRL 2–6	Pilot and Demonstration
					Bio-oil	✓	N/A	TRL 5–9	Early Commercial Deployment
(Dornau et al. 2020)	Laboratory Scale	OFMSW	Thermal and Enzymatic hydrolysis	Fermentation by various microbial species	Bioethanol	✓	N/A	TRL 3–4	R&D
					Butanol	✓	✓	TRL 3–4	R&D
					Acetone	✓	✓	TRL 3–4	R&D
(Moreno et al. 2021)	Laboratory Scale	OFMSW	Mechanical	Ethanolic fermentation	Bioethanol	✓	N/A	TRL 7–9	Early Commercial Deployment
				AD	Methane	✓	N/A	TRL 9	Commercially Established
(Ebrahimian et al. 2022a, b)	Laboratory Scale	OFMSW	Acetone organosolv and Enzymatic hydrolysis	Acetone-butanol-ethanol (ABE) fermentation	Butanol	✓	✓	TRL 3–4	R&D
					Acetone	✓	✓	TRL 3–4	R&D
					Bioethanol	✓	N/A	TRL 3–4	R&D
					Hydrogen	✓	N/A	TRL 3–4	R&D
(Ebrahimian et al. 2022a, b)	Laboratory Scale	BFMSW	Ethanol organosolv and Enzymatic hydrolysis	Acetone-butanol-ethanol (ABE) fermentation	Hydrogen	✓	N/A	TRL 3–4	R&D
					2,3-Butanediol	✓	✓	TRL 3–4	R&D
					Acetone	✓	✓	TRL 3–4	R&D
					Butanol	✓	✓	TRL 3–4	R&D

Table 3 (continued)

Reference	Scale	Input	Pretreatment	Conversion technology (process)	Main product(s)	Value-added product[1]	High-value-added product[1]	Technology Readiness Level (scale of maturity)	Technology Readiness Stage
					Bioethanol	✓	N/A	TRL 3–4	R&D
				AD	Methane	✓	N/A	TRL 9	Commercially Established
(Gianico et al. 2021)	Laboratory Scale	FW	Thermal	AD					
					Methane	✓	N/A	TRL 9	Commercially Established
(Parmar & Ross 2019)	Laboratory Scale	Various types organic wastes	Thermal	AD	Methane	✓	N/A	TRL9	Commercially Established
(Mahmoodi et al. 2018)	Laboratory Scale	OFMSW	Hydrothermal	Ethanolic fermentation	Bioethanol	✓	N/A	TRL 7–9	Early Commercial Deployment
				AD	Methane	✓	N/A	TRL9	Commercially Established
(Salimi et al. 2021)	Laboratory Scale	FW	Dehydration Solid–liquid fat extraction–leaching and Enzymatic hydrolysis	Ethanolic fermentation	Bioethanol	✓	N/A	TRL 7–9	Early Commercial Deployment
				AD	Methane	✓	N/A	TRL9	Commercially Established
(Rossi et al. 2022a, b, c)	Pilot Scale	OFMSW	Physical and preservation	AD					
					Methane	✓	N/A	TRL9	Commercially Established
(Valentino et al. 2018)	Pilot Scale	OFMSW	Mechanical	AD	Methane	✓	N/A	TRL9	Commercially Established
(Papa et al. 2022)	Laboratory Scale	OFMSW	Biopulping						
				AD	Methane	✓	N/A	TRL9	Commercially Established
(Papa et al. 2020)	Laboratory Scale	OFMSW	Mechanical and mixing	AD	Methane	✓	N/A	TRL9	Commercially Established

N/A, not applicable; NS, not showed; BFMSW, biodegradable fraction of municipal solid waste; WAS, waste activated sludge; CEFW, rice straw cellulosic ethanol fermentation waste; MSWF, municipal solid waste derived fiber; R&D, research and development

[1] The classification was based on Budzianowski (2017)

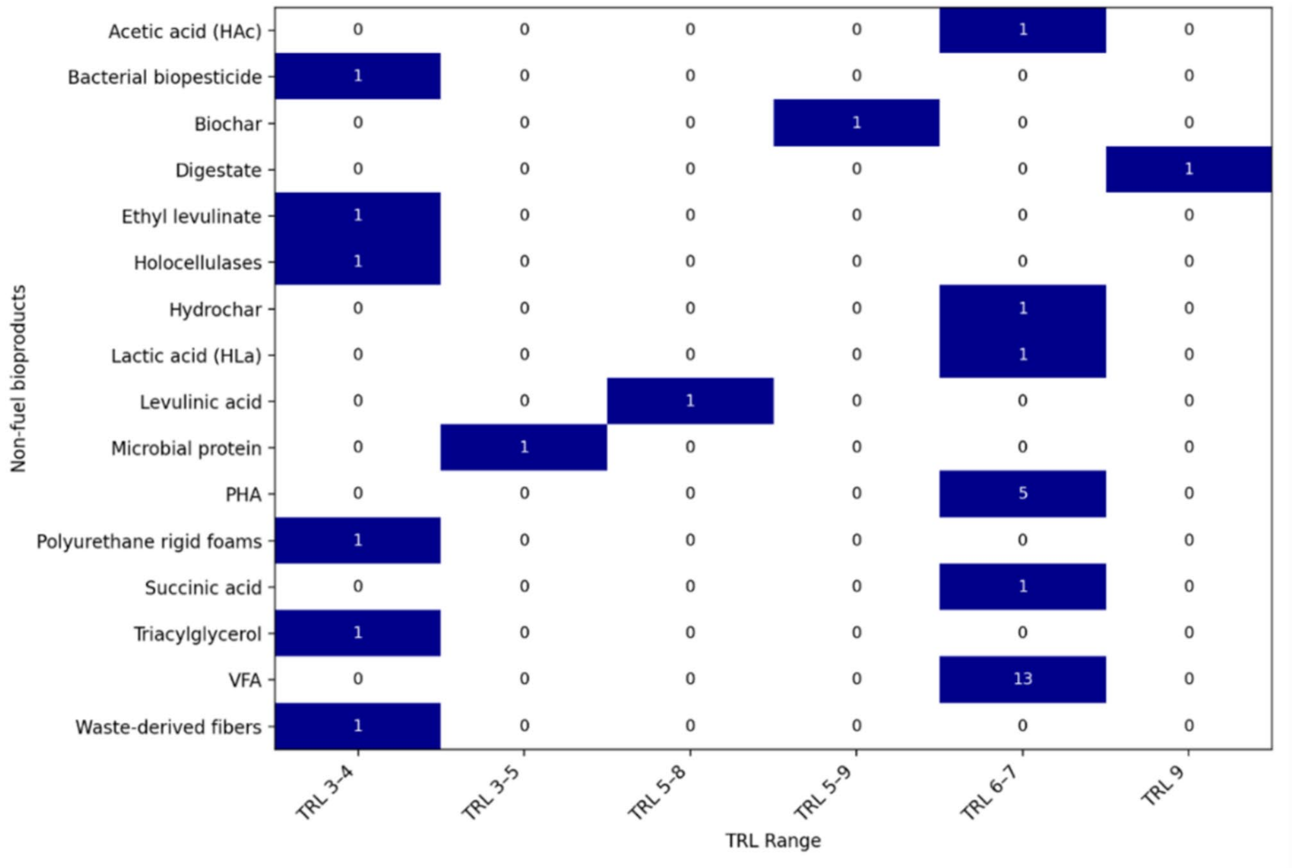
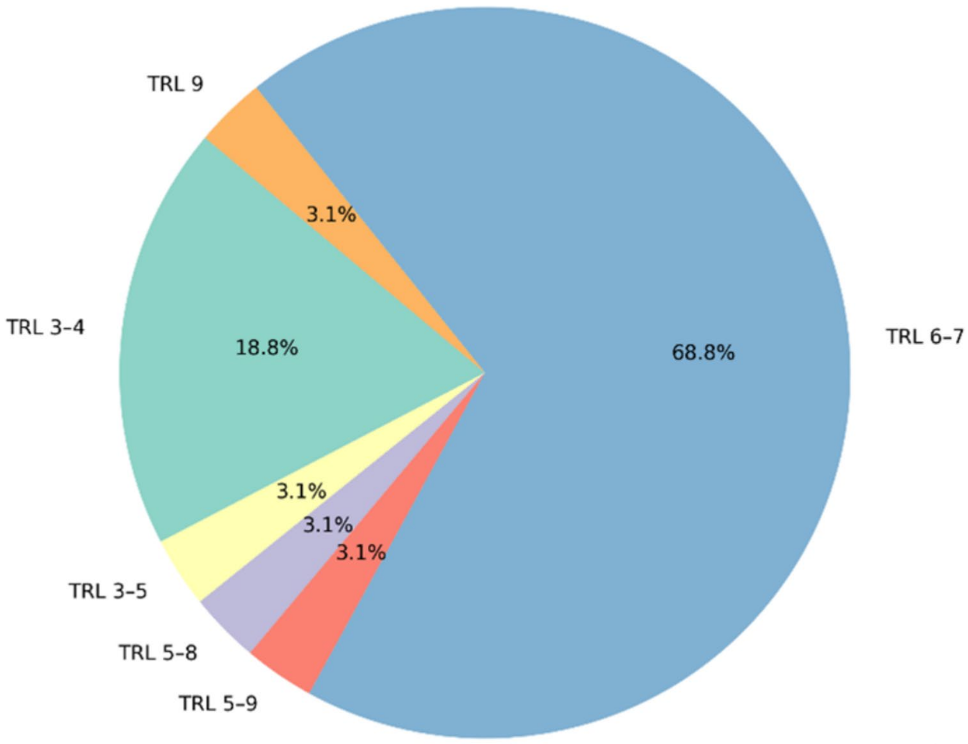


Fig. 5 Heatmap of non-fuel bioproduct occurrences across TRL ranges ($n=32$)

Fig. 6 Distribution (%) of non-fuel bioproducts from municipal biowaste according to TRL range ($n=32$)



TRL 3–4 (18.8%), with isolated cases in TRL 3–5, TRL 5–8, TRL 5–9, and TRL 9 (each 3.1%). Therefore, these results indicate that non-fuel bioproducts from municipal biowaste are predominantly positioned in developmental or pre-commercial stages, with only limited evidence of fully commercialized applications.

Biofuel conversion technology readiness Unlike non-fuel bioproduct conversion technologies, biofuel conversion technologies tend to be more advanced, with many reaching TRL 7–9 (Table 3). The results indicate that biofuel production processes from biowaste have achieved early commercial deployment and become commercially established. Hence, conversion technologies are often backed by pilot and demonstration projects that validate their performance in real-world applications.

The non-mature and mature TRL of biofuel conversion processes from various organic waste streams was studied more recently by Arias et al. (2024) and in the EU-focused assessment of advanced feedstocks and technologies by Cerruti et al. (2020). Both studies present relevant information; for instance, methane derived from several waste sources via AD is commercially established, achieving a TRL of 9. In contrast, other technologies, such as gasification to liquid fuels (TRL 6–7) and syngas fermentation (TRL 6–7), remain at lower levels of maturity. As to the most advanced biofuel (second-generation), including isobutanol to isobutene and glycerol tertiary butyl ether (GTBE), Kowalski et al. (2022) found that production technologies are still at earlier stages of development, primarily within prototype (TRL 4–5) and demonstration (TRL 6–7) levels. These findings underscore the complexities associated with transitioning from laboratory-scale innovations to commercially viable technologies.

For this study, advanced bioethanol production technologies were found to range from TRL 3–4 (non-ethanolic fermentation) to TRL 7–9 (classical ethanolic fermentation), typically representing demonstration prototypes that are not yet fully commercialized (Ebrahimian et al. 2022a, b; Mahmoodi et al. 2018; Moreno et al. 2021; Salimi et al. 2021). In contrast, AD, widely used for methane production, has reached TRL 9 due to its technological maturity (Allegue et al. 2020; Begum et al. 2016; Ebrahimian et al. 2022a, b; Gianico et al. 2021; Moreno et al. 2021; Papa et al. 2020, 2022; Parmar & Ross 2019; Salimi et al. 2021; Valentino et al. 2018). This high level of maturity is attributed to its proven effectiveness with a diverse range of biowastes, including organic waste fractions, industrial waste, sewage, manure sludge, energy crops, and crop residues (Brown et al. 2020).

Thermochemical conversion processes, such as pyrolysis, are widely used technologies demonstrated in industrially relevant environments, with TRL varying depending on the type of recovered biofuel (Okolie et al. 2022; Strzalka et al. 2017). Since the study by Agarwal et al. (2013) included in the systematic review is somewhat outdated, more recent studies offer updated perspectives: Al-Rumaihi et al. (2022) report that pyrolysis gas is currently positioned between TRL 2–6 (depending on feedstock), whereas pyrolysis oil (bio-oil) ranges from TRL 5–9. In addition, Hu et al. (2025) indicate that thermochemical conversion technologies more broadly remain in the intermediate range of TRL 6–7.

Other biological conversion processes, recognized as emerging technologies, include microbial pathways such as dark fermentation and photofermentation with purple phototrophic bacteria (PPB), which were classified by Dehghanimadvar et al. (2020) as early-stage processes (TRL 3–5) with limited technological maturity. In the research by Cesaro et al. (2020), the TRL was similarly considered within this range, with typical products including hydrogen. More recently, Chen et al. (2024) and Sun et al. (2024) demonstrated that other microbial pathways with selected microorganisms, including acetone–butanol–ethanol (ABE) fermentation from organic waste, are still conducted mainly in lab-scale bioreactors (TRL 3–4) to produce acetone, butanol, bioethanol, and 2,3-butanediol (Ebrahimian et al. 2022a, b).

In summary, this study identified 32 occurrences of biofuels derived from municipal biowaste. Figures 7 and 8 illustrate the distribution of these occurrences across TRL ranges. The heatmap (Fig. 7) shows that methane clearly dominates at TRL 9, representing a fully commercialized and mature technology, while other biofuels such as hydrogen, bioethanol, acetone, and butanol are mainly clustered at much lower TRL (3–4 and 3–5), reflecting their status as emerging or pilot-scale processes. Additional pathways such as pyrolysis gas, bio-oil, and 2,3-butanediol appear at early to intermediate TRL levels. The percentage distribution (Fig. 8) confirms that most occurrences are concentrated in TRL 9 (40.6%) and TRL 3–4 (37.5%), with smaller shares in TRL 7–9 (9.4%), TRL 3–5 (6.2%), and isolated cases in TRL 2–6 and TRL 5–9 (each 3.1%).

Technologies for biowaste pretreatment

Experimental studies frequently highlight thermal processes, often combined with other methods such as mechanical and enzymatic hydrolysis, as highly effective for breaking down complex materials. Meanwhile, techniques such as thermal hydrolysis and mechanical–thermal processes improve bioavailability, further boosting the efficiency of biowaste conversion during AD and fermentation (Ramos-Suarez et al. 2021).

Overall, the type of pretreatment applied to biowaste directly influences the midstream processing and the type of

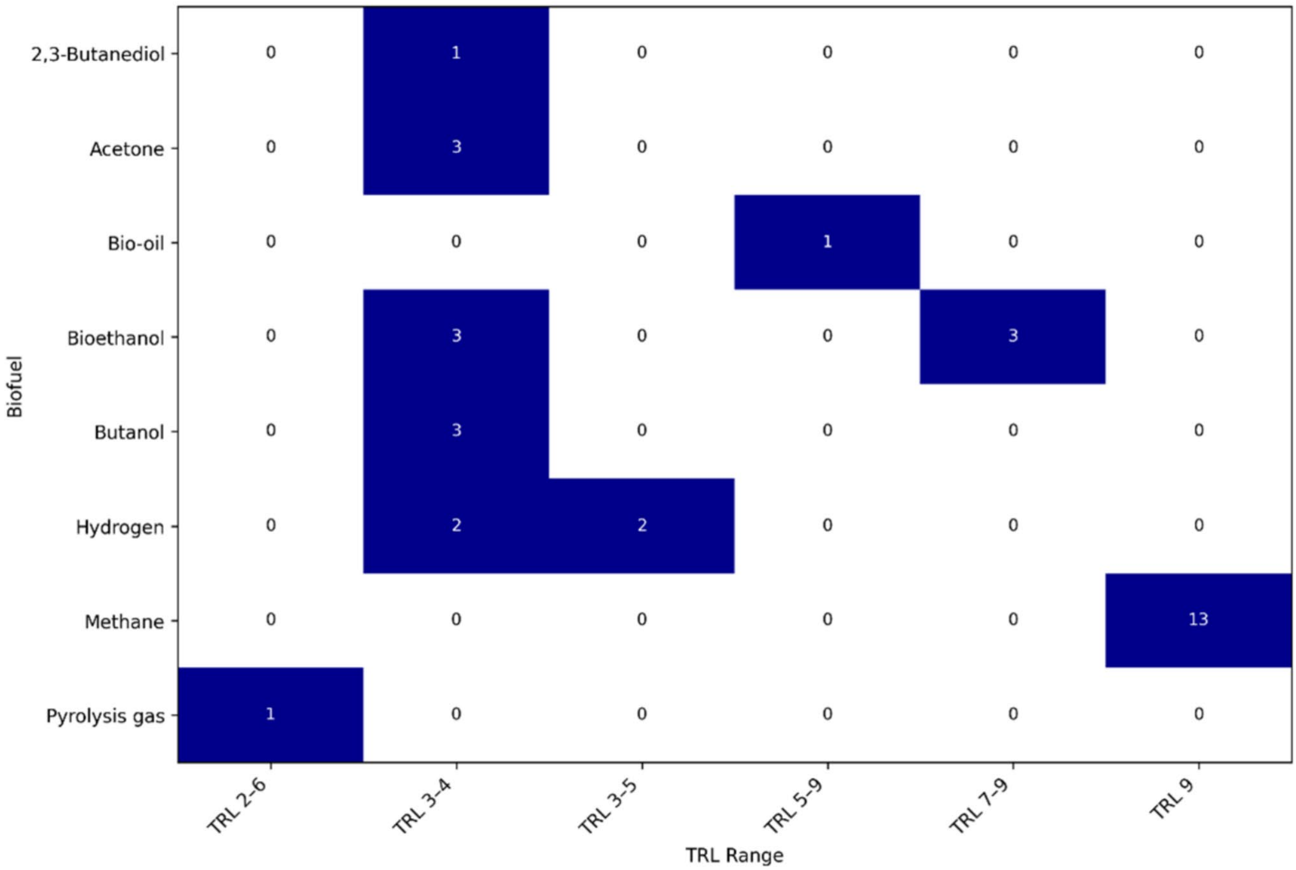


Fig. 7 Heatmap of biofuel occurrences across TRL ranges ($n = 32$)

bioproduct generated. Pretreatment methods such as thermal hydrolysis, enzymatic hydrolysis, and combined thermal-chemical treatments are particularly effective in maximizing the production of both biofuels (e.g., methane) and non-fuel bioproducts (e.g., VFA and succinic acid). Molina-Peñate et al. (2022) emphasize enzymatic hydrolysis as crucial for unlocking the potential of organic waste by fractioning structural components into functionalized molecules. This method has been successfully applied to enhance biogas yield during AD by accelerating the hydrolysis step, which is typically the rate-limiting phase before acidogenesis, acetogenesis, and methanogenesis. The relationships between pretreatments and output conversion underscore the importance of choosing suitable methods to enhance the content of targeted bioproducts (Strazzera et al. 2018).

Highlighting real-world commercial and non-commercial demonstration cases

Real-world commercial and non-commercial demonstration cases of municipal biowaste conversion technologies of industrial initiatives and demonstration projects are shown in Table 4. It underscores the heterogeneity of municipal biowaste conversion pathways and their varying TRL. These demonstration cases provide evidence that a few technologies have already advanced beyond the laboratory stage into pilot, demonstration, and even full-scale commercial implementation.

In total, 37 real-world projects and companies implementing municipal biowaste valorization technologies were mapped across TRL levels. The bubble chart (Fig. 9) illustrates the distribution of main products by TRL, showing that VFA and PHA/bioplastics dominate at intermediate maturity (TRL 6–7), while bioethanol, methane, and hydrochar reach higher maturity (TRL ≥ 8). Other products, such as fertilizers/biostimulants, SCP, and biosurfactants, appear at multiple stages but remain less frequent. The Sankey diagram (Fig. 10) provides a systems perspective, linking municipal biowaste inputs with conversion technologies, end-products, and TRL bands. The flows highlight the predominance of biological fermentation as the central pathway, particularly for VFA, PHA, and related products, while thermal and chemical approaches are mainly associated with biofuels and hydrochar at higher TRL. Together, these figures emphasize that although consolidated outputs such as methane, biofuels, and hydrochar are already commercialized, innovative

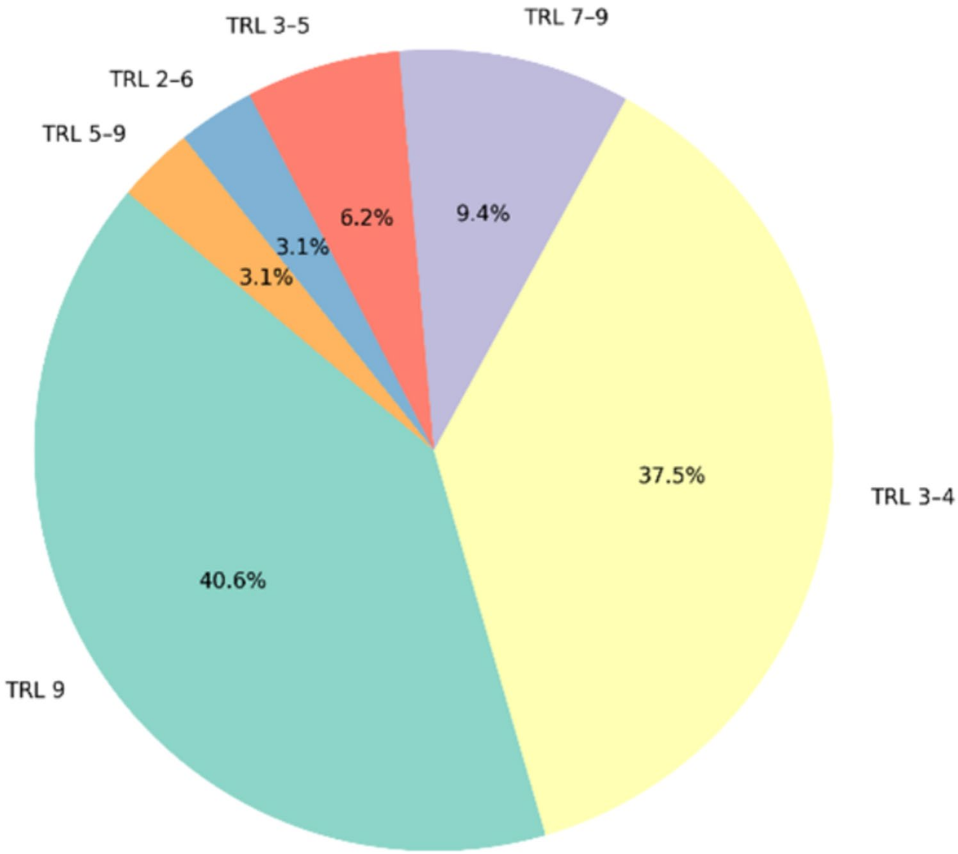


Fig. 8 Distribution (%) of biofuels from municipal biowaste ($n = 32$)

pathways for biopolymers, organic acids, and protein are emerging at pilot-to-demonstration scales, bridging the gap toward circular bioeconomy applications.

In a disaggregated manner, classical AD (e.g., Biogen in the UK, TRL 9; Circular Biocarbon/ Urbaser in Spain, TRL 8–9) is rightly recognized as a consolidated and fully commercialized route for energy and fertilizer recovery. However, it highlights a diversification trend toward innovative high-value products. Demonstration-scale projects such as LUCRA (TRL 7, bio-succinic acid), Waste2Func (TRL 7, biosurfactants and lactic acid), Afyren (TRL 7, VFA and organic acids), and ChainCraft (TRL 7–8, VFA) illustrate how second-generation biorefineries are establishing new market niches by exploiting fermentation platforms and downstream bioconversions. Similarly, YPACK, RES URBIS, SCALIBUR, Mango Materials, and Bio-on are pushing forward PHA-based bioplastics production from OFMSW, while initiatives like UniBio (TRL 8, single-cell proteins) and VALUEWASTE (TRL 8, insect and microbial protein) showcase protein recovery for feed applications, addressing to the food–feed–materials interface.

Thermochemical conversion is also entering the commercial landscape, as demonstrated by Ingelia, TerraNova Energy, and HTCycle, all operating hydrothermal carbonization plants at TRL 8–9 for hydrochar production as a soil amendment and energy carrier. Meanwhile, innovative transatlantic start-ups such as Capro-X (USA, TRL 5–6) and Mango Materials (USA, TRL 6) show the global relevance of medium-chain VFA and PHA routes derived from food and dairy waste.

Finally, a clear spectrum of readiness levels is showed from exploratory projects validating new microbial platforms (GoodByO, TRL 4–5) to consolidated industrial operators (Neste, TRL 9). This reinforces the need to position AD as a mature baseline technology, while shifting analytical emphasis toward emerging high-TRL processes that convert municipal biowaste into VFA, lactic acid, succinic acid, proteins, bioplastics, surfactants, and biopesticides. By integrating these industrial and demonstration cases, the review more effectively bridges laboratory research, such as the experimental studies discussed in the previous section, with real-world applications, including private sector biorefineries and emerging start-up projects.

Technology gap analysis from the laboratory to full scale

This section highlights relevant points for identifying the gaps between laboratory-scale research and industrial-scale applications.

Table 4 Real-world commercial and non-commercial demonstration cases of municipal biowaste conversion technologies

Companies/projects	Type of municipal biowaste treated	Conversion Technology	TRL	Main products	Location	Continent	Primary references and key underpinning sources
LUCRA	Urban organic food waste	Biological (fermentation) + electrochemical extraction	7	Bio-succinic acid	Gent, Belgium	Europe	LUCRA (2023)
LIFE EBP	MBW	Biological	5	Fertilizers, plant biostimulants, anti-pathogen agents, biopolymers to make plastics, surfactants to make detergents	Torino, Italia	Europe	LIFE EBP (2020)
Biogen	FW	Biological (AD)	9	Biogas, methane, biofertilizer and energy recovery	UK	Europe	Biogen (2005)
bioSOILUTIONS	Biowaste	Biological (Insect frass, Blood hydrolysate, N-struvite and K-struvite recovery)	6–7	Fertilizers	Spain and Belgium	Europe	BioSOILUTIONS (2023)
RES URBIS	Urban biowaste from households, restaurants, caterers and retail premises	Biological (acidogenic fermentation, microbial enrichment, PHA Production and PHA extraction)	4–6	PHA and related PHA-based bioplastics as well as ancillary productions: biosolvents and fibers (to be used for PHA bio-composites)	Italy and other European countries	Europe	RES Urbis (2017)
B-FERST	OFMSW and Food industry side streams	Multi-treatment (physical, chemical and biological)	6–7	Bio-based mineral fertilizers, organo-mineral fertilizers, fertilizers enhanced with microbial and non-microbial plant biostimulants	Madrid, Spain	Europe	B-FERST (2025)
GoodByO	Organic waste from the food processing industry and gas fermentation liquid effluent	Biological and chemical	4–5	Bio-hexanol, bio-octanoic acid and carotenoids & proteins	Genova, Italy	Europe	GOODBYO (2025)
YPACK	FW	Biological	6–7	PHA (bioplastics)	Spain	Europe	YPACK (2017)
VOLATILE	OFMSW	Biological (fermentation and microbial conversion)	5–6	PHA biopolymers, SCO, Omega-3 fatty acids and others	Spain	Europe	VOLATILE (2016)
Capro-X	Greek yogurt waste	Biological (fermentation)	5–6	Caproic acid (C6) and Caprylic acid (C8)	USA	North America	Holtzapple et al. (2022)
CIRCULAR BIOCARBON / URBASER	OFMSW	Biological (AD)	8–9	Methane, biofertilizer, microalgae biomass	Zaragoza, Spain	Europe	CIRCULAR BIOCARBON (2024a)

Table 4 (continued)

Companies/projects	Type of municipal biowaste treated	Conversion Technology	TRL	Main products	Location	Continent	Primary references and key underpinning sources
CIRCULAR BIOCARBON / CAP	OFMSW	Biological	7–9	Coatings, biodegradable materials, biofertilizer	Sesto San Giovanni, Italy	Europe	CIRCULAR BIOCARBON (2024b)
Waste2Func	OFMSW, FW	Biological (fermentation)	7	Biosurfactants, lactic acid	Ghent (Belgium), Israel	Europe / Asia	Waste2Func (2021)
Neste	OFMSW-derived oils, food waste lipids	Chemical / Thermal (hydrotreatment)	9	Biofuels	Finland	Europe	Neste (2025)
CAFIPLA	A mix of municipal biowaste, SS and others	Biological	6	Carboxylic acid production and fiber recovery	EU	Europe	CAFIPLA (2020)
PERCAL/PERSEO Biotechnology	OFMSW	Biological (fermentation)	7–8	Bioethanol, lactic acid, succinic acid and biosurfactants	Valencia, Spain	Europe	PERCAL (2017)
URBIOFIN / URBASER	OFMSW, UWWS	Biological (AD + fermentation)	7–8	Methane, biopolymer, biofertilizer, microalgae	Zaragoza, Spain	Europe	URBASER S.A, (2017; URBIOFIN (2017)
URBIOFIN / CLaMber	OFMSW	Biological (fermentation)	7	Biopolymer	Puertollano, Spain	Europe	Clamber (2017); URBIOFIN (2017)
DEEP PURPLE	OFMSW	Biological (multi-platform biorefinery)	6	biopolymers, cosmetics, biofertilizer	Spain and other countries	Europe / Mixed	DEEP Purple (2019)
Mango Materials	OFMSW and WWTP sludge	Biological (microbial synthesis of PHA)	6	PHA (bioplastics)	USA	North America	Mango Materials (2025)
Bio-on	OFMSW, WWTP sludge	Biological (microbial synthesis of PHA)	6	PHA (bioplastics)	Italy	Europe	Fabbri et al. (2018)
Normec OWS	OFMSW, FW	Biological (fermentation, microbial conversion)	7	VFA	Belgium	Europe	Fabbri et al. (2018; Normec OWS, (2025)
InnovEN	OFMSW	Biological	7	VFA	France	Europe	(Fabbri et al. (2018)
Twence	OFMSW, food waste	Biological fermentation, microbial conversion)	7	VFA	Netherlands	Europe	Fabbri et al. (2018; Twence (2025)
Afyren	OFMSW, FW	Biological (fermentation)	7	VFA, organic acids	France	Europe	AFYREN (Fabbri et al. 2018; Holtzapple et al. (2022; ; ; 2025)
UniBio	Biogas from AD of OFMSW	Biological (fermentation with methanotrophs)	8	SCP (animal feed)	Denmark	Europe	Suárez Valdés et al. (2024; Unibio (2025)
VALUEWASTE	OFMSW, AD digestate	Biological	8	SCP, insect protein	EU	Europe	Suárez Valdés et al. (2024; Valuewaste (2025)
SCALIBUR (PHA line)	OFMSW, other hydrolyzable biowaste	Biological (fermentation)	7	PHA (bioplastics)	EU	Europe	Pei et al. (2025; Suárez Valdés et al. (2024)
SCALIBUR (biopesticides line)	OFMSW, other hydrolyzable biowaste	Biological (fermentation)	6–7	Biopesticides	EU	Europe	SCALIBUR (2016; Suárez Valdés et al. (2024)
Greentech Innovators	Hydrolyzed OFMSW, biowaste streams	Biological (microalgae cultivation)	5–6	Microalgae biomass	Norway	Europe	Greentech Innovators (2025; Suárez Valdés et al. (2024)

Table 4 (continued)

Companies/projects	Type of municipal biowaste treated	Conversion Technology	TRL	Main products	Location	Continent	Primary references and key underpinning sources
WAYSTUP!	OFMSW, SCGs	Biological (fermentation)	7–8	PLA, ethanol, SCG-derived products	EU	Europe	Greentech Innovators (2025; Suárez Valdés et al. (2024)
ChainCraft	UWWS, OFMSW	Biological (acidogenic fermentation)	7–8	VFA	Netherlands	Europe	ChainCraft (2023; Suárez Valdés et al. (2024)
ADBioplastics	Fruit/vegetable waste, OFMSW	Biological (fermentation)	5–6	PLA	Spain	Europe	Suárez Valdés et al. (2024)
VAMOS	Fruit/vegetable waste, OFMSW	Biological (fermentation)	5–6	PLA, fibers	EU	Europe	Suárez Valdés et al. (2024; VAMOS (2025)
Ingelia	OFMSW, UWWS	Thermal (hydrothermal carbonization)	8–9	Hydrochar	Spain	Europe	INGELIA (2025; Suárez Valdés et al. (2024)
TerraNova Energy	OFMSW, UWWS	Thermal (hydrothermal carbonization)	8–9	Hydrochar	Germany	Europe	Suárez Valdés et al. (2024)
HTCycle	OFMSW, UWWS	Thermal (hydrothermal carbonization)	8–9	Hydrochar	Germany	Europe	Suárez Valdés et al. (2024)

MBW, municipal biowaste; SCO, single-cell oil; UWWS, urban wastewater sludge; SCGs, spent coffee grounds; PLA, polylactic acid

Gap 1: Advancing upscaling for downstream processes

To advance any technology toward industrialization, it is necessary to demonstrate its effectiveness in upscaling and to develop large-scale downstream processes. System complexity associated with biomass–solute separation and downstream processing is the main challenge in the commercialization of non-advanced technology (Keglevich 2016). In the biofuels sector, most advancements in biowaste valorization have concentrated on biogas upgrading and bioethanol production (Demichelis et al. 2020), as these remain the most extensively studied and widely implemented technologies. Nonetheless, there is a growing interest in the separation of valuable chemical building blocks. In this context, certain value-added bioproducts formed during midstream processes, such as VFA mixtures (non-separated acids), require a downstream processing stage for conversion into high-value chemicals (Asunis et al. 2022; Budzianowski 2017; Haddadi et al. 2018). In particular, the separation and purification of VFA require energy-intensive processes, which typically account for 60–80% of the total production costs (Wu et al. 2021). Additionally, chemical reagent consumption, negligible in laboratory settings, becomes crucial for economic feasibility in scaled-up processes (Castro-Fernandez et al. 2024; Liu et al. 2018).

Therefore, a comprehensive scale-up assessment is essential not only for validating the technical feasibility of the technology but also for optimizing the hotspots of economic and environmental areas, showing which characteristics could be optimized to provide an eco-friendly and competitive system for manufacturing bioproducts (Pinto et al. 2023). This assessment is crucial for advancing and scaling-up the biowaste conversion platform in biorefineries. Additionally, further research is needed to reduce costs and ensure the integration of all elements within the value chain (Holtzapple et al. 2022).

Gap 2: Cost of technology scaling-up for producing and commercialization of end-product

Efficient purification of end-products is critical, particularly for biofuels; it must meet compatibility requirements with existing fuel distribution networks and adhere to stringent quality standards. Integrated biorefineries must incorporate cost-effective utilization of co-products, such as heat and electricity, to enhance operational efficiency (Barampouti et al. 2019). Ultimately, the successful commercialization of these processes relies on favorable economics at every stage of the value chain, from biowaste to high-value products. Techno-economic analysis is essential for determining biomass-to-product yield, energy efficiency, and overall production value (Ahmed et al. 2023).

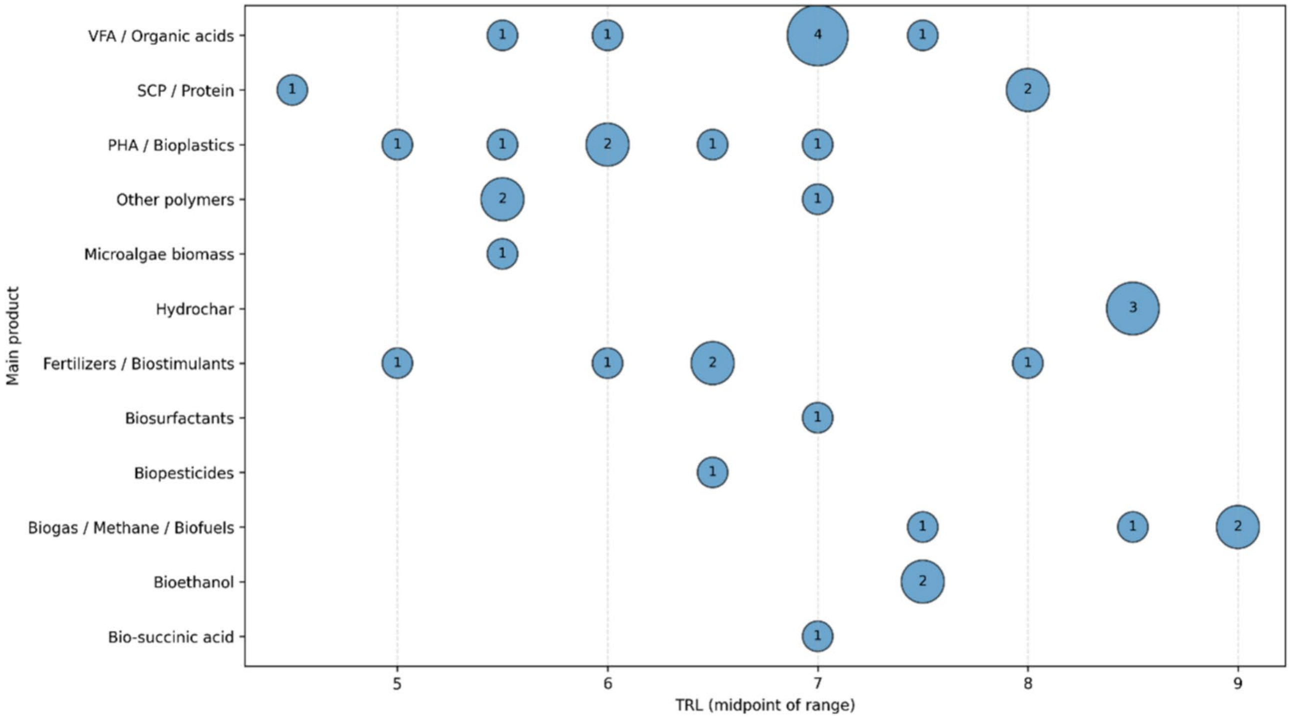


Fig. 9 Main products obtained from municipal biowaste across TRL. Bubble size represents the number of companies/projects

Manufacturing appeal must also be considered, including further requirements for efficiency, selectivity, mass transfer, and throughput rate. A techno-economic analysis on overall cost and profitability is essential to evaluate the optimum design, fixed capital investment, equipment service life, material and energy balance, transportation and logistics, and product sensitivity analysis (Xiong et al. 2019). In achieving this, understanding scale economies and applying the "0.6 rule" (Tribe & Alpine 1986) can provide essential insights. This rule allows for the estimation of cost implications as production scales up, where costs increase by a factor of 0.6 for each increase in equipment capacity. Such a model aids in estimating the economic feasibility of scaling-up biorefinery operations. With this approach, fixed costs are effectively spread across a larger production volume, helping to lower per-unit costs and enhance economic viability as biorefineries progress from laboratory to full-scale implementation.

Gap 3: Challenges in biowaste composition

The composition of municipal biowaste varies significantly depending on the collection area, regions of origin, or seasonal factors, which must be considered in scale-up designs to ensure a consistent and reliable feedstock supply (Barampouti et al. 2019). In most countries, municipal biowaste is predominantly composed of food waste (FW), which mainly includes lignocellulose, starch, lipids, and proteins, along with smaller amounts of extractives, vitamins, and pectin (Ebrahimian et al. 2023). This complexity and heterogeneity present significant challenges to the viability of processing FW in biorefineries (de Abreu et al. 2023). Traditional biorefineries typically operate with raw materials of low variability to maintain process stability. Herein, high variability in feedstocks can lead to the formation of undesired by-products, complicating downstream processing and reducing overall efficiency (Molina-Peñate et al. 2022).

Building on this, de Abreu et al. (2023) emphasized that the significant chemical variability of food waste (FW), influenced by waste type and region, poses a major challenge for its use in biorefineries. Their study analyzed 163 FW samples from five regions and four types of FW sources, revealing high variability, especially in carbohydrates, proteins, starch, and lipids, with coefficients of variation (CVs) exceeding 100% in some cases (e.g., supermarket waste). The study also noted that this high chemical variability of FW composition could lead to substantial reductions in biofuel yields, such as an 83% reduction in bioethanol production (Taheri et al. 2021) and a nearly 100% reduction in biodiesel production due to lipid variation (Phankosol et al. 2014). To address these challenges, the authors suggest that adaptable technologies and the integration of biofuels and value-added chemicals may help mitigate economic losses and improve the viability of FW-based biorefineries.

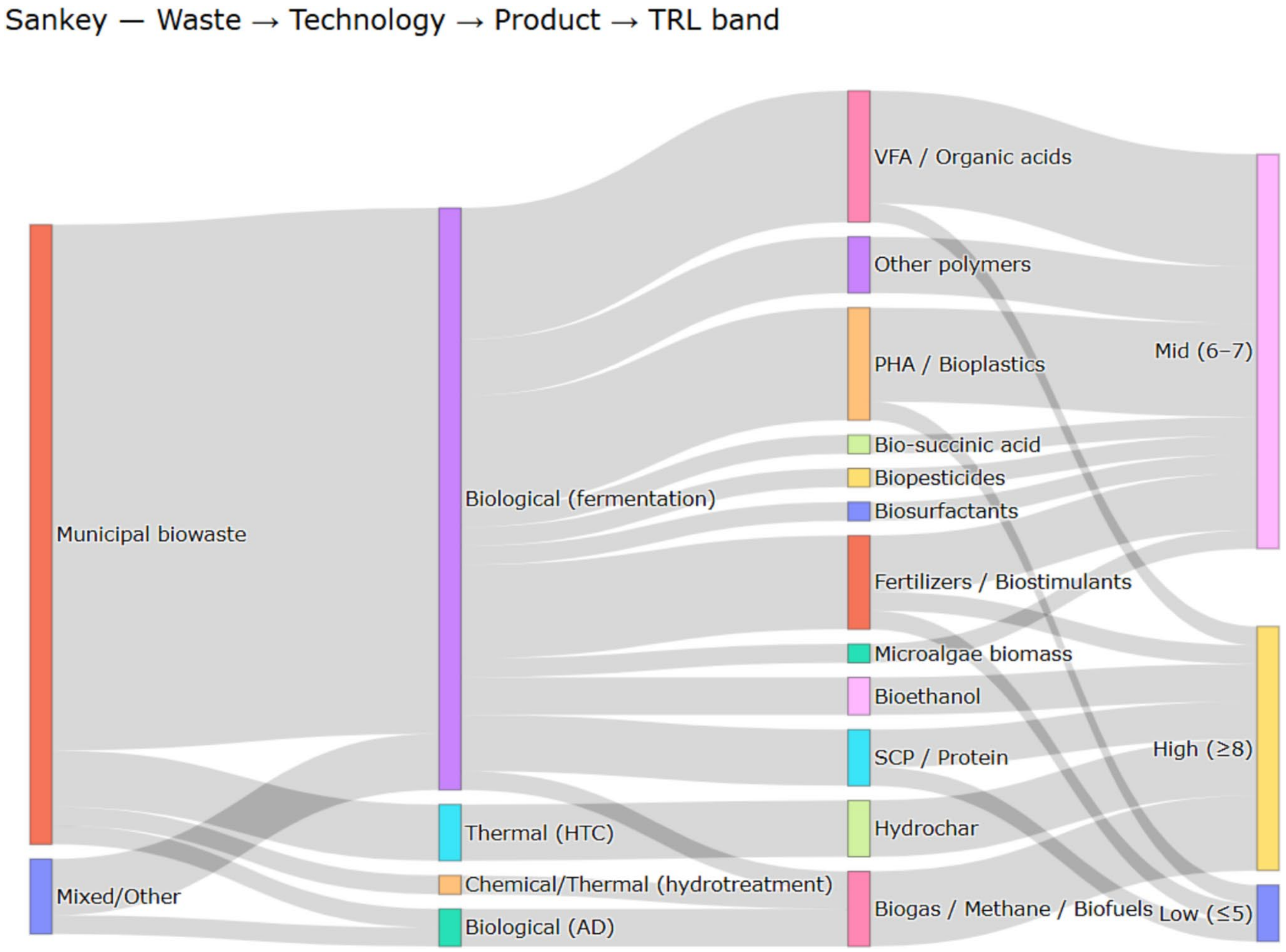


Fig. 10 Linking municipal biowaste inputs, conversion technologies, end-products, and TRL bands in real-world demonstration cases

Gap 4: Biowaste pretreatment techniques (upstream processes)

Various pretreatment techniques have been explored to enhance the conversion of municipal biowaste into value-added products, particularly in biofuel production. Pretreatment reduces substrate particle size, increases the concentration of soluble organic compounds, and decreases the levels of inhibitory chemicals that can harm digestion efficiency (Mishra et al. 2022). However, each pretreatment method comes with specific advantages and disadvantages that impact its scalability from laboratory to full-scale implementation (Lytras et al. 2021). A method that proves efficient to produce one type of biofuel may be less effective or even unsuitable for another.

According to reviewed studies by Ebrahimian et al. (2023), physical pretreatments such as mechanical size reduction are advantageous due to their minimal chemical requirements but can be energy-intensive, posing challenges at larger scales. Chemical pretreatments such as alkali addition and ozonolysis offer benefits like simple equipment and inhibitor-free processes, but issues such as high chemical costs and complex recovery processes can limit their economic feasibility (Jose et al. 2022). Physicochemical methods like steam explosion are promising due to low waste generation but may suffer from inhibitor formation like aliphatic acids (e.g., acetic acid, levulinic acid, formic acid), furan derivatives (e.g., 5-HMF, furfural), and phenolic compounds (e.g., vanillin, vanillic acid), as well as the need for precise temperature control, all of which increase operational costs and complicate scalability that complicates scaling (Tan et al. 2021; Yu et al. 2022). Biological pretreatments, including fungal and enzymatic methods, are energy-efficient and eco-friendly, but face challenges like slow processing rates and high enzyme costs. Therefore, transitioning these methods to full-scale operations necessitates to ensure sustainable and efficient production of value-added products thorough techno-economic assessments, integrating cost analysis, resource management, resource requirements, chemical usage, volume handling, and compatibility with downstream processes to ensure sustainable and efficient production of value-added products (Biswas et al. 2015).

In this context, Brémond et al. (2018) classified various biological pretreatments based on their TRLs. Enzymatic pretreatment, while considered a mature technology, remains limited to a TRL of 7–8 due to the high costs associated with scaling-up. Conversely, aerobic pretreatment processes, despite being demonstrated in some full-scale applications, have a lower TRL of 4–6, indicating they are still in developmental stages.

Gap 5: Biowaste conversion TRL of midstream process

According to the findings of this review, the TRL of biowaste conversion processes (midstream process) into non-fuel bioproducts and biofuels presents a significant challenge in bridging the gap between laboratory-scale research and full-scale industrial application. Although many midstream technologies show potential at laboratory (TRL3–TRL4) or pilot scales (TRL5–TRL7), advancing to higher TRL levels demands thorough validation to confirm technical robustness, economic viability, and environmental sustainability. This gap highlights the importance of comprehensive evaluations that assess not only process performance but also integration with upstream and downstream operations, along with the scalability of equipment and resource requirements. In this regard, an insightful report by Lindorfer et al. (2019) on biorefinery concepts provides a summary of various biorefinery systems under development, detailing their progress according to their Technology Readiness Level (TRL), ranging from 1 to 9. The report highlights the positioning of municipal biowaste in both green biorefineries (TRL5–TRL7) and lignocellulosic biorefineries (TRL5–TRL8), based on the specific characteristics of the waste streams involved (Duque et al. 2021).

Based on the above, addressing this challenge involves optimizing process efficiency and developing adaptable technological solutions that can be consistently implemented at larger scales, thereby supporting the sustainable and economically feasible production of value-added products from biowaste conversion.

Conclusions

This review successfully achieved its main goal of addressing the gap between laboratory-scale and full-scale implementation for converting municipal biowaste into value-added products within the circular bioeconomy. It explored the state-of-the-art theoretical frameworks, analyzed key insights from existing literature on biowaste conversion, and examined barriers to upscaling emerging technologies, focusing on TRL from a global perspective. The content analysis revealed prominent research topics including food waste, biorefineries, VFA, biofuels, MSW, and the OFMSW, highlighting areas for future study.

Case studies provided valuable insights, with a notable focus on optimizing biorefinery processes. However, there are limited real-world applications for implementing full-scale industrial operations for municipal biowaste conversion to value-added products, with examples such as a large-scale industrial AD plant in Italy for biogas, and a pilot plant in Brazil producing biodiesel, biogas, and compost from organic waste. Studies in some European countries evaluated wet and dry digestion configurations for MSW, examining various technological setups. Sustainability assessments were critical in evaluating social, environmental, and economic impacts, offering a holistic view of biorefinery integration.

Experimental studies showed a growing interest in diverse technologies for converting biowaste into both biofuel and non-biofuel products, with anaerobic conversion emerging as the most commonly employed technology. Midstream technologies show potential between laboratory (TRL3–TRL4) and pilot scales (TRL5–TRL7), a region known as “The Valley of Death” of technologies and, therefore, significant challenges remain for scaling these technologies to full-scale applications. Five major technology gaps were identified for scaling biowaste conversion from lab to full-scale implementation. The primary challenges include upscaling downstream processes, where biowaste conversion for high-value products requires intensive separation processes. Scaling-up technology economically requires a thorough techno-economic analysis to evaluate production costs, energy requirements, and logistics. Municipal biowaste's composition variability adds complexity to ensuring consistent feedstock for large-scale processes. Pretreatment techniques, critical in biofuel production, also face scale-up barriers due to cost and efficiency considerations. Lastly, the midstream processes’ TRL levels remain low, indicating that most technologies have yet to reach a stage in which they are industrially viable.

For future research, further studies should focus on optimizing biowaste processing at industrial scales, particularly through improved separation, purification, and pretreatment methods. Comprehensive techno-economic assessments will be essential to support large-scale implementation, alongside exploring novel technologies that enhance process efficiency, reduce operational costs, and increase product quality. By addressing these critical gaps, our findings contribute to making municipal biowaste conversion in biorefineries sustainable and feasible within the Global South. This supports the implementation of a circular bioeconomy as a pathway to achieving the United Nations Sustainable Development Goals.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10098-026-03419-6.

Acknowledgements This work was supported by the National Council for Scientific and Technological Development (CNPq) [grant number 140706/2024-0] and the São Paulo Research Foundation (FAPESP) [grant numbers 2024/09865-9 and 2022/10615-1].

Author contributions JMAC involved in writing—review and editing, writing—original draft, methodology, investigation, conceptualization. TKK took part in writing—original draft, methodology, investigation, conceptualization. GHDO took part in writing—review and editing, supervision, conceptualization. LTF took part in writing—review and editing, supervision, conceptualization. JFCA involved in writing—original draft, investigation, conceptualization. ARO took part in writing—review and editing, supervision, conceptualization.

Funding The Article Processing Charge (APC) for the publication of this research was funded by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) (ROR identifier: 00x0ma614).

Data availability No datasets were generated or analyzed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

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