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Review

A Scoping Review on Environmental, Economic, and Social Impacts of the Gasification Processes

Zahir Barahmand * and Marianne S. Eikeland

Department of Process, Energy and Environmental Technology, University of South-Eastern Norway, 3918 Porsgrunn, Norway; marianne.eikeland@usn.no
* Correspondence: zahir.barahmand@usn.no; Tel.: +47-31-00-80-00

Abstract: In recent years, computer-based simulations have been used to enhance production processes, and sustainable industrial strategies are increasingly being considered in the manufacturing industry. In order to evaluate the performance of a gasification process, the Life Cycle Thinking (LCT) technique gathers relevant impact assessment tools to offer quantitative indications across different domains. Following the PRISMA guidelines, the present paper undertakes a scoping review of gasification processes' environmental, economic, and social impacts to reveal how LCT approaches coping with sustainability. This report categorizes the examined studies on the gasification process (from 2017 to 2022) through the lens of LCT, discussing the challenges and opportunities. These studies have investigated a variety of biomass feedstock, assessment strategies and tools, geographical span, bioproducts, and databases. The results show that among LCT approaches, by far, the highest interest belonged to life cycle assessment (LCA), followed by life cycle cost (LCC). Only a few studies have addressed exergetic life cycle assessment (ELCA), life cycle energy assessment (LCEA), social impact assessment (SIA), consequential life cycle assessment (CLCA), and water footprint (WLCA). SimaPro® (PRé Consultants, Netherlands), GaBi® (sphere, USA), and OpenLCA (GreenDelta, Germany) demonstrated the greatest contribution. Uncertainty analysis (Monte Carlo approach and sensitivity analysis) was conducted in almost half of the investigations. Most importantly, the results confirm that it is challenging or impossible to compare the environmental impacts of the gasification process with other alternatives since the results may differ based on the methodology, criteria, or presumptions. While gasification performed well in mitigating negative environmental consequences, it is not always the greatest solution compared to other technologies.

Keywords: gasification; life cycle assessment; life cycle cost; social impact assessment; scoping review

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1. Introduction

After coal, petroleum, and natural gas, biomass is the world's fourth-largest energy source, accounting for a considerable amount of global primary energy consumption [1]. Biomass presently contributes roughly 14% of the world's yearly energy consumption in all forms [2]. As an alternative, biomasses, such as agricultural waste, forestry waste, municipal solid, and industrial waste, are renewable energy resources used for producing either solid or liquid fuels [3,4]. There are different processes to produce biomass energy, such as thermochemical, biological, and physical conversion (oilseed extraction). Thermochemical conversions can be categorized into combustion, pyrolysis, and gasification. Biological conversion can be achieved by fermentation or anaerobic digestion [5–8]. Moreover, there are some novel approaches to merging microbiology, electrochemistry, and electronics, such as microbial electrochemical technologies (METs) [9]. Converting organic sources into electricity and treating organic waste stream in microbial fuel cells (MFCs) [10], hydrogen or methane generation in microbial electrolysis cells (MEC) [11], CO2 elongation to volatile fatty acids (VFAs) in microbial electro-synthesis (MES) cells [12], low-cost desalination in microbial desalination cells (MDCs) [13], and microbial reverse electrodialysis cells (MRCs) using a combination of MFC and reverse electro-dialysis (RED) stack [14] are all examples of MET that may be used for wastewater treatment.

Contributing significantly to generating renewable energy, biomass gasification is an efficient and promising technology that can transform any biomass into valuable products via thermochemical process [15]. Gasification, pyrolysis, and direct combustion are the main thermochemical conversion technologies [16], where gasification is the most efficient process [17]. Gasification is the partially oxidation of carbonaceous materials at elevated temperatures to generate syngas, primarily carbon monoxide and hydrogen [18]. Moreover, this process produces variable amounts of biochar, pyroligneous acids, and tars [16].

Table 1 provides a list of main reactions in biomass gasification processes. One of the most severe problems encountered during biomass gasification is the formation of tar [19]. Tar condenses at lower temperatures and forms sticky deposits, increasing the difficulty of downstream handling and treatment [20]. Due to its numerous applications and benefits, the gasification process has received much interest worldwide. Biomass gasification may be widely used for different purposes, including biodiesel production through the Fischer Tropsch synthesis or conversion to valuable chemical products such as methanol, methyl ether, and polymers [21]. Moreover, the produced gas from the gasification (syngas) process can be used as a source of heat energy and electricity generation [16,22] or for the biological production of chemicals and biofuels through anaerobic fermentation processes [23–25].

Table 1. Main reactions in biomass gasification processes adapted with permission from [20], biomass and bioenergy; published by Elsevier, 2022.

Process	Stoichiometry	The Heat of Reaction (kJ/mole)
Char combustion reactions		
Partial combustion	$C + 1/2O_2 \rightarrow CO$	−111
Complete combustion	$C + O_2 \rightarrow CO_2$	−394
Char Gasification reactions		
Boudouard reaction	$C + CO_2 \rightleftarrows 2CO$	+173
Steam gasification	$C + H_2O \rightarrow CO + H_2$	+131
Hydrogasification reaction	$C + 2H_2 \rightarrow CH_4$	−75
Homogeneous volatile reactions		
CO oxidation	$CO + 1/2O_2 \rightarrow CO_2$	−283
H_2 oxidation	$H_2 + 1/2O_2 \rightarrow H_2O$	−242
CH_4 oxidation	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	−283
WGS reaction	$CO + H_2O \rightleftarrows CO_2 + H_2$	−41
Methanation	$CO + 3\,H_2 \rightleftarrows CH_4 + H_2O$	−206
Tar reactions		
Partial oxidation	$C_nH_m + (n/2)O_2 \rightarrow nCO + (m/2)H_2$	Between −715 and ≈ −2538
Steam reforming	$C_nH_m + nH_2O \rightarrow nCO + (m/2 + n)H_2$	Between +740 and ≈ +2302
Dry reforming	$C_nH_m + nCO_2 \rightarrow 2nCO + (m/2)H_2$	Between +980 and ≈ +3112
Hydrogenation	$C_nH_m + (2n\text{-}m/2)H_2 \rightarrow nCH_4$	Between −498 and ≈ −1815
Thermal cracking	$C_nH_m \rightarrow (m/4)CH_4 + (n\text{-}m/4)C$	Between −161 and ≈ −505
Biomass devolatilization	Biomass → char + tar + H_2O + light gases ($CO + CO_2 + H_2 + CH_4 + N_2 + C_xH_yO_z$...)	

However, replacing fossil fuels with biobased fuels can positively impact the environment; since biomass is considered a renewable resource, every technology has its limitations, and biomass gasification is no exception.

Unless suitable and efficient preventive measures are implemented and consistently enforced, biomass gasification plants result in environmental pollution, occupational health, and safety risks [22]. For example, the produced gas in its normal state is highly contaminated with condensable hydrocarbons, soot, char particles, and ash [26]. Gasification plants have many environmental issues, such as mass-burn incinerators, water, air pollution, ash, and other by-product disposals [27]. Economy, society, and the environment are the three elements of sustainability [28]. The LCT broadens the idea of cleaner production to include the product's complete life cycle and sustainability [29]. The term "life cycle thinking" refers to how a product's life cycle assessment (LCA), life cycle cost (LCC), and social impact assessment (SIA) are considered over its entire life cycle [30].

More precisely, LCT is a theoretical approach that studies improvements and reductions in all mentioned impacts at all processing stages (cradle-to-grave). These stages include extraction, conversion, transformation, distribution, use, demolition, and end-of-life treatment [31]. Nevertheless, it is not clear what kind of information is available in the literature about the scopes and challenges of assessing the environmental impacts of the biomass gasification process. Therefore, the present study aims to conduct a systematic review of biomass gasification processes' environmental, economic, and social impacts through a scoping review to discover how much LCT research has been undertaken. This study follows the PRISMA guidelines [32]. The problem is addressed in this study by answering the following four research questions:

- What are the significant interests in the most recent investigations on life cycle thinking of gasification processes?
- Which dimension (environmental, economic, and social) is these studies' most frequently used aspect?
- What are the main life cycle assessment tools, methodologies, and impact categories?

The research focuses on the challenges associated with the gasification process. However, the question remains whether or not this process has a lower environmental impact than commercial processes for producing chemicals and fuels from fossil sources. The remainder of the article is organized as follows. Section 2 provides a background to gasification process technology and its environmental impacts; Section 3 describes the research methodology; Section 4 gives research results; Section 5 discusses them; and Section 6 concludes the review.

2. Gasification Technology

Biomass gasification for energy generation may appear to be a new technique, although it has been around for over a century [33]. Even though gasification technology has been around for decades, it has yet to reach its full potential. The fundamental principles governing its operation, notably feedstock variability and the type of gasification system, are still ambiguous [34]. Gasification technology is a thermochemical process used to convert organic substances into valuable gas (so-called syngas, a mixture of CO and H_2). Temperature, equivalent ratio, and pressure impact the syngas composition [35]. The gasifier (reactor) and its configuration are the most critical factors affecting the reactions and products [36]. Generally, gasifiers are classified based on their fluidization regime (gas–solid contacting mode) and gasifying medium [37,38]. Based on the gas–solid contacting mode, fixed bed gasifiers (also known as the moving bed (a moving bed is also known as this type of gasifier since the fuel moves downward in the gasifier)), fluidized bed gasifiers, and entrained flow gasifiers are the three main types of gasifiers with commercial or near-commercial applications [34,39]. However, there are some other uses that employ specific gasifier types or gasification processes.

These technologies are usually targeted at utilizing a wider variety of feedstock than only coal and demonstrate innovative applications of gasification [40]. As illustrated in Figure 1, each type can be further subdivided into specific commercial types. In all gasification processes, however, the phenomena of pyrolysis followed by partial oxidation of the residual carbon are prevalent [41]. In general, due to the wide range of raw materials available, developing a valid theory to describe the entire gasification process is quite challenging [42]. Over the years, different suppliers have developed gasifiers commercially. Table 2 summarizes the technological development of the gasification process during the past decades [40,42–49].

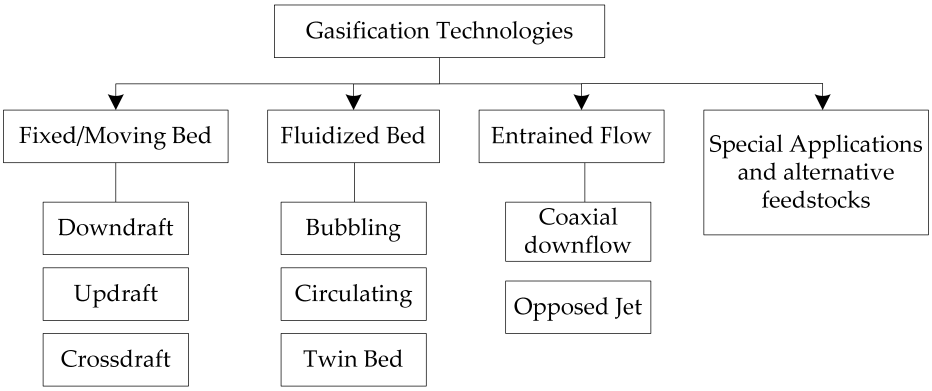

Figure 1. Gasification technologies.

Table 2. Gasifier technology development.

Commercial Technologies	**Development Started/Patented**	**Commercially Launched**
Entrained flow		
Koppers-Totzek gasifier	1938–1944	1948
Seimens SFG gasifier	1975	1984
CB&I E-Gas gasifier		1987
MHI gasifier	early 1980s	2007
EAGLE gasifier	1995	2002
GE Energy gasifier		1978
Shel gasifier	1956	1987
UHDE—PRENFLO gasifier	Late 1980s	1997
ECUST gasifier	early 1990s	
HCERI gasifier	1993	2005
MCSG gasifier	1980s	
TSINGUA OSEF gasifier		2003
Fixed bed		
Lurgi dry-bottom gasifier	early 1930s	1936
BGL slagging gasifier	1958	1974
Fluidized bed		
Winkler process		early 1930
KBR transport gasifier		1999
Twin reactor gasifier		1990
Rotating fluidized bed gasifier	1979	
Internal circulating gasifier		
Foster Wheeler CFB gasifier	early 1980s	mid 1980s
Great Point Energy gasifier	late 1970s	2005
GTI membrane gasifier		
U-GAS gasifier		2006
Special application		
Biomass and municipal solid waste (MSW) Gasification		2000
Plasma gasification		1999
Aerojet Rocketdyne Gasifier		2013
HT-L gasifier		2008
Black liquor gasification		2003
Hydrogasification	early 2000s	
Catalytic gasification	early 1970s	1979
Oil and gas partial oxidation	late 1940s	2006
Biological coal gasification	late 1980s	1990
Underground coal gasification		1939

2.1. Process Challenges

The gasification process still has to be optimized to reduce the energy loss caused by pretreatment of the biomass prior to the conversion process, optimizing the carbon conversion efficiency in the reactor, reducing tar production, and cleaning the syngas for further processing [16].

Both the gasifier's performance and the composition of syngas are affected by the moisture content of the biomass. Brammer and Bridgwater showed that high moisture content in the biomass has a negative impact on the quality of the produced syngas and the system's overall performance [50].

Although a high moisture content might not be a big problem in a fluidized bed due to using steam as the fluidizing agent, the entrained gasifier is more sensitive to the moisture. A downdraft gasifier's maximum moisture content is typically 25%, whereas an updraft gasifier's maximum moisture content is often 50% [51]. Drying biomass before gasification might result in high capital and energy expenditures in small- and medium-scale gasification plants [16].

The contaminants within the biomass might reduce the efficiency of the thermochemical conversion process [52]. The most significant challenge for chemical production and energy generation using biomass gasification may be the high cost of auxiliary equipment required to produce clean contaminant-free syngas. Consequently, the overall cost of the process increases significantly, accounting for more than half of the ultimate price of biofuel produced [53].

One of the most severe problems encountered throughout the various biomass gasification methods is tar formation [54]. Condensable hydrocarbons, with or without additional oxygen-containing hydrocarbons, and more complex polycyclic aromatic hydrocarbons make up the tars formed during gasification [55]. Tar formation results in the deactivation of catalysts, the halting of the downstream operations, and the generation of carcinogenic compounds [56].

2.2. Gasification's Environmental Impacts

The environmental impact of biomass gasification is related to input and output values of material flows, energy flows, emissions to air and water, and by-products. The input material composition depends on the type of biomass used and its origin. The gasification process is robust, and mixtures of biomasses can be used, which challenges the evaluation of the biomass feed. The contaminants in the material will vary and affect the environmental impact assessment. Other input flows related to water resources, the energy sources for heating the reactor, and catalytic compounds used in the reactor must be considered in the assessment. The output of emissions to air and water needs to be carefully monitored. Fly ash generation, dust, gaseous emissions, and water pollution are significant adverse environmental impacts [57]. Moreover, combustible gases, vapors, dust, fire risks, carbon monoxide poisoning, and gas leaks are the primary hazards of gasifier operation [58].

Dust is created during storage, handling, feeding, feedstock preparation, and fly ash removal [59]. Because of the acidic conditions in landfills, the ash that remains after gasification is hazardous and poses particular problems [60]. The gasification process produces many tiny solid particles, mostly fly ash and char (unburned carbons). These cause a similar issue as dust and biomass ash. Ash may also constitute a fire hazard, demonstrating the need to keep it wet and sealed [22]. During the cooling and cleaning of produced syngas, wastewater is produced as an effluent [61]. The disposal of some contaminates in effluents, such as phenolic and terry components, reveals severe environmental problems and requires adequate pretreatment before discharging into the environment [26].

3. Research Design

The present study adopts a scoping review methodology to summarize and analyze the history and status of life cycle thinking in the gasification technology context and indicate related challenges and limitations. In addition, the possible promising areas for improvement and knowledge gaps were identified. A scoping review, at a general level, aims to map the key concepts rapidly underpinning a research area and the main sources and types of evidence available which can be undertaken as stand-alone projects in their own right, especially where an area is complex or has not been reviewed comprehensively before [62]. At least four frequent reasons exist for conducting a scoping study: to evaluate the study's scope, range, and nature; to assess the practicality of conducting a comprehensive systematic review study; to summarize and share findings; and to explore knowledge gaps in the literature [63]. This technique is chosen because it is much more rigorous than a simple search and requires multiple and systematic searches [64].

There is a contrast between systematic and scoping reviews [65]. In the systematic review, the main concern is based on a well-defined research question with a relatively narrow range for answers, while a scoping review addresses broader questions and topics [63].

3.1. Searching Procedure

The following steps were conducted under the scoping review protocol illustrated in Figure 2:

1. Four main research questions were defined.
2. After multiple tries and errors, an initial search was undertaken utilizing available scientific databases (Scopus, ScienceDirect, and Web of Science (WoS)). The search strings are provided in Table 3. At this level, no limitations were set to the initial search. The search was applied to the title, abstract, and keywords in Scopus and ScienceDirect and all WoS categories. As a result, 6682, 9755, and 2460 documents (in all categories) were listed in Scopus, WoS, and ScienceDirect, respectively. Because of the number of AND/OR operator limitations, the string was divided into three strings. The asterisk (*) is a regularly employed symbol that broadens a search by finding terms with identical initial letters. It may be used in conjunction with distinctive word stems to obtain variants of a phrase with less keystrokes. For example assess* can find assess, assessing, assessment, assessed, etc.
3. Since life cycle studies on gasification technologies have mainly gained prominence over the past two decades, this study focused on published literature (2017–2022). Applying this limit, the number of documents dropped to 2363, 5515, and 1310 for Scopus, WoS, and ScienceDirect, respectively.
4. As another limitation, the language of the studies was limited to English. As a result, only a few documents were eliminated. The remaining studies became 2275, 5480, and 1310 for Scopus, WoS, and ScienceDirect, respectively.
5. By applying the search strings to only the title, a significant reduction in the number of documents was observed. The listed studies experienced a significant drop to 144, 116, and 91 for Scopus, WoS, and ScienceDirect, respectively.
6. For the final step at the screening stage, by tailoring the string and eliminating "OR environmental," more accurate results were achieved, and the number of documents was reduced to 40, 43, and 35 for Scopus, WoS, and ScienceDirect, respectively (118 studies in total).
7. There were many duplicates in the list. Therefore, in this stage (step 3 in Figure 2), by trimming the list and removing duplicates, 48 documents remained. These were listed in Excel to perform the necessary investigation.
8. The eligibility of the studies was assessed by a full-text screening. As a result, six studies were considered non-relevant and were eliminated from the list. All in all, the final list consisted of 42 publications.
9. The bolographic information of the results, such as the title, the country of origin, the technology, the year of publication, the aim of the study and scope, the methodology, and the barriers and challenges, was extracted.

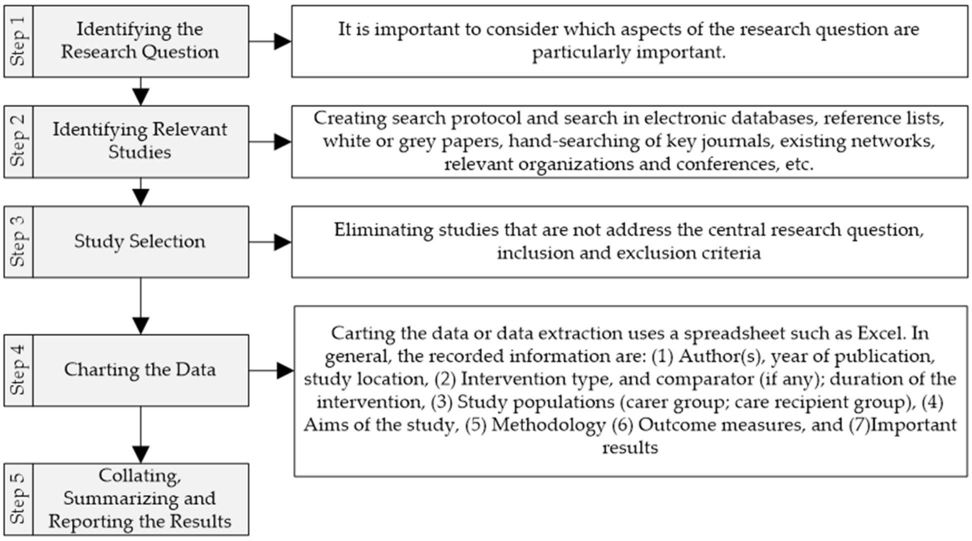

Figure 2. Overall research process scheme.

Table 3. Initial strings used in databases.

Scopus:
TITLE-ABS-KEY(gasification AND (((life AND cycle AND assessment) OR LCA OR environmental) OR social OR ((life AND cycle AND cost) OR (cost AND assess *))))
Web of Science (WoS):
ALL (gasification AND (((life AND cycle AND assessment) OR LCA OR environmental) OR social OR ((life AND cycle AND cost) OR (cost AND assess *))))
ScienceDirect:
1. (gasification AND(life AND cycle AND assessment) OR LCA OR environmental), 2. (gasification AND Social) 3. ((life AND cycle AND cost) OR (cost AND assess))

Figure 3 illustrates the PRISMA flow diagram of the present study. PRISMA methodology is a well-established reporting template for scoping reviews. It illustrates the screening processes' results to report the remaining studies at each stage.

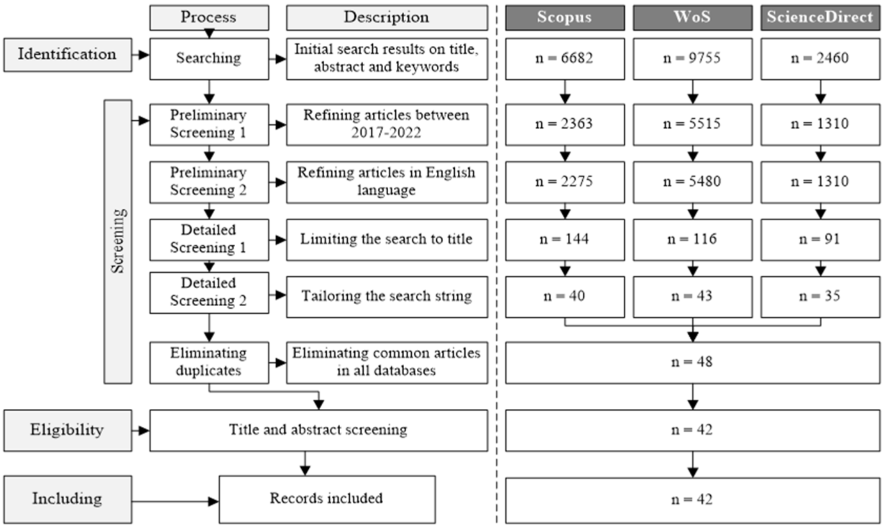

Figure 3. PRISMA flow diagram.

3.2. Limitations

The present study is limited to English language studies and the literature published after 2017. Furthermore, although it covers conference papers and proceedings, this study did not cover grey literature such as publicly accessible records and reports.

4. Results

This section provides the descriptive information associated with the latest studies on life cycle assessment (LCA), life cycle cost (LCC), and social impact assessment (SIA) of the gasification process.

4.1. Number of Publications

The year-wise analysis gives a picture of the research progress. It may be challenging to discern a clear trend based on recent studies. To better understand how interest has grown in this topic, the years 2000–2016 were added to the research period. Figure 4 provides information about the number of published studies from 2000 to February 2022. The overall trend emphasizes accelerated growing interest in gasification technologies' study through the lens of life cycle thinking. The highest contribution belongs to 2021 by 15 publications, almost 100% higher than publications in 2018. Although there are four listed publications within the first two months of 2022 so far, it is expected to have many more upcoming publications. The significant drop in 2020 may be due to the COVID-19 pandemic when it reaches its peak.

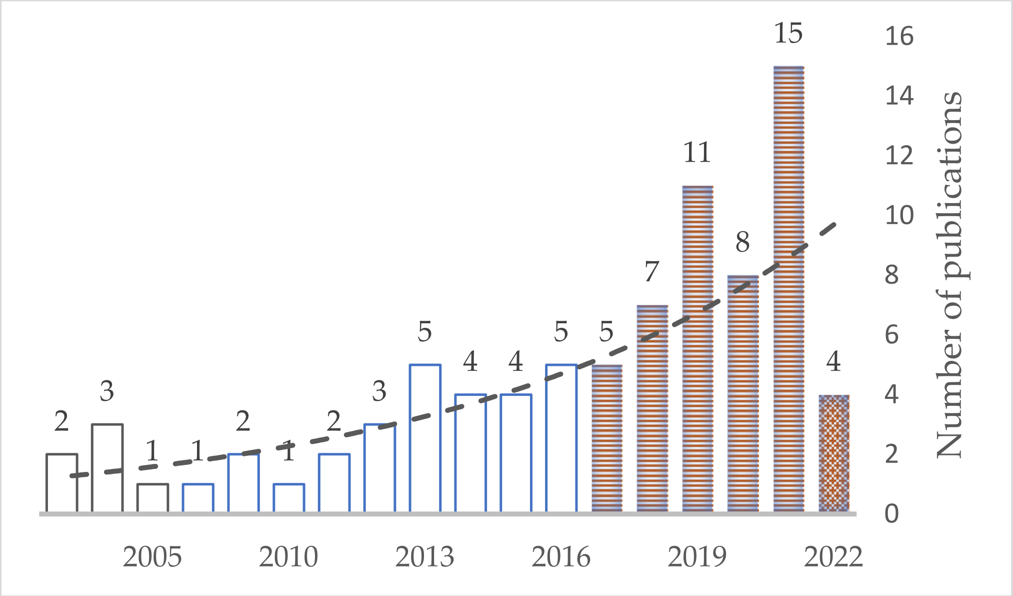

Figure 4. The number of selected studies and overall trend from 2000 to February 2022.

4.2. The Origin of Studies

Country-wise analysis of the selected publications shows that twenty-eight countries contributed to this topic. As seen in Figure 5, the highest contribution belongs to China with 15 studies, followed by the United States and Spain with seven publications each, and Italy with six. Fifteen countries were involved in only a single study categorized under "Other Countries." Austria, Chile, Colombia, Denmark, Iran, Ireland, Malaysia, Philippines, Qatar, Romania, Saudi Arabia, Singapore, South Africa, Switzerland, and Thailand belong to the group with one publication. In another classification, over seventy percent of the contribution belongs to the developed countries.

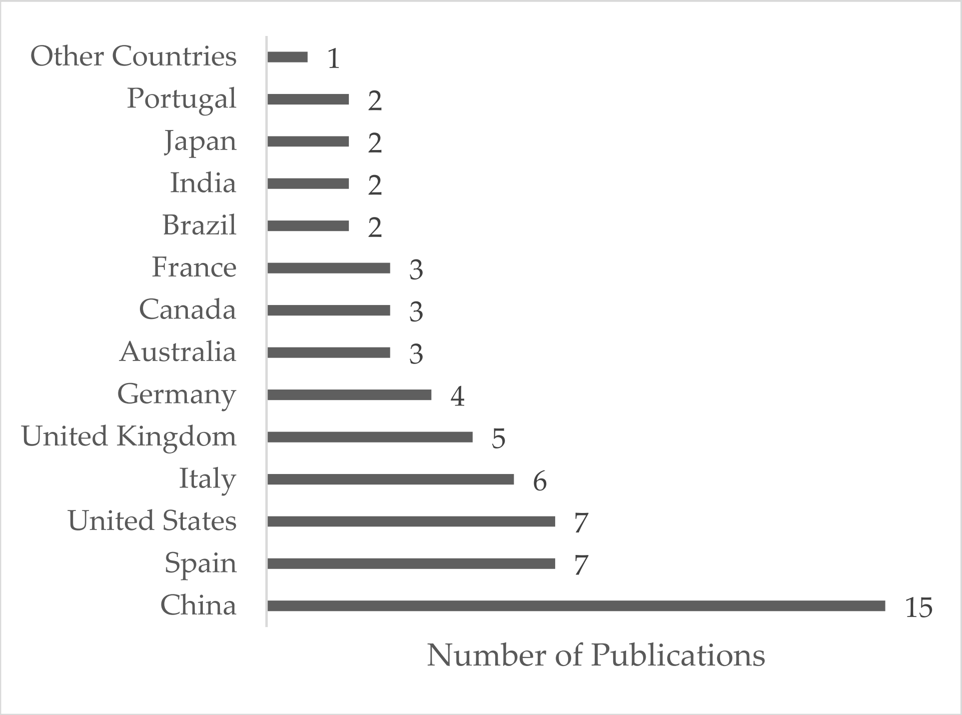

Figure 5. Country's contribution to publications (from 2017 to February 2022).

4.3. Publications by Document Type

As discussed earlier, all types of publications were considered in this review. Over eighty percent of selected documents were articles, followed by conference papers (fifteen percent) and book chapters and reviews (two percent each). As seen in Figure 6, only two review articles demonstrated the study's significance. Ramos and Rouboa [66] reviewed different aspects of life cycle thinking (environmental, social, and economic) on plasma gasification. On the other hand, Michaga et al. [67] conducted a techno-economic and life cycle assessment review on jet fuel produced through biomass gasification.

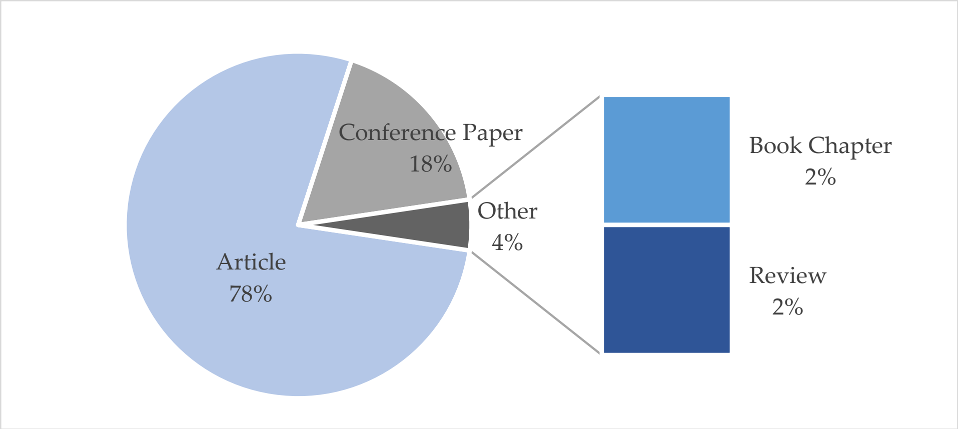

Figure 6. Categorization based on document types.

4.4. Publications by Subject Area

Fourteen studies on gasification processes addressed the life cycle thinking approaches (based on extracted data from Scopus). As seen in Table 4, energy, environmental science, and engineering have the highest contribution with 30, 27, and 17 percent, respectively, followed by chemical engineering.

Table 4. Subject areas in the selected publications.

Energy	30%	Physics and astronomy	3%
Environmental science	27%	Social sciences	3%
Engineering	17%	Economics, econometrics, and finance	2%
Business, management, and accounting	5%	Agricultural and biological Sciences	1%
Chemical engineering	5%	Chemistry	1%
Mathematics	4%	Computer science	1%
Earth and planetary sciences	3%		

5. Discussion

A comprehensive content-based analysis was performed to answer several research questions. This section focuses on recent research conducted during the previous five years. Among 48 selected studies belonging to the period between 2017 to February 2022, 42 studies were considered relevant to the topic. Except for review articles by Ramos and Rouboa [66] and Michaga et al. [67], other studies focused on a specific aspect of life cycle thinking in the gasification process. Table 5 lists different life cycle thinking aspects and their frequencies in the selected publications.

Table 5. LCT aspects and frequencies in the studies.

Life cycle assessment (LCA)	40
Life cycle cost (LCC)	10
Social impact assessment (SIA)	2
Life cycle energy assessment (LCEA)	3
Exergetic life cycle assessment (ELCA)	4
Consequential life cycle assessment (CLCA)	1
Water footprint (WLCA)	1

Among seven different approaches, LCA was dominating, followed by LCC. Most of the studies (over seventy percent) studied a single aspect. Almost twenty percent studied two different aspects, and ten percent studied three aspects. For example, Korre et al. [68] performed a life cycle environmental impact assessment on the underground coal gasification process, including CO_2 capture and storage. Li et al. [69] assessed ELCA and LCA of hydrogen production from biomass-staged gasification, and Li and Cheng [70] compared hydrogen production from coke oven gas and coal gasification from three different points of view (life cycle energy assessment, carbon emissions, and life cycle costs).

Different software and databases were employed to carry out the life cycle assessment. The software SimaPro® (PRé Consultants, Netherlands) and GaBi® (sphere, USA) showed the highest contribution, followed by OpenLCA. Ecoinvent and ELCD were at the top of the list of employed databases. Table 6 provides an overview of the selected articles' life cycle methods and different approaches using software and databases. The cradle-to-grave approach encompasses the whole life cycle of a resource, from its extraction ('cradle') to its use and disposal ('grave') [71]. Cradle-to-gate is another approach studied by different researchers [70,72–74]. Cradle-to-gate examines a product's partial life cycle, beginning with resource extraction (cradle) and ending at the factory gate before transporting to the consumer [75]. Cradle-to-gate evaluations are occasionally used to develop environmental product declarations (EPDs), referred to as business-to-business EDPs [71]. As mentioned earlier, all the assessments were performed based on process simulations. Among fourteen studies that referred to their process software, eleven simulations were conducted using Aspen Plus® (Aspen Technology, Inc., USA) versions 8.8, 11, 9 [21,68,69,73,76–82]. The other three software were EASETECH [83], the integrated environmental control model (IECM) [84], and DeST [85]. Uncertainty analysis was considered in fifty percent (22 out of 42) studies. Only sensitivity analysis and Monte Carlo simulation were employed among many methods and tools to model and analyze uncertainty in a system. Sixteen studies only used sensitivity analysis, three applied Monte Carlo simulation to cope with uncertainty, and the remaining three employed both methods. More information is given in Table 6.

Table 6. Overview of life cycle methods, approaches, used software, and databases in 42 articles.

Life Cycle	Uncertainty Analysis	Approach	LCA Software	Database	Reference
LCA		Well-to-wheels	SimaPro 8.5.0.0		[21]
LCA			GaBi 6	CLCD	[68]
LCA + ELCA	SA				[69]
LCA + LCC + LCEA	SA	Cradle-to-Gate			[70]
LCA	SA	Cradle-to-Gate			[72]
LCA		Cradle-to-Gate	SimaPro 8		[73]
LCEA + LCA	SA	Cradle-to-Gate	OpenLCA 1.10.3	Ecoinvent 3.7.1	[74]
LCA	MCS		SimaPro 9.1.1.1		[76]
LCA	SA		GaBi 9		[77]
LCA		Cradle-to-Grave	SimaPro	Ecoinvest 3.5	[78]
LCA + ELCA			SimaPro 8.5.0.0	Ecoinvest 3.2, CML	[79]
LCA	SA, MCS		OpenLCA	ELCD 3.2	[80]
LCA + ELCA					[81]
LCA + LCC	SA				[82]
LCA	SA		GaBi 9.2.0		[83]
LCA + LCC					[84]
LCA					[85]
LCA			SimaPro 9		[86]
LCA + LCC	MCS		GaBi 7.3.3.153	v 6.115	[87]
CLCA	SA		SimaPro	Ecoinvent	[88]
LCA	SA		GaBi		[89]
LCA	MCS		SimaPro		[90]
LCA + ELCA			GaBi 7.0		[91]
WLCA	SA, MCS		-	-	[92]
LCA	SA				[93]
LCA	SA	Cradle-to-Grave	SimaPro 8.5.2	Ecoinvent 3.4	[94]
LCA	SA, MCS	Cradle-to-Grave			[95]
LCA			Microsoft Excel		[96]
LCA	SA				[97]
LCA		Cradle-to-Grave	OpenLCA, Microsoft Excel		[98]
LCA	MCS		SimaPro 8.0.4		[99]
LCA			OpenLCA	ELCD 3.2	[100]
LCA	SA		GaBi 7.3		[101]
LCA + LCC + SIA			SimaPro 8.5.2.0	Ecoinvent 2016	[102]
LCA + LCC + SIA				SILCA	[103]
LCA + LCC					[104]
LCC			-	-	[105]
LCA + LCC + LCEA	SA				[106]
LCA + LCC	SA				[107]
LCA	SA	Cradle-to-Grave	GaBi 7.0		[108]
LCA				Ecoinvent 2.0	[109]
LCA			GaBi 4.131		[110]

Table 7 summarizes the different processes and their used feedstock, the number of scenarios in the analysis, and the year of publication in 42 recent articles. As seen, a wide range of raw materials has been covered, such as municipal solid wastes [78,86,89–91,111], wheat straw [69,92,93], biomass, water for supercritical water gasification processes [81,94], pinewood [80], etc. The majority of the articles used scenario-based analysis to compare different alternatives.

Table 7. Overview of processes, feedstock, and the number of publication scenarios in 42 articles.

Process	Feedstock	Scenarios	Reference
Gasification	Pet coke	6	[21]
Gasification	Underground coal	20	[68]
Staged gasification	Wheat straw	2	[69]
Gasification	Coke oven gas and coal	4	[70]
Combined biomass gasification with a 199 kW solid oxide cell	Different chips or pellets	4	[72]
Combustion vs. gasification	Sugarcane or agave	4	[73]
Combined gasification and internal combustion engine	Rice Straw	1	[74]
Gasification vs. fast pyrolysis	Biomass (AW)	2	[76]
Fermentation vs. pyrolysis vs. gasification	Corn Stover	3	[77]
Supercritical water gasification and oxidation	MSW	2	[78]
Integrated gasification SOFC	Cedar	1	[79]
Biomass-integrated gasification combined cycle	Pinewood	1	[80]
Supercritical water gasification	Biomass and water	1	[81]
Fluidized bed (FB) and entrained flow (EF) gasification	Biomass	2	[82]
Gasification vs. pyrolysis	RDF (MSW + MRP)	3	[83]
Gasification	Underground Coal	1	[84]
Gasification	Biomass	1	[85]
Incineration vs. gasification	MSW	2	[86]
Gasification	Wastewater	6	[87]
Gasification	Swine manure	1	[88]
Incineration vs. gasification	MSW	3	[89]
Gasification vs. landfilling	MSW	2	[90]
Incineration vs. gasification	MSW	4	[91]
Chemical looping gasification	Corn and wheat straw	2	[92]
Wheat straw gasification	Wheat straw	1	[93]
Supercritical water gasification	Biomass and water	1	[94]
Pulverized coal entrained flow gasification (PEF)	Pulverized coal	1	[95]
Four scenarios of operation	Dry MSW (SRF)	4	[96]
Syngas fermentation vs. gasification	Prosopis Juliflora	2	[97]
Biochar gasification	Woodchip	1	[98]
Incineration vs. gasification–pyrolysis	Paper and plastic packaging waste	2	[99]
Hydrothermal carbonization vs. gasification	USW	2	[100]
Blast furnace—basic oxygen furnace (BF-BOF)	Coal	6	[101]
Gasification	Cork wastes	4	[102]
Gasification vs. steam reforming	Biomass and natural gas	2	[103]
Gasification vs. steam reforming	Biomass and natural gas	2	[104]
Gasification	Woody biomass	1	[105]
Gasification	Rice husks and straw	2	[106]
Gasification	Woody straw biomass	4	[107]
Pyrolysis vs. gasification vs. incineration	SRF	7	[108]
Gasification	Coal	6	[109]
Plasma gasification	MSW	1	[110]

Among selected articles, fourteen studies compared gasification and another method for biomass conversion or disposal, such as incineration, pyrolysis and fast pyrolysis, landfilling, hydrothermal carbonization, combustion, fermentation, and steam reforming. Keller et al. [83] conducted a comparative life cycle analysis of two feedstock recycling technologies: waste gasification and pyrolysis. Although both feedstock recycling paths decrease greenhouse gas emissions under similar production system assumptions, gasification resulted in a greater reduction than pyrolysis. Similarly, Alcazar-Ruiz et al. [76] conducted a comparative life cycle study to measure the sustainability of two processes (gasification and fast pyrolysis) for bio-oil production from agricultural wastes. Separation stages were the primary contributors to all mid-point impact categories in the fast pyrolysis. Finally, contrary to the results reported in [83], the most ecologically beneficial method of creating one MJ bio-oil was not the gasification process. Bianco et al. [86] focused on the environmental consequences of generating power from the incineration and gasification of municipal solid waste. The study revealed that, depending on the accounting rules, the effect outcomes might vary greatly and can lead to opposing conclusions for some impact categories. Corvalán et al. [100] performed a comparative LCA analysis on the hydrothermal carbonization (HTC) of urban organic solid waste and gasification process. Upon evaluating the conversion of 1 ton of organic fraction USW, the results indicated that gasification performed better than HTC. Considering the generation of 1 MWh, HTC has a lower environmental effect than gasification because of its better energy efficiency. Similarly, Parascanu et al. [73] compared the LCA of four scenarios of gasification and combustion with two feedstock each (agave bagasse and sugarcane bagasse) in Mexico.

The results indicated that, environmentally, agave bagasse combustion is the best option, followed by agave bagasse gasification, sugarcane bagasse gasification, and sugarcane bagasse combustion. A comprehensive LCA was conducted by Sun et al. [77] to compare the environmental performance of converting corn stover to biofuels in fermentation, pyrolysis, and gasification processes. They conclude that the total environmental performance of the system for producing high-grade jet fuel from maize stover by gasification synthesis is optimum. Moreover, fermentation scores poorly in almost all environmental effect categories for 1 GJ of biofuel, whereas pyrolysis has the greatest comparable CO2 emission. Similarly, Tang et al. [91] found that, in comparison with incineration, although gasification-based systems were excellent in mitigating environmental impacts, they had a greater impact on global warming. Muthudineshkumar and Anand [97] reported that for biofuel production from biomass, between gasification and syngas fermentation, gasification reduced pollution emissions and was an ecologically friendly method of fuel use. Nevertheless, in contrast, due to economic and societal problems, Valente et al. [103,104] found that hydrogen from biomass gasification cannot currently be regarded as a viable alternative to conventional hydrogen. On the other hand, considering economic and economic performances separately, environmentally, hydrogen from biomass gasification performs substantially better than hydrogen from steam methane reforming, although the opposite result was reached in economics. Zang et al. [80] examined the technological alternatives of biomass gasification, syngas combustion, and CO_2 emission control in the LCA of eight biomass-integrated gasification combined cycles (BIGCCs). Results showed that the GWP of BIGCC systems is less than 240 kg CO_2-equivalent/MWh, which is negative when BIGCC systems are integrated with CO_2 capture and storage technology. In addition, the exterior syngas combustion technique has a lower GWP, human toxicity potential, and ozone depletion potential than the internal syngas combustion technology, and the Selexol CO_2 capture [112] method is more environmentally friendly than the MEA CO_2 capture [113] method.

In another approach, two studies addressed by Ouedraogo et al. [90] compared LCA of gasification and landfilling for the disposal of MSW. The LCA found that, in comparison with gasification, landfilling is a significant contributor to global warming, ecotoxicity, eutrophication, acidification, smog formation, and cancer and non-cancer human health outcomes. Finally, Demetrious and Crossin [99] assessed the environmental performance of mixed paper and mixed plastic waste management in landfills, incineration, and combined gasification–pyrolysis using LCA for impacts mentioned in Table 8. According to the data, mixed paper handled with incineration or gasification–pyrolysis created fewer greenhouse gas emissions than mixed plastic managed in landfill. The studies above confirm that it is impossible to make conclusions about the gasification process because the studies could have opposite results under different methodology, boundaries, or assumptions.

Six studies have investigated a combined process (gasification combined with one or more processes). Through LCA, Reaño et al. [74] evaluated the environmental performance and energy efficiency of rice straw power generation utilizing a combination of gasification and an internal combustion engine (G/ICE). The results showed that the GWP of this process was 27% lower than the GWP of rice straw on-site burning, and that biogenic methane emissions from flooded rice fields may be mitigated to lower the system's GWP by 34%. Using energy generated by the G/ICE system to supply farm and plant activities might reduce the environmental impact and increase the effectiveness of the process. Iannotta et al. [78] investigated the environmental performance of a novel integrated process based on supercritical water gasification and oxidation for treating carbon black and used oil as model wastes. It is demonstrated that this process decreases effects in several categories and results in a positive energy balance during the life cycle, ensuring good environmental performance. Moretti et al. [72] offered the LCA of novel high-efficiency bio-based power technology that combines biomass gasification with a 199 kW solid oxide fuel cell to generate heat and electricity. It demonstrated superior environmental performance compared to natural gas and the German/European grid. The other two studies were also discussed above [80,99].

Table 8. Overview of impact categories and life cycle methodology in 42 articles.

Impact Category	Methodology	Reference
GWP, ODP, SF, AP, EP, CP, NCP, RE, ETP, FFD	GREET	[21]
GWP, ADP, AP, EP, FAExP, HTP, ODP, MAExP, POFP, TExP	CML2011	[68]
GWP, POFP		[69]
GWP, En-C, Ec-C	IPCC AR5,GWP100	[70]
CCP, MFRRD, PF, POFP, AP, TEP, WRD	Attributional LCA	[72]
GWP, AP, EP, HTP, MExP, ODP, FDP	Midpoint ReCiPe 2016	[73]
GWP, NER	ReCiPe	[74]
GWP, ODP, HOFP, EOFP, TAP, FEP, MEP, HTPs, HTPnc, FFP, WCP	Mid-point ReCiPe	[76]
GWP, AP, EP, HTP, ODP	CML 2001	[77]
CCP, ODP, HTPc, HTPnc, PF, IR-HH, IR-E, POFP, AP, TEP, FEP, MEP, MExP, LO, WRD, MFRRD		[78]
GWP, ADP, AP, EP, En-C	CML 2015	[79]
GWP, AP, EP, HTP, ODP		[80]
GWP, AP, EP, ODP		[81]
	GREET	[82]
GWP	IPCC AR5, GWP100	[83]
GWP		[84]
GWP, AP, POFP, HTP, SWP, AEP, NRDP, PF		[85]
GWP, AP, EP, HTP, MExP, ODP, FDP	Mid-point ReCiPe	[86]
GWP, HTPnc, LO, IR, TE, MEP, FEP, CCP, HTPc, AEP, TAP, FAP	Environmental Footprint 3.0	[87]
GWP, WRD, MEP, AEP, FRD	IMPACT World+, IPCC, GWP100	[88]
	EDIP 2003	[89]
GWP, SF, AP, EP, HH, ExP	GREET, LandGEM, HELP	[90]
GWP, AP, NEP, POFP	EDIP 9	[91]
WRD		[92]
GWP, ODP, AEP, AAP, AExP, TExP, IR, MRD, LO, RI	IMPACT 2002+	[93]
GWP, ADP, AP, EP, ODP, POFP	CML-IA, ReCiPe Endpoint, CED	[94]
GWP, ODP, HH, MEP, TAP, AEP, C, NC, FExP	SDU model	[95]
GWP	ReCiPe	[96]
GWP		[97]
GWP, AP, E, HTP, MExP, ODP, FDP	CML baseline	[98]
AP, CCP, EP, POFP	IPCC AR4,GWP100	[99]
GWP, AP, EP, HTP, MExP, ODP, FDP	ReCiPe, DALY	[100]
GWP, AP, EP, HTP, MExP, ODP, FDP	CML 2001	[101]
GWP	ReCiPe midpoint, CED	[102]
GWP, AP		[103]
GWP, AP, CED	ISO	[104]
-	-	[105]
	IPCC	[106]
GWP		[107]
GWP, AP, TEP, POFP, HT-a, HT-s, Exs		[108]
GWP	GWP100	[109]
	CML 2001	[110]

In another approach, Li et al. [107] performed a multi-criteria optimization model (TOPSIS) based on LCA for a biomass gasification-integrated combined cooling, heating, and power system to study the overall performance criterion, the primary energy saving ratio, the total cost saving ratio, and the CO_2 emission reduction ratio. It is concluded that the system fueled by biomass greatly differs from that fueled by fossil fuels in energetic, economic, and environmental aspects. Consequently, exclusive assessments and optimizations are required.

The remaining 23 studies have addressed different aspects of LCT (mostly LCA) for a single gasification process in different impact categories. Table 8 gives an overview of covered different impact categories and the life cycle methodologies employed by these articles.

6. Conclusions

The current research addresses a need left by the absence of thorough reviews on life cycle thinking approaches for gasification processes. Even though the gasification process's environmental and techno-economic aspects are well recognized, measuring their social impacts is still infrequent. Following the PRISMA methodology and a scoping review, 42 studies between 2017 and 2022 were selected. Among different LCT approaches, LCA received the most attention, followed by LCC. In a limited number of studies, exergetic life cycle assessment (ELCA), life cycle energy assessment (LCEA), social impact assessment (SIA), consequential life cycle assessment (CLCA), and water footprint (WLCA) were investigated. It can be concluded that the life cycle impact and cost assessments have received the most attention since 2017. SimaPro®, GaBi®, and OpenLCA were employed significantly. The uncertainty analysis was performed in more than half of the studies using sensitivity analysis and Monte Carlo simulation.

Moreover, the results indicate that the recent studies were interested in adopting scenario-based and comparative life cycle assessments. The results confirm that it is hard to draw conclusions regarding the environmental impacts of the gasification process since findings may vary depending on the technique, parameters, or assumptions. Although the gasification process significantly reduces negative environmental impacts, it is not always the best alternative compared to different processes. While these studies suffer greatly from the uncertainties, in future works, it is suggested that uncertainty analysis should be considered in all the investigations.

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Nomenclature

ADP	abiotic depletion potential	LO	land occupation
AP	acidification potential	LCA	life cycle assessment
AW	agricultural waste	LCC	life cycle cost
AAP	aquatic acidification potential	LCEA	life cycle energy assessment
AEx	aquatic ecotoxicity potential	MAExP	marine aquatic ecotoxicity potential
AEP	aquatic eutrophication potential	MEP	marine eutrophication potential
C	carcinogens	MExP	marine ecotoxicity potential
CCP	climate change potential	MRP	materials rich in plastics
CED	cumulative energy demand	MRD	mineral resource depletion

CLCA	consequential life cycle assessment
Ec-C	economic Costs
ExP	ecotoxicity Potential
Ex-s	ecotoxicity via solid
En-C	energy Consumption
EF	entrained Flow
EP	eutrophication potential
ELCA	exergetic life cycle assessment
FB	fluidized bed
FDP	fossil depletion potential
FFP	fossil fuel potential
FRD	fossil resource depletion
FAP	freshwater acidification potential
FAExP	freshwater aquatic ecotoxicity potential
FExP	freshwater ecotoxicity potential
FEP	freshwater eutrophication potential
GWP	global warming potential
HH	human health
HTPc	human toxicity potential—cancer
HTPnc	human toxicity potential—non-cancer
HT-a	human toxicity via air
HT-s	human toxicity via solid
HTP	human toxicity potential
IR	ionizing radiation
IR-E	ionizing radiation—environment
IR-HH	ionizing radiation—human health
MFRRD	mineral, fossil, and renewable resource depletion
MCS	Monte Carlo simulation
MSW	municipal solid waste
NRDP	National Rural Development Program
NER	net energy ratio
NC	non-carcinogens
NEP	nutrient enrichment potential
ODP	ozone depletion potential
PF	particulate formation
POFP-E	photochemical oxidation formation potential—ecosystems
POFP-H	photochemical oxidation formation potential—humans
RDF	refuse-derived fuel
RI	respiratory inorganics
SA	sensitivity analysis
SF	smog formation
SIA	social impact assessment
SRF	solid recovered fuel
SWP	sustainable water partnership
TAP	terrestrial acidification potential
TExP	terrestrial ecotoxicity potential
TE	terrestrial eutrophication
USW	urban solid waste
WCP	water consumption potential
WLCA	water footprint
WRD	water resource depletion

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