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Research Trends in Valorization of Waste Glycerol-derived from Biodiesel: A Bibliometric Perspective (2017-2024)

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Abstract: This bibliometric analysis investigates global research trends in glycerol waste utilization, spanning 2017 to 2024, leveraging Scopus data and VOSviewer software for comprehensive insights. Driven by the dual imperatives of environmental concerns and economic potential, research on this biodeisel byproduct has witnessed significant growth. This surge peaked in 2023, followed by a slight decline potentially attributable to external factors like the COVID-19 pandemic and shifts in global research priorities. The analysis reveals a geographically diverse research landscape, with China, India, Brazil, and Malaysia emerge as leading contributors, highlighting widespread global interest. Key research themes indentified include biofuel production, enzymatic conversion, and the development of novel catalyst for glycerol transformation. This themes highlight the interdisciplinary nature of the field, drawing upon expertise from biotechnology, chemical engineering and materials science. The analysis identifies critical research gaps and emphasizes the need for continued research, international collaboration, and strategic funding to optimize glycerol waste utilization processes. By illuminating current trends and future directions in glycerol waste valorization, this study provides valuable insights for researchers, policymarkers, and industry stakeholders invested in environmental sustainability, economic development, and global resource management.

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1. Introduction

The utilisation of glycerol waste, a byproduct of biodiesel production, has emerged as a critical area of research and development, driven by its potential to yield valuable products across various industries [1]. Glycerol, also known as glycerin or glycerine, a trihydroxy sugar alcohol, possesses unique properties such as high viscosity, solubility in water, and non-toxicity, making it a versatile feedstock for the synthesis of numerous value-added products [2–4]. One promising avenue is the conversion of glycerol into biofuels, such as hydrogen and methane, through microbial fermentation or thermochemical processes [2,5–7]. These biofuels offer sustainable alternatives to fossil fuels and contribute to reducing greenhouse gas emissions, thereby addressing environmental concerns associated with glycerol disposal [5].

Moreover, glycerol can be transformed into high-value chemicals and materials, including pharmaceuticals, cosmetics, and polymers, through various catalytic and chemical conversion routes [8]. For instance, glycerol can serve as a precursor for producing epichlorohydrin, a key intermediate in synthesising epoxy resins, which are widely used in coatings, adhesives, and electronic materials [9]. Additionally, glycerol-derived polyols have shown promise in developing biodegradable plastics, offering sustainable alternatives to conventional petroleum-based polymers [10–12]. These advancements add value to glycerol waste and contribute to the circular economy by promoting resource efficiency and waste reduction [7].

Furthermore, using glycerol waste presents economic opportunities for biodiesel producers and industries seeking sustainable feedstocks [13,14]. By integrating glycerol valorisation processes into existing biodiesel production facilities, companies can enhance their profitability and competitiveness while reducing waste management costs and environmental footprint [15]. Additionally, government incentives and policies promoting bio-based industries and renewable energy further incentivise developing and adopting glycerol-based technologies. Overall, glycerol waste utilization aligns with United Nations Sustainable Development Goal 7 (SDG 7) - Affordable and Clean Energy, by contributing to renewable energy sources and fostering a transition towards a circular and bio-based economy, thus promoting environmental sustainability and economic viability.

Understanding the evolution and trajectory of research in glycerol waste valorization is crucial for guiding future innovation and investment. Bibliometric analysis offers a powerful tool to map the research landscape, identify emerging trends, and highlight knowledge gaps. This paper presents a comprehensive bibliometric analysis of glycerol waste utilization, examining publication trends, key research themes, influential authors, and leading research institutions. By providing a data-driven perspective on this rapidly evolving field, this study aims to inform researchers, policymakers, and industry stakeholders, fostering collaboration and strategic decision-making towards a more sustainable and circular bioeconomy.

2. Literature Review

Glycerol is abundantly produced as a primary byproduct during biodiesel synthesis through the transesterification of oils [16–18]. The resulting crude glycerol contains impurities like alcohol, catalysts, soaps, and metals, necessitating purification for generating usable glycerol [19]. This need for volarization has spurred extensive research into converting both crude and purified glycerol into various value-added chemicals, with a particular focus on fuel additives.

For instande, glycerol etherification into fuel additives using heterogeneous catalysts has been widely explored. Gonçalves et al. [20] treated coffee ground-derived black carbon with acids to impart sulfonic groups, using it to catalyse glycerol etherification with tert-butyl alcohol. High yields of mono-tert-butyl glycerol and di-tert-butyl glycerol demonstrated its viability as an Amberlyst-15 substitute. Kaya Ekinci and Oktar [21] esterified crude glycerol over MCM-41 supported tungstated and zirconated catalysts to produce triacetin. Brønsted and Lewis acid sites promoted esterification with high conversion and selectivity.

The biological valorisation of crude glycerol into cellular metabolites and enzymes has also been investigated. For example, André et al. [22] grew two white-rot fungal strains on glycerol to accumulate single-cell oil and biomass. Similarly, Magdouli et al. [23] cultured *Yarrowia lipolytica* on crude glycerol and crustacean waste, showing enhanced lipase production while accumulating 35 % w/w lipids through olive oil fortification. This approach highlights the possibility of utilizing crude glycerol for both enzyme production and waste valorization. Further exploring its potential in bioconversion, Fountoulakis and Manios [24] co-digested crude glycerol with organic solid waste and agro-industrial byproducts in anaerobic reactors, increasing methane production compared to glycerol-free cultures.

Moving beyond biological methods, chemical conversion of glycerol into various high-value derivatives has been widely attempted. Dibenedettoa et al. [25] reduced CO_2 into formic acid using glycerol as a hydrogen source in the presence of $RuCl_2(PPh_3)^3$ catalyst, generating glycolic acid as an intermediate. In other study, Yang et al. [26] demostrated the use of glycerol as a reagent in fast-pyrolysed forestry waste,leading to improved methanol yields by promoting depolymerisation reactions. Furthermore, glycerols versatality is evident in its efficient electrochemical conversion into tartronic acid with 95% selectivity [27]. This example showcases the possibility of using electrochemical methods for glycerol valorization.

Continuing with chemical transformations, glycerol can be directly converted into epichlorohydrin, a valueable chemical intermediate, through two-step process involving dichloropropanol synthesis by chlorination and subsequently base-catalysed cyclisation with 98% cumulative yield [9]. Additionally, researchers have explored the synthesis of glycerol carbonate, another useful platform chemical, from glycerol and dimethyl carbonate using heterogeneous catalysts [28,29].

Beyond these chemical transformations, crude glycerol also holds significant potential for biological conversion into value-added products, such as poly-ε-lysine, biosurfactants and flavour compounds. For instance, a halotolerant *Streptomyces albulus* strain efficiently produced 0.1 g poly-ε-lysine per g biomass using crude glycerol as the sole carbon source [30]. In another example, enriched microbial consortia converted crude glycerol into 1,3-propanediol through anaerobic fermentation [31].

Expanding on its applications, glycerol has also been investigated as a hydrogen source for transfer hydrogenation reactions to produce amines, further chowcasing its versatility as a chemical feedstock [32]. Moreover, Miyuranga et al. [33] using purified crude glycerol for biodiesel production by reacting it with waste cooking oil via glycerolysis, effectively converting free fatty acids into triglycerides.

Therefore, waste crude glycerol holds tremendous scope for biological and chemical conversion into commercially relevant value-added products. Sustainable processes integrating crude glycerol remediation with its valorisation can be designed to fully utilise this biodiesel byproduct.

3. Data collection and methadology

Bibliometrics involves collecting, organising, and analysing bibliographic data from scientific publications [34–36]. The study includes fundamental descriptive statistics, including publishing journals, publication year, main author classification, and advanced approaches such as document co-citation analysis. In order to conduct a successful literature review, one must engage in an iterative process that includes identifying relevant keywords, conducting a literature search, and performing a thorough analysis to develop a comprehensive bibliography and obtain reliable results [37]. The study aimed to focus on top-tier papers to provide valuable insights into the theoretical perspectives influencing the development of the research field. The study ensured the reliability of the data by utilising the SCOPUS database for collecting data [38–40]. Scopus of Elsevier, renowned for its comprehensive coverage, gathered publications from 2017 to February 2024 for study.

3.1 Data search strategy

The study began with a screening process to identify relevant search terms for article retrieval, initiating the search in the Scopus database, resulting in the assembly of 2525 articles. Subsequently, the query string was refined to focus specifically on the utilisation of glycerol waste into value-added products, resulting in a final search string, detailed in Table 1, which yielded 1526 articles for bibliometric analysis. Exclusion criteria outlined in Table 2 were applied during this refinement process. As of February 2024, all articles about glycerol waste utilisation into value-added products from the Scopus database were included in the study.

Table 1 - The search string used for identifying relevant literature on glycerol volarization

Scopus	TITLE-ABS-KEY ((glycerol OR glycerin OR glycerine) AND waste AND (value* OR valor* OR product OR precursor)) AND PUBYEAR > 2016 AND PUBYEAR < 2025

Table 2 - The selection criterion applied to literature search results on glycerol volarization

Criterion	Inclusion	Exclusion
Timeline	2017 – 2024	< 2017

3.2 Analysis

VOSviewer is a bibliometric software initially developed by Nees Jan van Eck and Ludo Waltman at Leiden University in the Netherlands. It is notable for its user-friendly interface and outstanding capabilities in visualising and analysing scientific literature [41,42]. Renowned for its intuitive network visualisations, clustering capabilities, and density mapping features, VOSviewer provides researchers with a comprehensive toolkit for navigating complex research landscapes. The interactive interface of the software allows for efficient exploration of enormous datasets, with regular updates to keep it dynamic and adaptable to changing research needs. Versatile in its functionality, VOSviewer can calculate metrics, customise visualisations, and seamlessly integrate various bibliometric data sources, making it an invaluable resource for researchers looking to gain deeper insights into their research areas.

The strength of VOSviewer lies in its ability to translate complex bibliometric datasets into visually comprehensible maps and charts, specifically emphasising network visualisation [42]. By employing robust clustering algorithms and analysing patterns of keyword co-occurrence, the software enables researchers to effortlessly extract meaningful insights from intricate datasets. Its user-friendly interface caters to both novice and experienced users, ensuring accessibility and efficiency in navigating research landscapes. Furthermore, ongoing of VOSviewer enhancements underscore its dedication to remaining at the forefront of bibliometric analysis, providing researchers with unparalleled capabilities in metrics computation and customisation of visualisations. With its capacity to accommodate various types of bibliometric data, including co-authorship and citation networks, VOSviewer emerges as an essential tool for scholars seeking deeper comprehension and actionable insights within their respective research domains.

The publication datasets spanning from 2017 to February 2024 were extracted from the Scopus database to conduct the analysis and processed in PlainText format. Subsequently, VOSviewer software version 1.6.19 was employed to analyse these datasets, utilising clustering and mapping techniques to create visual representations of the research landscape. Setting itself apart from conventional Multidimensional Scaling (MDS) approaches, VOSviewer focuses on positioning items within low-dimensional spaces, ensuring their proximity accurately reflects their relatedness and similarity [42]. While sharing similar objectives with MDS, VOSviewer diverges in its methodology by employing alternative normalisation techniques for co-occurrence frequencies, such as association strength (a_{ij}), which is computed to gauge the strength of association between the concepts *i* and *j* is defined as [43]:

$$a_{ij} = \frac{mc_{ij}}{c_{ii}c_{jj}}$$

Where c_{ij} is the number of items in which the concepts *i* and *j* both occur, c_{ii} is the number of items in which *i* occurs, and *m* is the total number of items. The association strength of two concepts can be interpreted as the ratio between the co-occurrence frequency of the concepts and the expected co-occurrence frequency of the concepts obtained under the assumption that occurrences of the concepts are statistically independent. Hence, with the help of this index, the VOSviewer places items in the form of a map after reducing the weighted sum of the squared distances between all item pairs. Following the methodology outlined by Appio et al. [44], the LinLog/modularity normalisation technique was applied to enhance the accuracy of the analysis. Through visualisation of VOSviewer capabilities, mathematical patterns within the dataset were elucidated, enabling in-depth analyses, including keyword co-occurrence, citation analysis, and co-citation analysis.

Keyword co-occurrence analysis, as highlighted by Zhao [45], offers a robust method for investigating the evolution of research areas over time and identifying prevalent topics across various fields [46]. In parallel, citation analysis serves as a valuable tool for discerning pivotal research themes, trends, and methodologies while also providing insights into the historical context of a primary areas discipline of interest [47]. Additionally, document co-citation analysis, a commonly employed bibliometric technique [37,44,48], leverages network theory to map the interconnected structure of data, thereby revealing pertinent relationships and structures within the scholarly landscape [48].

4. Result

4.1 Number of publications from 2017 to 2024

Figure 1 shows the number of publications regarding glycerol waste utilisation as a value-added product over the years 2017 to 2024 that was extracted from Scopus Analyzer. It reveals a fluctuating trend over the specified timeframe. From 2017 to 2023, there has been an increase in publications, peaking at 285 publications in 2023. This growth likely reflects heightened interest and technological advancements for converting glycerol waste into valuable products during this period. However, a subsequent decline in publications was observed in 2020. These fluctuations could be influenced by factors such as the impact of COVID-19 on the entire world, shifts in research priorities, changes in funding availability, and advancements in related fields, highlighting the dynamic nature of research in this area.

Looking ahead, the implications of these trends suggest the need for strategic focus and diversification in research efforts. Future directions should prioritise sustainability and efficiency in glycerol waste utilisation processes, aiming to optimise conversion technologies while minimising environmental impact. Interdisciplinary collaboration across fields such as chemistry, engineering, and biotechnology will drive innovation and address complex challenges. Embracing a multidisciplinary approach can foster breakthroughs and accelerate the development of sustainable solutions, ensuring the continued advancement of glycerol waste utilisation as a viable pathway towards resource recovery and environmental stewardship.

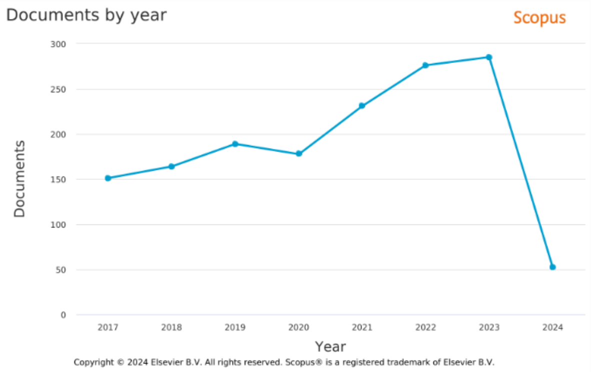

Fig. 1 The graph of the number of publications for the year 2017 to 2024.

4.2 Top of countries by the number of publication

The publication trends across the top 10 countries in glycerol waste utilisation research from 2017 to 2024 extracted from Scopus Analyzer are depicted in Figure 2. China emerges as the leading contributor, with a significant output of 195 publications. This dominance is likely linked to its rapidly growing industrial sector and government initiatives promoting sustainable development. India follows closely with 183 publications, reflecting its focus on waste management and a growing biofuel industry. Brazil, with 155 publications, demonstrates a strong commitment to bio-based solutions, potentially driven by its large-scale biofuel production from sugarcane.

While their publication numbers are lower than the top three, countries like the United States, Indonesia, Spain, Italy, Poland, and the United Kingdom underscore the global interest and diverse geographic distribution of research efforts in this area. The United States, with 93 publications, reflects its longstanding leadership in scientific research and innovation. Interestingly, countries like Indonesia and Poland are showing a marked increase in publications over the years, suggesting emerging reasearch hubs in glycerol waste utilization.

The distribution of publications across these countries suggests opportunities for international collaboration and knowledge exchange to address common challenges and accelerate progress in glycerol waste utilisation. Collaborative efforts could leverage complementary expertise, resources, and infrastructure to develop innovative solutions, overcome barriers, and maximise the impact of research outcomes. Overall, the findings underscore the global significance of glycerol waste utilisation as a research area and highlight the potential for international collaboration to drive advancements in sustainable waste management and resource recovery.

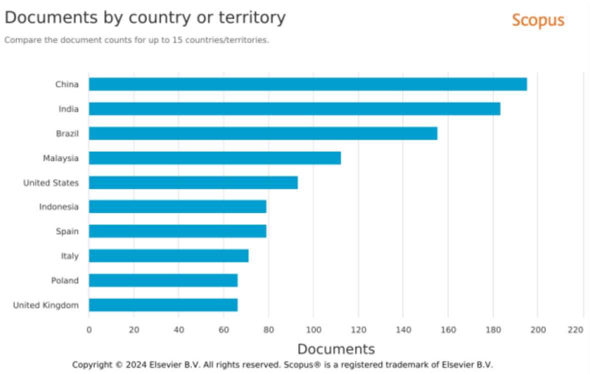

Fig. 2 The graph of number of publications by top 10 country

4.3 Top affiliation and funding

Table 3 and 4 show the top 10 affiliations and top 10 funding sponsors for glycerol waste utilisation into value-added products extracted from Scopus Analyzer. This table provides valuable insights into this field for global research landscape and funding. Firstly, the most prolific affiliations include renowned institutions such as Universidade de São Paulo, Chinese Academy of Sciences, and Universidade Federal do Rio de Janeiro, indicating a diverse international collaboration in glycerol waste research. This diversity of affiliations highlights the interdisciplinary nature of research efforts, with contributions from academia, research institutes, and governmental organisations, underscoring the collaborative approach towards addressing complex waste valorisation and resource recovery challenges.

Moreover, the top funding sponsors include prestigious funding agencies such as the National Natural Science Foundation of China, Conselho Nacional de Desenvolvimento Científico e Tecnológico, and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior. The significant investment by these funding sponsors reflects the strategic prioritisation of research in glycerol waste utilisation, emphasising the importance of advancing knowledge, technology, and innovation in sustainable waste management practices. The involvement of international funding sources such as the European Commission and Horizon 2020 Framework Programme further highlights the global recognition of glycerol waste as a critical research area with implications for environmental sustainability and economic development.

Table 3 – Top 10 funding sponsors for glycerol waste utilisation into value-added products extracted from Scopus Analyzer

Affiliation	Number of publications	Percentage (%)
Universidade de São Paulo	28	1.83
Chinese Academy of Sciences	22	1.44
Universidade Federal do Rio de Janeiro	20	1.31
Universiti Teknologi PETRONAS	18	1.18
Ministry of Education of the People's Republic of China	18	1.18
Academy of Scientific and Innovative Research AcSIR	17	1.11
Universiti Sains Malaysia	16	1.05
Universidade Estadual Paulista Júlio de Mesquita Filho	15	0.98
Centre Eau Terre Environnement	15	0.98
University of Chinese Academy of Sciences	14	0.92

The alignment between top affiliations and funding sponsors underscores the synergy between research institutions and funding agencies in driving impactful research outcomes. Collaborative efforts between academia, industry, and government entities facilitate the translation of research findings into practical applications, contributing to the development of sustainable solutions for glycerol waste utilisation. Overall, the findings highlight the collective commitment towards addressing global challenges related to waste management and resource scarcity, emphasising the importance of collaborative research, interdisciplinary collaboration, and strategic funding support in advancing knowledge and innovation in glycerol waste valorisation.

Table 4 – Top 10 funding sponsors for glycerol waste utilisation into value-added products extracted from Scopus Analyzer

Funding Sponsor	Number of publications	Percentage (%)
National Natural Science Foundation of China	99	6.5
Conselho Nacional de Desenvolvimento Científico e Tecnológico	88	5.8
Coordenação de Aperfeiçoamento de Pessoal de Nível Superior	85	5.6
European Regional Development Fund	56	3.7
European Commission	35	2.3
Fundação de Amparo à Pesquisa do Estado de São Paulo	32	2.1
Fundação para a Ciência e a Tecnologia	32	2.1
Horizon 2020 Framework Programme	25	1.6
National Key Research and Development Program of China	25	1.6
Natural Sciences and Engineering Research Council of Canada	24	1.6

4.4 Top 10 authors in the field

Figure 3 shows the publication trends across the top 10 authors in glycerol waste utilisation research from 2017 to 2024 extracted from Scopus Analyzer. Pandey, A. emerges as the most prolific author in the field, with ten publications suggesting a significant contribution to advancing knowledge in glycerol waste utilisation. The author consistent output may indicate specialised expertise or leadership in specific aspects of glycerol waste research, potentially making their work highly influential within the academic community.

The distribution of publications among other authors such as Brar, S.K., Makris, D.P., and Papanikolaou, S., all with eight publications each, highlights a diverse range of contributors with substantial contributions to the field. This diversity of expertise suggests a collaborative and multidisciplinary approach to glycerol waste utilisation research, where researchers from different backgrounds and regions contribute to the collective understanding and advancement of the field.

The presence of authors like Błażejak, S., Kieliszek, M., and Tyagi, R.D., with seven publications each, underscores the global interest and participation in glycerol waste utilisation research. These authors may represent emerging voices or regional expertise in the field, contributing to the dissemination of knowledge and the exchange of ideas on a global scale. The findings highlight the collaborative nature of glycerol waste utilisation research and the diverse expertise driving innovation and progress in sustainable waste management and resource recovery.

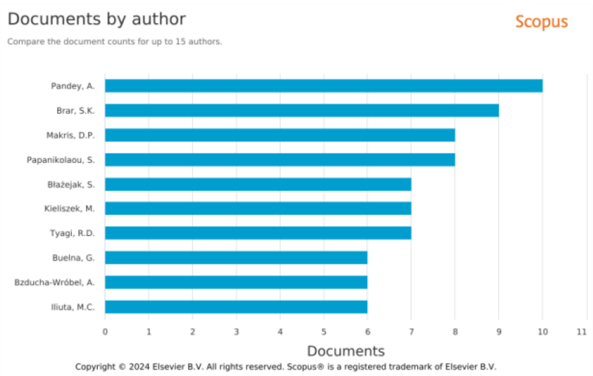

Fig. 3 The graph of the number of publications by the top 10 authors

4.5 Top 10 cited articles

Table 5 shows the top 10 most cited articles related to the bibliometric analysis of glycerol waste utilisation into value-added products from 2017 to 2024 extracted from the Scopus search engine. One notable finding is the emphasis on reviewing various aspects of waste valorisation, as evident in several articles such as Rezania et al. [49] and De Corato et al. [50]. These reviews provide comprehensive assessments of economic aspects, fuel properties, byproduct applications, and opportunities for integrated biorefining, offering valuable guidance for researchers, policymakers, and industry stakeholders seeking sustainable solutions for glycerol waste management and resource recovery.

Table 4 – Top 10 Most cited article articles related to the bibliometric analysis of glycerol waste utilisation

Authors	Title	Year	Source Title	Cited by

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Rezania S. et al. [49]	Review on transesterification of non-edible sources for biodiesel production with a focus on economic aspects, fuel properties and byproduct applications	2019	Energy Conversion and Management	236
Simón D. et al. [51]	Recycling of polyurethanes from laboratory to industry, a journey towards the sustainability	2018	Waste Management	169
Qin L. et al. [52]	From low-cost substrates to Single Cell Oils synthesised by oleaginous yeasts	2017	Bioresource Technology	156
De Corato U. et al. [50]	Assessing the main opportunities of integrated biorefining from agro-bioenergy co/byproducts and agroindustrial residues into high-value added products associated to some emerging markets: A review	2018	Renewable and Sustainable Energy Reviews	153
Ganesh Saratale R. et al. [53]	A comprehensive overview and recent advances on polyhydroxyalkanoates (PHA) production using various organic waste streams	2021	Bioresource Technology	148
De Clercq R. et al. [54]	Heterogeneous catalysis for bio-based polyester monomers from cellulosic biomass: Advances, challenges and prospects	2017	Green Chemistry	135
Luchese C.L. et al. [55]	Effect of blueberry agro-industrial waste addition to corn starch-based films for the production of a pH-indicator film	2017	International Journal of Biological Macromolecules	129
Kumar L.R. et al. [56]	A review on variation in crude glycerol composition, bio-valorisation of crude and purified glycerol as carbon source for lipid production	2019	Bioresource Technology	129
Kaur J. et al. [4]	Valorisation of crude glycerol to value-added products: Perspectives of process technology, economics and environmental issues	2020	Biotechnology Reports	123

Mohanty S.S. et al. [57]	A critical review on various feedstocks as sustainable substrates for biosurfactants production: a way towards cleaner production	2021	Microbial Cell Factories	120

Furthermore, the articles by Ganesh Saratale et al. [53] and Kumar et al. [56] described specific pathways for value-added product synthesis from glycerol waste, such as polyhydroxyalkanoates (PHA) production and lipid production. These studies highlight the potential of utilising glycerol as a versatile feedstock for generating high-value products, demonstrating the importance of innovative biotechnological approaches and process optimisation in maximising resource efficiency and environmental sustainability.

Moreover, the inclusion of articles addressing the utilisation of glycerol waste in biopolymer synthesis, such as De Clercq et al. [54] and Luchese et al. [55], underscores the broad spectrum of applications and the interdisciplinary nature of research in this field. These studies explore the feasibility of incorporating glycerol-derived compounds into biodegradable films and bio-based polyester monomers, reflecting efforts to promote circular economy principles and reduce reliance on fossil resources. Overall, the findings highlight the diverse pathways and emerging opportunities for valorising glycerol waste into value-added products, underscoring the importance of collaborative research, technological innovation, and sustainable practices in addressing global waste management and resource depletion challenges.

4.6 Publication by subject area

Figure 4 shows the analysis of publication trends across the subject area from 2017 to 2024 extracted from Scopus Analyzer. The analysis reveals several noteworthy findings. Firstly, Environmental Science emerges as the dominant subject area, representing 16.1% of publications, indicating a solid emphasis on glycerol waste utilisation for its environmental implications and sustainability. This focus underscores the growing recognition of glycerol waste as a potential environmental concern and the importance of developing sustainable solutions to mitigate its impact.

Secondly, Chemical Engineering and Energy rank prominently, constituting 14.7% and 12.7% of publications, respectively. These subject areas reflect glycerol waste utilisation in term of technological and engineering aspects, highlighting efforts to develop efficient conversion processes, optimise resource recovery, and harness glycerol as a renewable energy source. The significant representation of these fields suggests a concerted effort to translate research findings into practical applications and address pressing challenges in waste valorisation and energy sustainability.

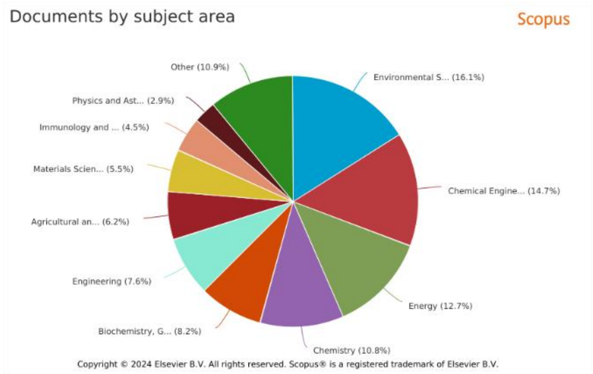

Fig. 4 Pie chart of publication by subject area

Furthermore, the distribution of publications across diverse subject areas such as Chemistry, Biochemistry, Genetics, and Molecular Biology underscores the interdisciplinary nature of glycerol waste utilisation research. Collaborative efforts across multiple disciplines, including Engineering, Agricultural and Biological Sciences, and Materials Science, are essential for addressing complex challenges and advancing knowledge in this field. The findings highlight the interconnectedness of various scientific domains in exploring innovative approaches to glycerol waste management and resource recovery, with implications for sustainable development and environmental stewardship

4.7 Publication by document type

Figure 5 and Table 6 show the analysis of publication trends across the document type from 2017 to 2024 extracted from Scopus Analyzer. Articles represent the predominant document type, comprising 80.2% of publications. The high publication percentages strongly emphasises original research findings and scholarly contributions to the field, reflecting the depth and breadth of ongoing investigations into glycerol waste utilisation. The high proportion of articles underscores the robustness of scientific inquiry and the rigorous examination of diverse aspects of glycerol waste conversion, valorisation, and environmental implications.

Additionally, reviews constitute 8.3% of publications, highlighting the importance of synthesising existing knowledge, identifying research gaps, and providing critical insights into the state-of-the-art in glycerol waste utilisation. Reviews serve as valuable resources for researchers, policymakers, and industry practitioners, facilitating informed decision-making and guiding future research directions. The presence of conference papers (7.0%) further emphasises the dissemination of novel findings and innovative approaches presented at scientific conferences and symposiums, contributing to the exchange of ideas and fostering collaboration within the research community.

Furthermore, the inclusion of document types such as book chapters, editorials, and short surveys underscores the diverse formats through which knowledge is disseminated in the field of glycerol waste utilisation. While representing a smaller proportion of publications, these document types are essential in providing specialised insights, addressing specific topics, and enhancing the scholarly discourse surrounding glycerol waste management and resource recovery. Overall, the findings underscore the multifaceted nature of research in glycerol waste utilisation and highlight the importance of diverse document types in advancing scientific understanding and promoting sustainable solutions in this critical study area.

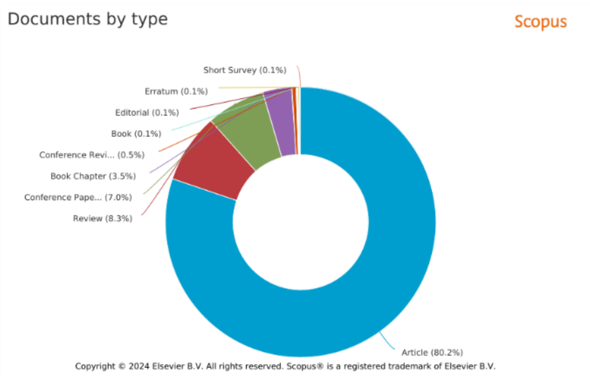

Fig. 5 Analysis of publication trends across the subject area from 2017 to 2024 extracted from Scopus Analyzer

Table 6 - Analysis of publication trends across the document type from 2017 to 2024

Document Type	Number of publications	Percentage
Article	1224	80.2
Review	126	8.3
Conference Paper	107	7.0
Book Chapter	53	3.5
Conference Review	8	0.5
Book	2	0.1
Editorial	2	0.1
Erratum	2	0.1
Short Survey	2	0.1

4.8 Co-Occurrence of keyword

Figure 6 shows the network visualisation of the co-occurrence analysis of all keywords (author and indexed keywords) for the study using VOSviewer. The co-occurrence of keywords in scholarly literature refers to the frequency with which specific terms appear together within documents, providing insights into the thematic relationships and prevalent topics within a research domain [58]. The co-occurrence analysis revealed a significant association between the keywords 'glycerol' and 'conversion,' indicating a strong focus on transforming glycerol waste into value-added products. Additionally, 'biodiesel production' and 'fermentation' frequently appeared alongside 'glycerol,' suggesting an emphasis on utilising glycerol as a feedstock for biofuel production through fermentation processes. This finding underscores the exploration of sustainable approaches to repurpose glycerol waste, aligning with the principles of green chemistry and circular economy.

Moreover, the occurrence of keywords such as 'lipid,' 'fatty acids,' and 'lipase' in conjunction with 'glycerol' indicates research interest in lipid metabolism and enzymatic conversion pathways, potentially exploring enzymatic routes for glycerol valorisation into lipid-based products. This finding suggests a multifaceted approach to glycerol utilisation, encompassing both microbial fermentation and enzymatic processes to enhance conversion efficiency and product diversity.

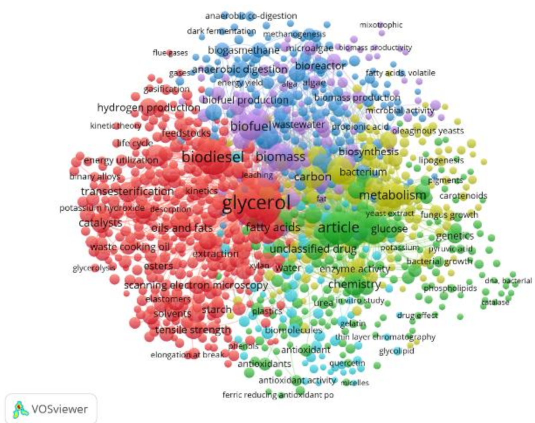

Fig. 6 Network visualisation of co-occurrence analysis by all keyword

Furthermore, the frequent co-occurrence of 'catalyst' and 'glycerol' underscores efforts to optimise catalytic systems for glycerol transformation to enhance reaction kinetics and selectivity towards desired products. This frequent co-occurrence reflects ongoing endeavours to develop efficient catalysts for various glycerol conversion routes, ranging from hydrogenolysis to oxidative processes, to achieve high yields and selectivity towards valuable compounds.

The analysis highlights a burgeoning interest in repurposing glycerol waste into value-added products, focusing on biofuel production, lipid metabolism, enzymatic conversion pathways, and catalyst development. These findings contribute to advancing sustainable solutions for glycerol valorisation, addressing environmental concerns associated with glycerol waste while unlocking its potential as a renewable feedstock for producing valuable chemicals and biofuels.

4.9 Bibliographic coupling by countries

Figure 7 and Figure 8 shows the network visualisation and overlay visualisation of bibliographic coupling by countries using VOSviewer. Bibliographic coupling analysis is a method used to explore the interconnectedness of research articles based on shared references [59]. Exploring the bibliographic coupling network unveils the leading contributors to glycerol waste valorisation research. Notably, India, China, Malaysia, Brazil, and the United States emerged as prominent figures, characterised by their significant publication outputs and strong connections within the scholarly community. This underscores their pivotal roles in driving advancements and collaborations in the field. This finding signifies not only the vast amount of research they produce but also their propensity to collaborate and build upon each of previous findings, evident in the thick links binding them together.

Beyond these leading forces, various countries like Australia, Canada, Germany, and others actively contribute to the research landscape. While their individual contributions may not be as voluminous, their presence signifies the burgeoning international interest in this field. This interconnected network paints a picture ripe with potential for collaboration, where knowledge sharing and expertise exchange can act as catalysts for progress, propelling research efforts forward and unlocking the true potential of glycerol waste valorisation.

Furthermore, the network reveals exciting patterns of collaboration. For instance, countries like Brazil and Malaysia share strong connections, potentially indicating joint research initiatives or shared focus areas. Similarly, the links between China and the United States suggest active knowledge exchange and co-development of technologies. These collaborations not only accelerate advancements in the field but also foster a global community working towards a common goal.

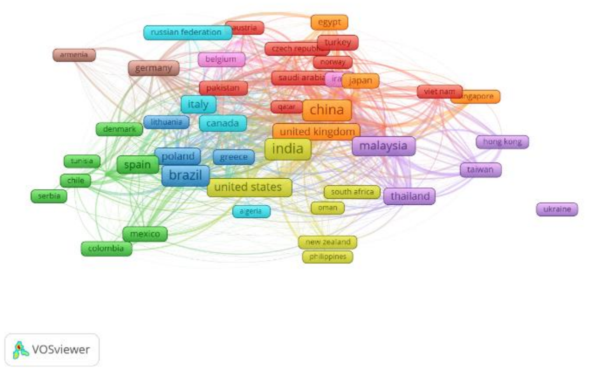

Fig. 7 Network visualisation of bibliographic coupling analysis by countries

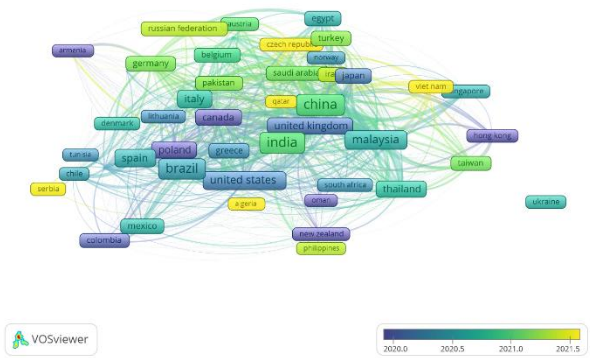

Fig. 8 Overlay visualisation of bibliographic coupling analysis by countries

4.10 Current and future development

The current research landscape on glycerol waste utilisation as a value-added product reflects a dynamic and evolving field, characterised by increasing interest and significant contributions from various countries, institutions, authors, and funding sponsors. Despite fluctuations in publication trends, there is a clear trajectory towards advancing technologies for converting glycerol waste into valuable products, driven by factors such as industrial sectors, government initiatives, and academic expertise in sustainable development and waste management.

Future developments should prioritise sustainability and efficiency in glycerol waste utilisation processes, aiming to optimise conversion technologies while minimising environmental impact. This will involve exploring promising avenues such as bioelectrochemical system, metabolic engineering of microorganisms, and integration with other biorefinery processes. Interdisciplinary collaboration across fields such as chemistry, engineering, and biotechnology will be crucial to drive innovation and address complex challenges in these areas.

While significant progress has been made, it is important to acknowledge the need to overcome technical hurdles in scaling up glycerol conversion processes and developing cost-effective purification methods. By embracing these future direction, adressing potential challenges, and fostering a global netwrok of researchers, industry stakeholders, and policymakers, we can unlock the full potential of glycerol waste as a valueable resource for a more sustainable future.

5. Conclusion

This bibliometric analysis reveals a burgeoning global research landscape focused on transforming glycerol waste into value-added products. Publication trends from 2017 to 2024, despite fluctuations, demonstrate a clear trajectory towards heightened interest and technological advancement in glycerol valorization. China, India, Brazil, and Malaysia emerge as key players, with international collaborations highlighting a global commitment to this field. Collaborative efforts between academia, research institutes, and governments are

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evident through the analysis of top affiliations and funding sponsors. Key research themes include biofuel production, lipid metabolism, enzymatic conversion, and catalyst development, showcasing a multifaceted approach to glycerol utilization. The current research landscape is dynamic and evolving, driven by industrial sectors, government initiatives, and academic expertise in sustainable development. Future developments should prioritize sustainable and efficient glycerol waste utilization processes, exploring avenues like bioelectrochemical systems, metabolic engineering, and integration with biorefineries. Interdisciplinary collaboration will be crucial to drive innovation and address challenges in scaling up processes and developing cost-effective purification methods. By embracing these directions, we can unlock the full potential of glycerol waste as a valuable resource for a more sustainable future.

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Statements and Declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of Generative AI and AI Assisted Technologies in the Writing Process

During the preparation of this work, the authors used Grammarly, Quillbot and ChatGPT in order to enhance the clarity, coherence, and grammatical accuracy of the manuscript. After using these tools/services, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Authors statements

Najwa Wajihah Mohd Rusli: Conceptualization, Methodology, Validation, Data curation, writing – original draft, Visualization. Ya Mohammad Nazir Syah Ismail: Conceptualization, Methodology, writing – original draft. Mohamed Hizam Mohamed Noor: Conceptualization, Validation, Supervision. Nurul Balqis Mohamed: Writing- review & editing. Fatin Amirah Razmi: Writing- review & editing.

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